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Hydropower Geotechnical Foundations:

Current Practice and Innovation Opportunities for Low-Head Applications

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Photograph (top-left) is of the Tennessee Valley Authority’s Norris hydropower dam and a rock core specimen taken from the dam’s foundation; located in Norris, Tennessee; photograph dated March 8, 2020.

Photographs (top-right and bottom) are of the US Army Corps of Engineers’ Chickamauga Lock replacement project; located in Chickamauga, Tennessee; photographs dated June 12, 2019.

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Environmental Sciences Division

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS, ACRONYMS, AND INITIALISMS

2D	two-dimensional
3D	three-dimensional
AACE	Association for the Advancement of Cost Engineering
AASHTO	American Association of State Highway and Transportation Officials
AEP	annual exceedance probability
AI	artificial intelligence
ASCE	American Society of Civil Engineers
ASDSO	Association Society of State Dam Safety Officials
BMP	best management practice
CFRD	concrete-face rockfill dam
CPT	cone penetration test
DOE	US Department of Energy
FEMA	Federal Emergency Management Agency
FERC	US Federal Energy Regulatory Commission
ICC	initial capital cost
IHRB	Iowa Highway Research Board
IRENA	International Renewable Energy Agency
LiDAR	laser imaging, detection, and ranging
LRFD	Load Resistance and Factored Design
MHK	marine and hydrokinetic
NAVFAC	Naval Facilities Engineering Command
NID	National Inventory of Dams
NPD	non-powered dam
NRCS	US Natural Resource Conservation Service
NSD	new stream-reach development
ORNL	Oak Ridge National Laboratory
PFMA	potential failure modes analysis
PLT	point load testing
R&D	research and development
RCC	roller-compacted concrete
SAR/InSAR	synthetic aperture radar/ interferometric synthetic aperture radar
SMH	Standard Modular Hydropower
SPT	standard penetration test

UCS	uniaxial compressive strength
USACE	US Army Corps of Engineers
USBR	US Bureau of Reclamation
USCS	Unified Soil Classification System
USGS	US Geological Survey
USSD	US Society of Dams
WBS	work breakdown structure
WPTO	Water Power Technologies Office

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EXECUTIVE SUMMARY

Hydropower is a renewable energy resource that produces electricity from flowing water under pressure. Engineered hydropower structures, such as dams, are used to create a hydraulic head, enabling a turbine-generator unit to convert pressurized flow into electricity. While hydropower has been a source of renewable energy since antiquity, new development in the United States has slowed in recent decades. Based on recent resource assessments, the largest opportunity to expand hydropower in the United States is from new stream-reach development (i.e., new hydropower development along stream-reaches that do not currently have hydroelectric facilities or other forms of infrastructure, such as dams). Roughly 75% of identified new stream-reach development potential is from low-head sites (less than 30 ft of head), which typically suffer from smaller power densities and higher normalized costs, given economies of scale. Hydropower developers and other stakeholders are thus interested in strategies to reduce initial capital costs while practicing sustainable development to maximize environmental compatibility with minimal disruption to natural aquatic life, sediment, and water flows.

Historically, civil works have represented a significant cost driver for new hydropower development, with the foundation system representing a major cost component and source of uncertainty. The foundation system is the collection of engineered structural features (e.g. cutoff trenches, walls, grouting, anchors) constructed at or below the preconstruction ground surface that interfaces between the overlying structures (superstructures) and the bed material below (subsurface). Development of a hydropower foundation system must consider the various characteristics of the surrounding stream environment and subsurface while adhering to the engineering requirements of the superstructure that it supports. The care of water, excavation, and other construction activities are important features of foundation design and construction. The design and construction cost of the foundation system is largely dependent on the site geology and riverbed composition and is influenced by the level of geotechnical assessment required and conducted. Thus, a hydropower facility’s geotechnical foundation is often highly site-specific, with proper site selection and assessment being important to project success.

The foundation system is designed to provide structural stability (of the foundation and dam), limit seepage, ensure public safety, and maintain functionality for the project life, during both construction and facility operations. Inadequate foundation or dam design can result in dam failure and the uncontrolled release of significant volumes of water, which could cause a high number of casualties and extensive property damage downstream of the failure. According to the Association of State Dam Safety Officials, approximately 30% of all historical dam failures in the United States are attributed to foundation or abutment defects, and another 20% are attributed to piping or seepage through the embankment, foundation, or abutment. To ameliorate these safety considerations, foundations often require massive amounts of construction material (e.g., grout, concrete, engineered dam fill) and long construction times.

Foundation design also requires significant analysis prior to construction because the initial in-stream and abutment subsurface conditions are site-specific, and sufficient data for them often are lacking. Current practice requires on-site assessment, using expensive drilling and invasive and non-invasive investigation methods, to determine the expected cost of foundation material and treatment. Additionally, foundation construction often requires site dewatering (and other care of water activities), which involves constructing temporary diversion structures upstream and often downstream, called cofferdams, and water diversion systems that route water around the construction site. Cofferdams and water diversion systems can drastically increase construction costs and contribute to environmental disruption, including modification of flow patterns and benthic habitats.

Given the technical, economic, and environmental challenges associated with hydropower foundations, opportunities exist to improve the current state of practice and to develop new and innovative solutions to

challenges frequently encountered with traditional approaches. With this understanding, it is critically important to understand and document the current state of practice for hydropower geotechnical foundations, identify key challenges, and define opportunities for innovative solutions.

To this end, this report[1] documents the current state of practice across the three main phases of geotechnical foundation development: (1) geotechnical site assessment, (2) design, and (3) construction for hydropower systems. It also describes the major challenges with conventional approaches and identifies opportunities for innovation to reduce hydropower foundations costs, timelines, and risks.

Key takeaways from this report include the following:

- Approximately 80% of available low-head sites are expected to have foundations on soil beds rather than rock beds, suggesting that rockfill and earthfill dams may be the most cost-effective conventional dam type for new projects.
- Geotechnical and geologic investigation activities are time-consuming and expensive but are essential to define the parameters and criteria needed for foundation design.
- Certain riverbed soil and bedrock types present significant technical challenges or require expensive foundation construction, which can prove financially prohibitive for low-head project development.
- Modular hydropower design and prefabricated modular foundations represent a promising but unproven paradigm for new hydropower development. Design and construction approaches using optimized and highly repeatable, reliable components would benefit project cost, time, and risk but require additional research and development.
- Temporary construction features for foundations, including cofferdams, water diversion, and water control systems, can prove costly and have inherent construction risk.
- For economically viable development, hydropower geotechnical foundations should be limited to 4 to 15% of the project's total initial capital costs. Many proposed projects have experienced cost overruns attributable to foundation difficulties or surprises during construction. These overruns may have been due to inadequate investigations, lack of adequate engineering effort to tailor the structures to site geology and topography, and/or contractual terms, among other considerations.
- Challenges for hydropower foundations and opportunities for innovative technology solutions are identified in the following areas (consistent with the three main phases of foundation development):
    - Geotechnical site assessment
    - Foundation design and materials
    - Construction methods and technology

Ultimately, this report aims to provide information about geotechnical foundations for low-head hydropower and to motivate transformative technologies to support hydropower growth.

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[1] Foundation-related site conditions and considerations are highly site-specific. The information presented herein is not intended to replace the professional site evaluations and geotechnical assessments necessary for accurate site characterization prior to hydropower development. The contents of this report are intended to provide concise information, rather than guidance.

1. INTRODUCTION

Over the past century, hydropower has been the world's leading source of renewable energy generation, comprising nearly 7% of total utility-scale generation. It generates 80 GW of installed capacity in the United States.[2] In addition to providing a flexible, low-cost source of renewable electricity, hydropower systems often provide non-power benefits including flood control, irrigation, water supply, navigation, and recreational opportunities (DOE, 2016). With strong growth in the 20th century through the 1970s, hydropower additions have declined in recent decades, primarily owing to economic and environmental challenges facing new development (Uria-Martinez, Johnson, and O'Connor, 2018). Unlike costs for other energy resources such as coal and natural gas, fuel costs for hydropower are not a significant cost driver;[3] instead, project feasibility largely depends on the developmental costs and timelines associated with the design and construction phases (Fang, 1991; O'Connor et al., 2015).

At the center of these key relationships is the foundation system, defined as the collection of engineered structural features constructed at or below the preconstruction ground surface that interfaces between the overlying structures and the bed material below. The foundation design process encompasses extensive geotechnical investigations into the site's subsurface conditions, or the engineering properties (e.g., strength, deformability, and permeability) of the underlying rocks and soils (Fang, 1991; Gulliver and Arndt, 1991; Day, 2010). The results of these investigations inform the extent and type of construction materials necessary for the associated foundation and superstructure (e.g., the dam in conventional hydropower facilities). The planned structure, bed material, seismic stability, and many other factors inform the types of foundation treatments that should be employed. Foundation construction can include various water control activities (e.g., dewatering, diversion, coffer damming), excavation, grouting, cutoff walls, and many other features or processes that vary depending on the subsurface characteristics and superstructure design.

Historically, many hydropower development projects have experienced cost overruns attributable to foundation difficulties or unexpected challenges (i.e., changed conditions) experienced during construction, some of which could be avoided through earlier and more thorough assessment and design considerations. Foundation construction costs and timelines become more challenging for low-head new stream-reach development (NSD; i.e., new hydropower development along stream-reaches that do not currently have hydroelectric facilities or other forms of infrastructure, such as dams), where *low-head* is defined as up to 30 ft of hydraulic head (i.e., the difference in elevation between upstream and downstream water levels) or roughly 50 ft of structural height (i.e., the distance between the top-of-dam and its foundation base).[4] Unlike other forms of hydropower development (e.g., non-powered dam [NPD] or canal/conduit development) that may leverage existing engineered foundations, NSD requires integration into a natural stream environment, where the geotechnical conditions may be highly uncertain.

Because properly designed foundations (including abutments) are key to ensuring dam safety and can present cost and timeline challenges during design and construction, the Department of Energy's (DOE) Water Power Technologies Office (WPTO) has sponsored a study focused on geotechnical site assessment[5], design, and construction for hydropower geotechnical foundations. The study, presented in

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[2] Available from https://www.eia.gov/energyexplained/hydropower/where-hydropower-is-generated.php (accessed August 10, 2020).

[3] Available from https://www.eia.gov/todayinenergy/detail.php?id=410 (accessed August 10, 2020).

[4] Example visual representations of hydraulic head, structural height, and dam height are provided in Figure 1. These terms are also defined in APPENDIX A.

[5] The term "geotechnical site assessment" is used extensively throughout this report to refer to both (1) general hydropower foundation-related siting considerations and activities related to a site's stream and terrain characteristics, and (2) geotechnical site assessments, such as subsurface characterization, investigation, and testing.

this report and led by Oak Ridge National Laboratory (ORNL) and Knight Piésold Consulting, (1) documents the current state of practice in hydropower foundation development in the United States and (2) identifies key challenges and innovation opportunities for hydropower foundations, with a focus on low-head NSD project development cost, timeline, and risk. Through this report, DOE WPTO aims to provide information about geotechnical foundations for low-head hydropower and motivate transformative technologies and methods needed to support future hydropower growth through cost, timeline, and risk reduction.

Although geotechnical foundations are required to construct a variety of hydropower system structures, this report focuses primarily on geotechnical foundations interfacing with conventional, low-head dam types (Section 3.4.1.1), because dams present the primary technoeconomic challenge for hydropower foundations owing to their size, external loads, and weight requirements. In addition, foundations for less-conventional modular superstructures (Section 3.4.1.2) are considered for their potential cost and timeline reductions. Given the current lack of prototype deployment, modular superstructures are not described in detail herein. Information about spillways and powerhouses is also provided in less detail. Thus, geotechnical foundations related to conventional hydropower are the main focus of this study.

Study Scope and Focus

- Geotechnical foundations related to conventional hydropower.
- Geotechnical foundations for low-head application (30 ft or less of head; 50 ft or less structural height).
- Hydropower development in new stream-reaches that do not currently have hydroelectric facilities or other forms of infrastructure (e.g., dams).
- Challenges and innovation opportunities related to foundation geotechnical site assessment, design, and construction.

The report is organized as follows:

- Section 2 gives a background overview of hydropower, including its benefits, typical conventional facility layout (Section 2.1), and US development (Section 2.2). It also presents a conceptual hierarchy of hydropower foundation systems used to frame the remainder of the report (Section 2.3).
- Section 3 describes various characteristics relevant to hydropower foundations for undeveloped US streams, including watershed and stream characteristics (Section 3.1) and subsurface and geologic characteristics (Section 3.2). Using available data on select stream and subsurface characteristics, an analysis of low-head NSD opportunities along undeveloped US streams is provided (Section 3.3). Finally, high-level superstructure characteristics and the suitability of conventional low-head dam types are presented (Section 0).
- Section 4 presents the current state of practice in foundation development across three main foundation development phases: geotechnical site assessment (Section 4.1), foundation design (Section 4.2), and foundation construction (Section 4.3).
- Section 5 provides a representative assessment of conventional hydropower foundation costs (Section 5.5) and timelines (Section 5.6).

- Section 6 addresses key challenges facing conventional hydropower foundations, aligned to the three main foundation development phases presented in Section 4.

- Section 7 presents opportunity areas and example opportunities for innovative hydropower foundation technologies across the three main foundation development phases presented in Section 4 and highlights some advances in non-hydropower industries.

- Multiple appendixes are included to provide supporting information.

2. BACKGROUND

In addition to the renewable energy produced, hydropower can provide a multitude of ancillary grid services—generation flexibility, frequency response and regulation, spinning and non-spinning reserves, and black start capabilities—that are crucial to safe, reliable, and economical power system operation (DOE, 2016). However, new hydropower facilities commonly face a long, expensive development process owing to unique site conditions (O'Connor et al., 2015; DOE, 2016; Uria-Martinez, Johnson, and O'Connor, 2018). In general, facility costs are site-specific, with NSD development being the most expensive class of hydropower development (DOE, 2016). To this end, DOE (2016) identifies technology innovation as a key cost reduction strategy to improve new hydropower cost competitiveness while meeting the need for environmental sustainability.

This section establishes the background of US hydropower and is organized into three sections:

- Section 2.1 illustrates how a typical conventional hydropower facility is composed and operated.
- Section 2.2 describes the current state of hydropower development in the United States.
- Section 2.3 presents a hydropower foundation system conceptual hierarchy to provide context and to distinguish among a hydropower facility subsurface, foundation, and superstructure.

2.1 HYDROPOWER FACILITY LAYOUT

The most common type of hydropower facility is impoundment (also referred to as conventional or traditional hydropower); others are diversion (or run-of-river) and pumped storage.[6] For a conventional facility, the resulting headwater (or reservoir) can offer significant non-power benefits, such as flood control, environmental services, navigation, storage for irrigation, storage for public water supply, and recreation. Although most hydropower facilities are unique (i.e., site-specific) to some degree, they share common features. Conventional hydropower development involves damming a flowing water source to amass potential energy (i.e., hydraulic head) for power generation. A penstock typically conveys the water from the upstream reservoir around or through the dam to a powerhouse before releasing it downstream to the tailwater (i.e., tailrace). In the powerhouse, the flowing water spins one or more turbine-generator units (i.e., a turbine with a shaft attached to a generator) to generate electricity through mechanical-to-electrical energy conversion. Hydropower facilities typically include one or more spillways and/or other outlet structures to release additional flows or draw down the headwater elevation when necessary. These flows can be used to pass debris, allow fish migration, maintain environmental flows, or pass flood water, among other purposes.

Like most other civil works, hydropower facilities require engineered foundations upon which the dam, spillway, powerhouse, and other structures sit to transfer loads between the superstructure (i.e., anything above the foundation interface constituting the facility's components) and subsurface (i.e., anything below the foundation-subsurface interface), facilitate relief of pore pressure, and control seepage and draining functions. Figure 1 shows an example schematic of a typical conventional hydropower facility (a concrete dam is shown). Foundation-related characteristics, along with scoping definitions for subsurface, foundation, and superstructure, are further described in Section 3. Additional information on hydropower foundation practices is provided in Section 4.

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[6] Available from https://www.energy.gov/eere/water/types-hydropower-plants (accessed August 10, 2020).

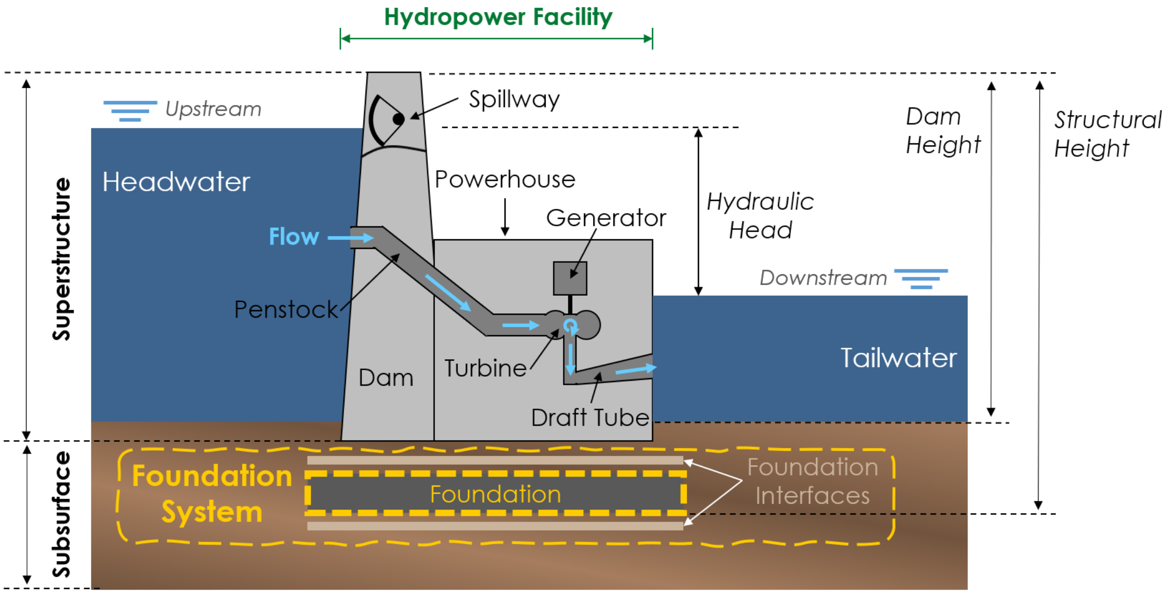

Figure 1. Typical conventional concrete-dam hydropower facility with important components indicated. Source: ORNL. Some facility components (e.g., abutments) are not illustrated. Not to scale.

2.2 STATE OF HYDROPOWER DEVELOPMENT IN THE UNITED STATES

The US hydropower fleet has roughly 80 GW of generating capacity across nearly 2,300 facilities (Uria-Martinez, Johnson, and O'Connor, 2018). Recent hydropower projects have come in the form of upgrades to existing facilities or refurbishments at NPDs or conduits, most of which were small (<10 MW); there have been few NSD sites (Uria-Martinez, Johnson, and O'Connor, 2018). These development trends strongly correlate with recent federal initiatives to bolster development in the hydropower industry. The Federal Energy Regulatory Commission (FERC), the primary power regulatory authority in the United States, recognized that the conventional hydropower licensing process is lengthy and complex, lasting multiple years. These issues, coupled with high initial capital costs (ICC) and extensive environmental concerns, lead to high project attrition rates in the project development pipeline (Uria-Martinez, Johnson, and O'Connor, 2018). Accordingly, exemptions were created for two types of development: <10 MW projects on nonfederal NPDs built before 2005, and <40 MW projects on man-made, non-powered conduits.[7]

For most types of new hydropower development (including NSDs), projects must strongly mitigate their impact on the surrounding aquatic, riparian, and terrestrial ecosystems while balancing public water resource and energy needs (DOE, 2016). Resource assessments sponsored by DOE WPTO in the past decade show untapped energy potential available at both NPD and NSD sites across the United States: total resource capacity estimated at nearly 12 GW and 66 GW, respectively (Hadjerioua, Wei, and Kao, 2012; Kao et al., 2014). With NSD opportunities representing the largest remaining potential for additional hydropower generation capacity, federal and private research and development (R&D) investments targeting hydropower technology are needed (DOE, 2016). Given the relatively small hydropower growth from NSD and the importance of maintaining environmental compatibility,

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[7] Available from https://www.ferc.gov/industries-data/hydropower/licensing/exemptions-licensing (accessed August 10, 2020).

successful NSD projects are likely to be small, run-of-river applications that emphasize stream and environmental functionality rather than employing reservoir impoundments.

2.3 HYDROPOWER FOUNDATION SYSTEM HIERARCHY

For the purposes of this report, an in-stream hydropower facility is modeled as a system of three interconnected components: subsurface, foundation system, and superstructure, which are described in the following points. Although these definitions may differ from standard industry usage, they provide a clear scope to consistently frame the remainder this report. Figure 2 illustrates these components and some of their major characteristics.

- The local *subsurface* describes the site conditions prior to development. It is highly site-specific and comprises the soil and geologic formations below the dam site and other facilities associated with the project. With the subsurface representing natural conditions at the site, subsequent design of the superstructure and foundation system must consider the conditions present. Thus, the design of both the superstructure and foundation system are dependent upon subsurface conditions, the characteristics of which can be modified (to some degree) by foundation treatment to meet engineered design specifications.

- The *foundation system* is a collection of engineered structural features constructed at or below the preconstruction ground surface that interfaces with the superstructure and subsurface between (and including) abutments (i.e., the sides of a valley against which a dam is constructed). The primary purposes of the foundation system are to provide structural stability and support, and to control seepage. The foundation system also includes the subsurface resulting from engineered treatment methods such as excavation, grouting, anchoring, and trenching, and could include modular foundation technologies, which are described in Section 3.4.1.2. Various construction activities (e.g., cofferdams, dewatering, excavation, and erosion and scour protection) are often required to enable engineered treatment. Design components that may be considered for a dam foundation include cutoff trenches, trenches, walls, and anchors (typically for concrete gravity dams). As shown in Figure 2, various innovative technologies could be used to develop a hydropower foundation.

- The *superstructure*[8] comprises the facility features above the foundation that provide the functions necessary for a hydropower facility, such as blocking and passing water, housing generation equipment, and providing maintenance access. Superstructures include dams, spillways, and powerhouses; modular superstructures providing generation or passage functions (e.g., fish, recreation, sediment, or water passage) are also plausible (Section 3.4.1.2). Dam subcomponents considered part of the superstructure include the dam core, filters and drains, and geotextile membranes/blankets.

As shown in Figure 2, information about the stream environment (Section 3.1) and subsurface (Section 3.2) is used to perform geotechnical site assessment (Section 4.1) and inform foundation design (Section 4.2) and construction (Section 4.3) through an iterative process, described in more detail in Section 4. Dam designers conventionally include both the treated subsurface and the foundation system (as defined in this report) when they use the term “foundation”; the same meaning is used in describing the foundation throughout this report. The way in which the foundation interface is designed and constructed depends on characteristics of both the superstructure and the subsurface (as indicated by the two-way arrows on the right of the diagram), with engineering and environmental characteristics (Section 4) as well as technoeconomic considerations (Section 5) influencing the development process.

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[8] Throughout this report, the term “superstructure’ is primarily used to refer to the dam, since the dam represents the primary challenge for hydropower foundations because of its size, external loads, and weight requirements.

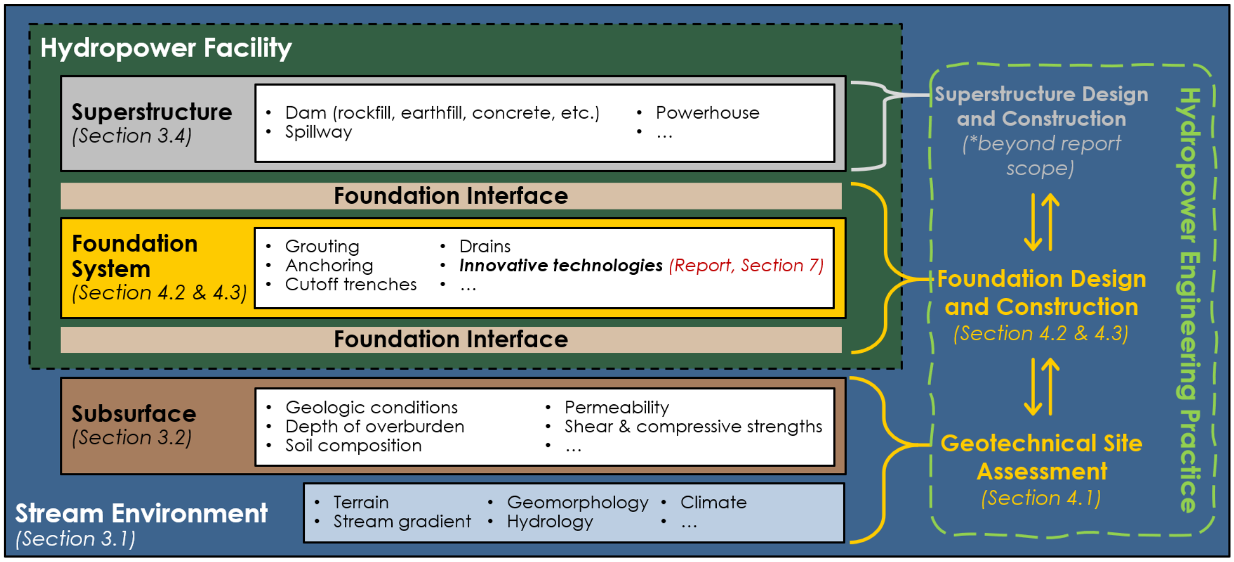

Figure 2. Hierarchy of hydropower foundation system within the context of a stream environment and engineering practice. Note that ellipses represent additional information beyond what is shown in the diagram. Section numbers identify where each topic is generally covered within this report.

3. FOUNDATION-RELATED CHARACTERISTICS FOR UNDEVELOPED US STREAMS

This section introduces the major concepts and characteristics relevant to hydropower foundations. To provide a high-level discussion, the authors focus on the major classes of subsurface conditions and superstructures, as well as consideration of the surrounding watershed and stream environment. However, hydropower development site conditions are highly specific, and the information presented herein is not intended to replace the professional site evaluations and geotechnical assessments necessary for accurate site characterization prior to hydropower development. The discussion is organized as follows:

- Section 3.1 describes key features, processes, and characteristics of watersheds and stream environments that influence subsurface conditions, as supplemented by APPENDIX B.
- Section 3.2 characterizes the major classes of subsurface conditions in the United States and the features that are important for foundation design and superstructure selection, as supplemented by APPENDIX C.
- Section 3.3 presents a high-level analysis of available low-head hydropower sites based on available national data. The estimates of likely subsurface presence are intended to help characterize common low-head NSD opportunities; the results are uncertain given the lack of site-specific assessments available for national-scale assessment and the assumptions made.
- Section 0 discusses high-level superstructure characteristics (described in more detail in Section 4) and presents results of a suitability assessment for conventional dam types among low-head NSD opportunities.

3.1 WATERSHED AND STREAM CHARACTERISTICS

At a given site, the characteristics of the upstream watershed and stream largely determine the riverbed composition and hydraulic conditions, shaped predominantly by geology, vegetation, soil type and thickness, erosion, runoff, and sediment transport processes. Surface runoff from rainfall carries eroded sediment from the surface of the catchment into the stream, and its hydraulic forces then carry the sediments downstream. Combined, these processes determine the amount of sediment entering the stream (sediment yield and stream turbidity), the deposition or buildup of the sediment, and the material characteristics of sediment (e.g., grain-size, sorting) in the stream (USBR, 2006b). These properties, in conjunction with regional and site geology, largely dictate design requirements for the foundation system and superstructure. For example, if the rate of sediment erosion is higher than the rate of deposition, the stream will likely have a fairly exposed or shallow bedrock channel. That is because sediment carried into the channel from adjacent slopes and upstream reaches is continuously transported downstream, further exposing and eroding the underlying bedrock. Additional information on relevant features, processes, and characteristics of watersheds and streams is presented in APPENDIX B.

A river system can be simplified into three primary zones based on the rates of sediment production, transfer, and deposition (e.g., Schumm, 1977):

- Zone 1: the headwaters reach, which is generally characterized by steeper surface slopes; faster erosion rates; incised bedrock channels; and large angular sediments such as gravel, cobbles, and boulders.
- Zone 2: the transitional reach, in which sediment transport (usually of moderate-sized sediments such as silt, sand, and gravel) is the dominant behavior but erosion still occurs and typical streams occupy areas of lower average topographic relief relative to the headwaters.

- Zone 3: the depositional or tailwaters reach, in which energy in the water column (proportional to the slope of the channel) generally drops to a point at which sediment transport occurs slowly, allowing sediment deposition, which is usually of finer materials (e.g., clays, silts, and sands), to be the dominant behavior.

These characteristic watershed reaches are depicted in Figure 3. This representation is idealized, as sediments can be eroded, mobilized, transported, and deposited along the stream system and can vary over time as hydrologic conditions and geomorphic processes evolve. The watershed's geologic and hydrologic history also greatly controls the type, size, and distribution of sediments transported in any given area.

The three primary zones are also generally associated with *mountainous* (Zone 1), *hilly* (Zone 2), or *valley* (Zone 3) "terrain classes," with streams in mountainous terrain generally having higher gradients (i.e., slopes) and streams in valley terrain having lower gradients. These terrain classes are used in Section 3.3 to characterize stream-reaches and in Section 5 to frame foundation classes used in the representative cost and timeline assessments in Section 5.

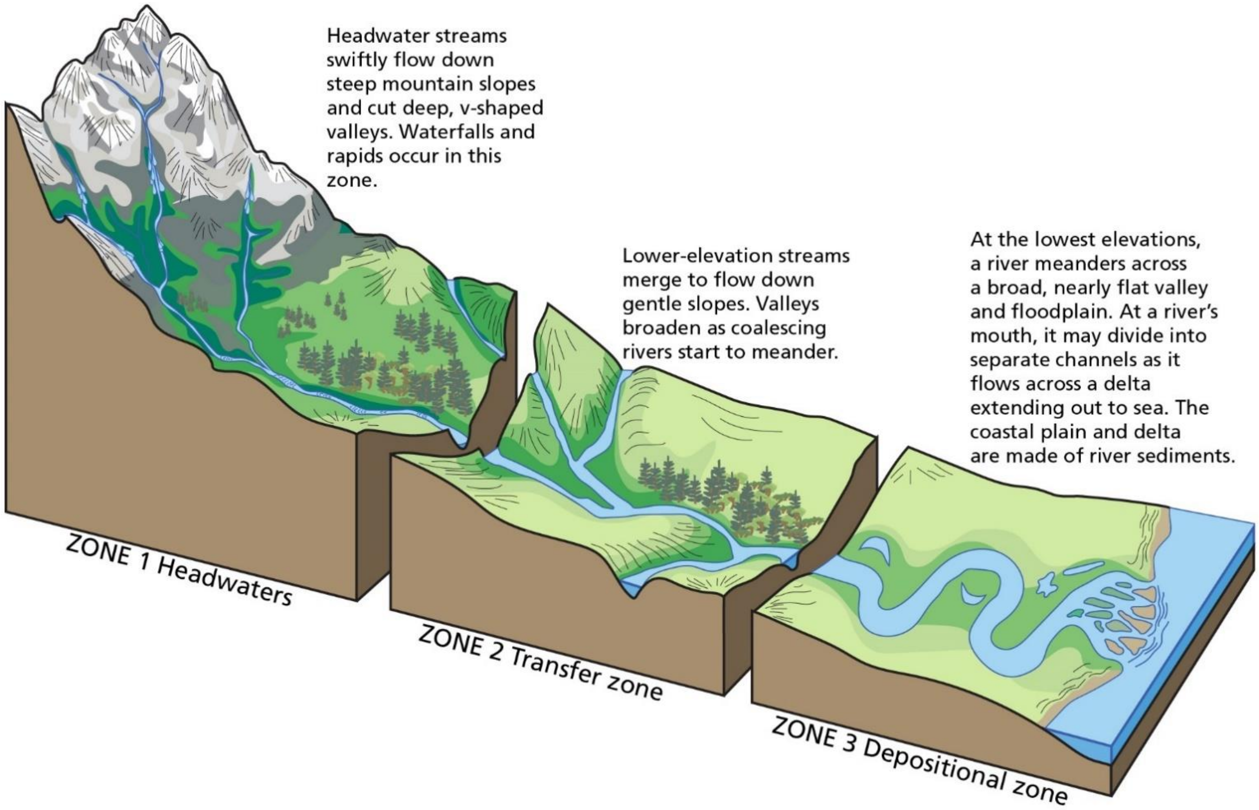

Figure 3. Coarse representation of a watershed's terrain classes in terms of sediment transport processes. Source: Trista L. Thornberry-Ehrlich, Colorado State University; redrafted from Miller, G. T. 1990. *Living in the Environment: An Introduction to Environmental Science*. Wadsworth Publishing, 60 pp.

3.2 SUBSURFACE AND GEOLOGIC CHARACTERISTICS

Dam designers must understand the underlying characteristics[9] of the *rock* and *soil* at a proposed site to inform foundation and superstructure designs. A geotechnical site assessment that is well planned, executed, and documented will reduce the risk of structural failure, and mitigate the potential for unanticipated costs during subsequent foundation design and construction. As project development progresses, developers gain increasingly refined information about the subsurface and geologic conditions at a site, as described in Section 4. As part of the geotechnical site assessment, subsurface conditions should be classified to inform foundation design. Although no single classification system is universally applied to dam projects, Figure 4 shows a classification system adopted from Fell et al. (2014) that includes most subsurface conditions commonly encountered and on which the analysis in Section 3.3 was framed. Section 4.1 provides additional information regarding the investigations needed to answer key questions related to each foundation type. A more detailed classification system by the US Geological Survey (USGS) (shown in Figure C.1 in APPENDIX C) provides a more granular basis for classifying sites beyond the hierarchy shown in Figure 4.

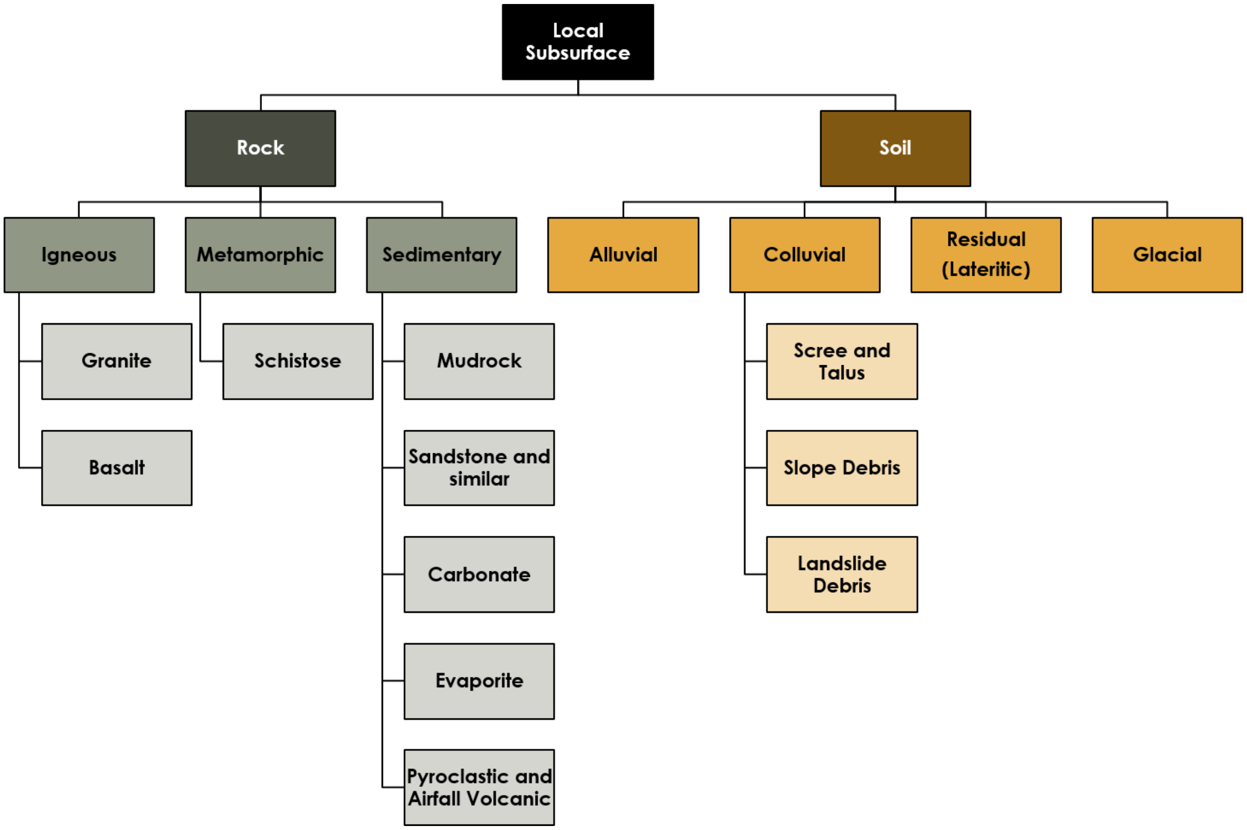

Figure 4. High-level hierarchy of subsurface classes. Source: Modified from Fell et al. (2014).

The local subsurface at a proposed site can usually be distinguished by whether it is primarily composed of soil or rock. The site subsurface can be further classified based on rock type and soil depositional environment (third and fourth levels in Figure 4). According to the US Army Corps of Engineers (USACE) National Inventory of Dams (NID) 2018 data[10] for the 25,836 reported low-head (less than 30-ft head) dams, 85% were built on soil and 5% on rock, with the remaining 10% built on sites comprising

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[9] APPENDIX C defines technical terms used in dam foundation design, including words in this section that are italicized.

[10] Available from https://nid.sec.usace.army.mil/ords/f?p=105:1:::::: (accessed August 10, 2020).

both rock and soil materials. From an engineering perspective, a key difference is that the mechanical behavior of rock is generally governed by discontinuities (e.g., joints and faults) and mechanical properties, whereas mechanical behavior of soil is largely governed by the properties of the soil mass as a whole. Therefore, rock and soil beds require distinct design and economic considerations, as discussed in Sections 3.3 and 4.2.1.

The following sections present additional details regarding the characteristics of rock (including identification of subsurface classes and a summary of important properties for foundation design) (Section 3.2.1) and soil (Section 3.2.2) subsurface layers, including key (high-level) information practical from both the geologic and geotechnical engineering views. The authors acknowledge that terminology use varies depending on practice, and alternate and varying terminology may exist in the literature. Some subsurface characteristics presented apply to both rock and soil, and the reader is encouraged to consult additional resources for more detailed descriptions of key characteristics; the information presented herein offers an overview of relevant characteristics.

The USGS[11] and US Department of Agriculture (including Part 631 of the National Engineering Handbook[12]) literature, among others, are recommended for further information and cover rock and soil characteristics to a greater level of detail than is presented in this report.

3.2.1 Rock Characteristics

Rocks (any naturally occurring solid mass or aggregate of minerals or mineraloid matter) can be classified into three major categories based on their formation process: *igneous*, *sedimentary*, or *metamorphic* (see Figure 4). When rock is at the surface (or the soil cover is thin), it can provide direct support for a dam's foundation. Most competent (non-weathered) to moderately weathered rocks have adequate mechanical properties (e.g., *hydraulic conductivity*; *hardness*; shear, tensile, and compressive *strength*) to safely support a low-head dam and associated infrastructure. However, many rock formations have defects or discontinuities that require treatment, as described below.

The extent of faulting, jointing, other discontinuities, and weathering has a major impact on rock mass strength and watertightness, which are important for foundation applications. The *rock mass* is "the total in situ medium containing bedding planes, faults, joints, folds and other structural features. Rock masses are discontinuous and often have heterogeneous and anisotropic engineering properties"(Brady and Brown 2004). When necessary, the properties of a rock mass can often be improved to a suitable level with various treatment methods; however, in some cases, improvement can prove too costly. For instance, a weathered rock foundation may be treated with consolidation grouting to provide predictable and somewhat uniform design parameters, particularly reduced hydraulic conductivity and improved shear resistance along the rock to concrete contact. Additionally, highly jointed and fractured areas of the foundation can be treated with rock replacement concrete or consolidation grouting.

Although certain rock types generally have better properties than others, site-specific features are also extremely important. Rock properties can vary over short distances and can be non-uniform within the same rock formation. In situ tests can study larger volumes of material and less disturbed samples than laboratory tests, but they still do not thoroughly characterize full-scale formation response. Back-calculation from large-scale performance data may significantly improve confidence in predictions of behavior, but such information is rarely available during foundation design. Engineering judgement is

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[11] USGS publications are available from: https://www.usgs.gov/products/publications/official-usgs-publications (accessed August 10, 2020).

[12] Available from https://directives.sc.egov.usda.gov/viewerFS.aspx?id=3848 (accessed August 10, 2020).

often necessary to account for scale effects. (Section 4.1 provides additional information on geotechnical site assessment).

More information about rock characteristics and their importance in geotechnical assessments is covered in Section 4.1 and APPENDIX C. Figure 5 visualizes the general lithology of the contiguous United States.

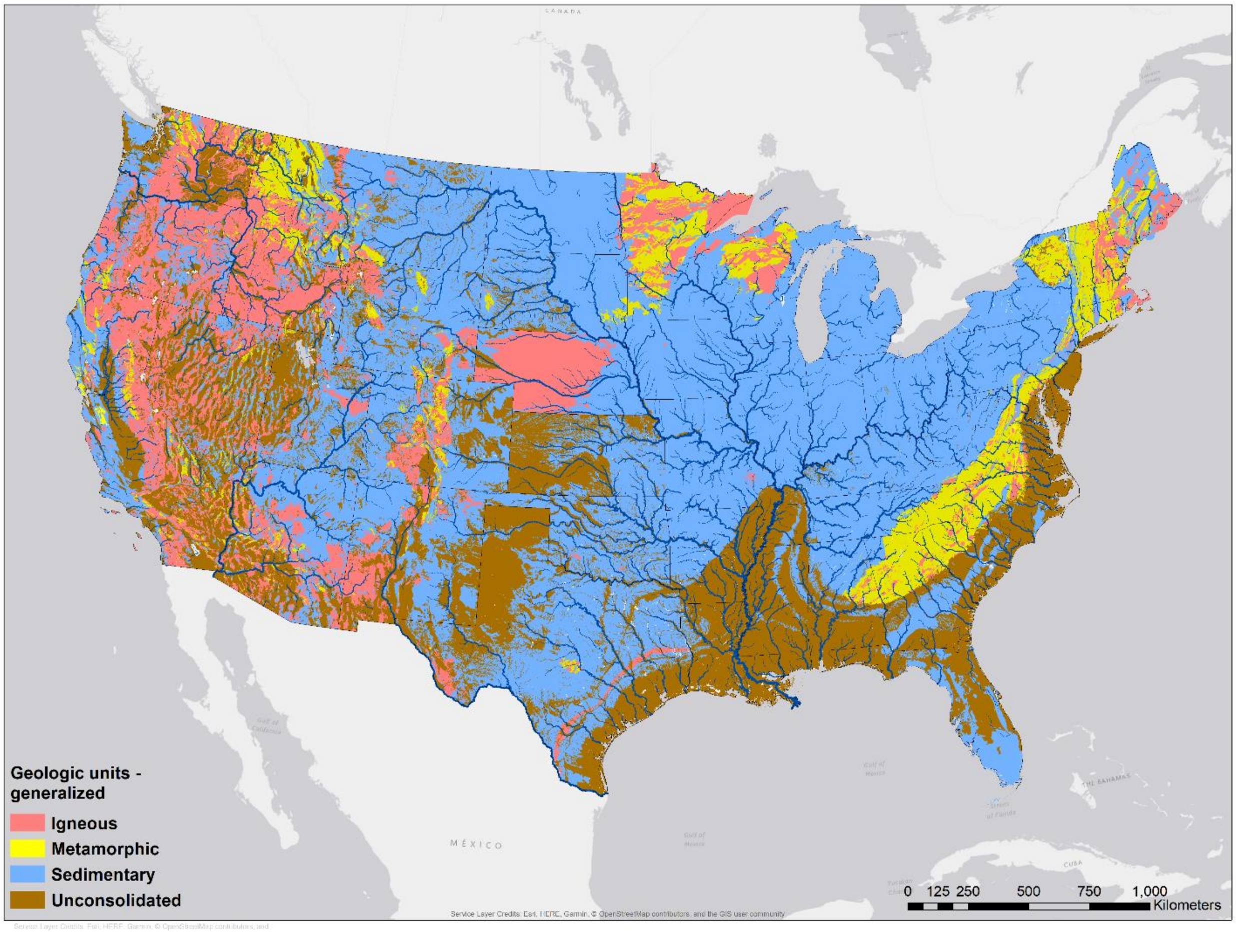

Figure 5. Map of generalized geologic units in the contiguous United States. Source: ORNL, based primarily on data from the USGS State Geological Map Compilation (Horton, San Juan, and Stoeser, 2017).

3.2.2 Soil Characteristics

Nearly all stream bed types contain some soil deposit, although it can be localized and thin, especially in mountainous terrain. (surface material composed of varying degrees of organic and mineral constituents, primarily resulting from the decay of plants and/or weathering of rock). Soil presence and characteristics are highly dependent on many factors, including a site's geology, climatology, and hydrogeological depositional environment. A general understanding of soil material classes will help inform superstructure selection and other engineering considerations for hydropower foundations. Figure 4 classifies the four major soil depositional environments that dam developers will encounter: *alluvial*, *colluvial*, *residual* (lateritic), and *glacial soils*.

Another important classification system is based on the engineering behaviors of the soil formations. Several soil taxonomies and classification systems exist, including the NRCS Soil Taxonomy, the

American Association of State Highway and Transportation Officials (AASHTO) Soil Classification System, and the Unified Soil Classification System (USCS). In these systems, materials with more than 50% sand and gravel sizes are designated as coarse grain, whereas materials with more than 50% silt and clay sizes are designated as fine grain. Organic soils such as peat are another class; but they are undesirable for dam foundations because they are highly deformable, and they should be completely removed from a dam foundation.

A site will contain a variety of soil formations along the streamwise, vertical, and lateral directions. Each formation will also contain specific compositions of each soil type. Properties of interest include *intrinsic particle properties*, *bulk properties*, and *soil mechanical properties*, as described in more detail in APPENDIX C. Therefore, in-person site assessments are crucial for identifying the rock and soil conditions. Soil properties of concern to dam designers can often be preliminarily estimated using published correlations with USCS soil type. However, more accurate information characterizing these properties is gathered through field and laboratory measurements; a list of common geotechnical laboratory tests for soils is provided in Table D.3 in APPENDIX D. Therefore, in-person site assessments are crucial for identifying the rock and soil conditions. Properties of interest include *intrinsic particle properties, bulk properties,* and *soil mechanical properties*.

For coarse soils, gradation is particularly important because it impacts permeability and other engineering properties. Without fine material to fill in gaps, poorly graded coarse material can allow water through (seepage), which represents an economic loss and can threaten the stability of the foundation or embankment if particles are mobilized or high piezometric levels develop in the downstream embankment or foundation.

Gravel foundations are generally suitable for earthfill or rockfill dams, but they require seepage control measures. Seepage control measures and other considerations are further described in Section 4.

Coarse-grain soils (cobbles, gravels, or sands) are typically permeable; seepage within a foundation can result in internal erosion (piping) or excessive loss of water (leakage) from the reservoir. Therefore, foundation and abutment seepage control is usually a key consideration during the design of dams founded on coarse materials. Additionally, saturated or nearly saturated loose sands, gravels, and some silts can liquefy either in response to seismic loading or through a complicated phenomenon known as *static liquefaction*. Settlement of sands is also a key consideration for the design of structural foundations and is a concern for earthfill and rockfill dams. Sand foundation settlement generally occurs as the dam structure is constructed, and non-uniform settlement is a significant concern.

Fine-grain soils (silts and clays) often present design challenges and may result in an uneconomical site for low-head hydropower. Soils generally become less permeable and soil moisture has a larger influence on the engineering properties as the percentage of silt and clay size particle size increases. Silts are often primarily non-plastic fines that can be difficult to compact, susceptible to liquefaction, and vulnerable to internal erosion. The behavior of clay soils depends significantly on the clay mineralogy; smectites are particularly problematic. The behavior of clayey soils is also strongly influenced by the stress and strain history of the deposit. Although clays are firm when dry, they are weak and compressible if deposited over relatively short geologic timescales or if they have been submerged and never heavily loaded. Clays are useful construction materials because their low permeability makes them an excellent seepage barrier if they are not dispersive (easily suspended in water because of their mineralogical characteristics). However, low strength, compressibility, and consolidation may create concerns. Clayey soils may also shrink or expand when the moisture content changes, which is particularly concerning for building and equipment foundations. The use of dispersive clays should be avoided. Specialized treatment such as the addition of lime is possible but would rarely be cost-effective for low-head hydropower projects.

Engineering properties of soils used for dam and foundation construction are sensitive to compaction moisture content, especially for silts and clays. Compacting soils that are either too dry or too wet may result in poor engineering characteristics. Borrow sites often have variable stratigraphy, and excavation can disturb soil structure and moisture content; consequently, engineers must be careful to monitor soil properties throughout the borrow, processing, placement, and compaction process. Compaction control is an important but complex consideration for foundation design. For more information about the intricacies of compaction and various control strategies, refer to the US Bureau of Reclamation (USBR) Earth Manual (USBR 1998a) and Design of Small Dams (USBR 2006).

More information about soil characteristics and their importance in geotechnical assessments is covered in Section 4.1 and APPENDIX C. Figure 6 illustrates the surface lithology for the contiguous United States with a 1:5,000,000 resolution.

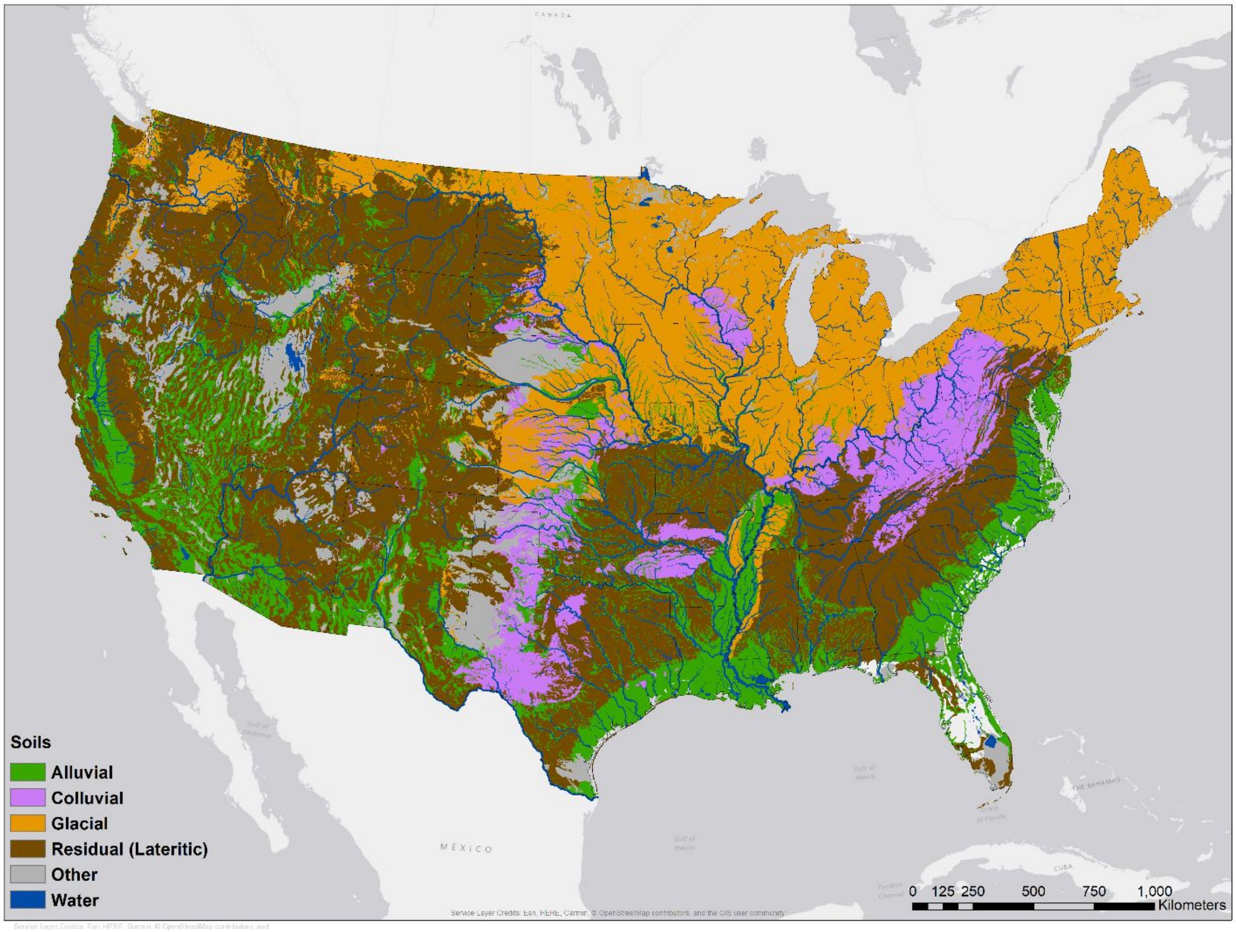

Figure 6. Map of surface lithology classes in the contiguous United States. Source: ORNL, based primarily on data from Cress et al. (2010).

3.3 ANALYSIS OF UNDEVELOPED LOW-HEAD US STREAM-REACHES

This section aims to provide insight into the distribution of available NSD sites among the subsurface classes described in Figure 4 and present other relevant information about NSD foundation-related site characteristics. The estimates of subsurface class presence and dam type suitability presented herein are uncertain, given the lack of site-specific assessments available for national-scale analysis and the assumptions made. However, these estimates are intended to help characterize (from a high level) common characteristics among NSD opportunities.

The NSD resource assessment (Kao et al., 2014) identified 8,891 low-head sites (less than 30 ft of estimated hydraulic head) with at least 1 MW of power capacity, which represent the sample for this analysis. These sites have a total cumulative potential of 37.2 GW. Because comprehensive and reliable data are not available for instream subsurface characteristics, subsurface classes were determined based on the best available land-based measurements. For example, the USGS Surficial Lithology Map and the USGS State Geological Map Compilation geodatabase were used for the soil and bedrock classifications (Horton, San Juan, and Stoeser, 2017). These data sets extrapolate field measurements, remote sensing analyses, and other relevant data sets into maps representing general subsurface formations. These measurements are limited in depth of study and spatial resolution. Additionally, although land-based measurements of the local depositional environment and bedrock character likely correlate with the instream characteristics, the instream conditions may differ significantly from those of the surrounding catchment because of the erosive force of water. Therefore, these classifications do not directly identify the thickness of the stream bed material or the exact subsurface composition of the NSD sites. The data for each NSD site are first presented with no distinctions between bedrock or soil foundations to provide an unbiased representation of the data. At the end of the section, a simplified method for distinguishing between likely rock and soil subsurface is used to provide a high-level classification of the NSD sites.

As discussed in Section 3.1, the depth of overburden is determined by local sediment transport processes, but it generally correlates with stream gradient, stream confinement, and terrain. Streams with higher slopes and narrower channels will have faster velocities for a given flow compared with streams that are broader and have fewer steep banks. Faster water velocities lead to higher erosive forces, which can mobilize larger sediment particles. By extension, rivers in mountainous terrain, which are likely to have higher stream slopes, are more likely to have exposed bedrock or large gravels/cobbles/boulders as bed material because the smaller particles are transported downstream.

The first step in the analysis was to determine the terrain classes for each NSD site. Given the available data, stream gradient was selected as a proxy to differentiate between mountainous, hilly, and valley terrains at a national scale. Using stream gradient alone ignores several other topographic factors that signify terrain; however, more detailed geospatial analysis is needed, which is outside the scope of this report. In the literature, the definition of steep vs. shallow stream gradients depends on the research context (Comiti and Mao, 2012, and references therein); the classification shown in Figure 7 was selected based on a general stream classification system developed at ORNL (McManamay and DeRolph, 2019). Of the 8,981 NSD sites, only 24 sites had high gradients (defined as >4%), which make up 43 MW. As shown in Figure 7, the vast majority of NSD sites fall under the low-gradient classification (defined as <0.5%).

As a second step, the NSD sites were classified as either *confined*, *moderately confined*, or *unconfined* based on the methodology from McManamay and DeRolph (2019). The valley confinement describes the control of the surrounding physical environment on the lateral migration of a river, thus indicating the strength of the interaction between the river and its floodplain. For instance, if a river is unconfined, it likely flows through erodible alluvium and is thus freer to migrate laterally. According to the analysis by McManamay and DeRolph (2019), rivers are determined to be unconfined if the valley bottom width is at least four times that of the river width along over half of the stream reach. Streams are moderately confined if they have a valley to river width ratio above 4 along 25–50% of the stream reach length, or if they have valley-to-river width ratios between 2 and 4 along more than 50% of the stream reach. All other streams are classified as confined, with relatively narrower valleys. The confinement characteristic is used hereinafter as one of the conditions to determine whether an NSD site is likely to have a soil substrate. Valley confinement can also inform the dam type selection and thus be relevant for foundation design.

Overall, low-head NSD sites are distributed relatively equally among the three confinement classes, with 43% of sites classified as unconfined, 25% as moderately confined, and 32% as confined. The predicted subsurface class results (Figure 11; located at the end of Section 3.3) were only minimally affected when the selected valley confinement criterion was included.

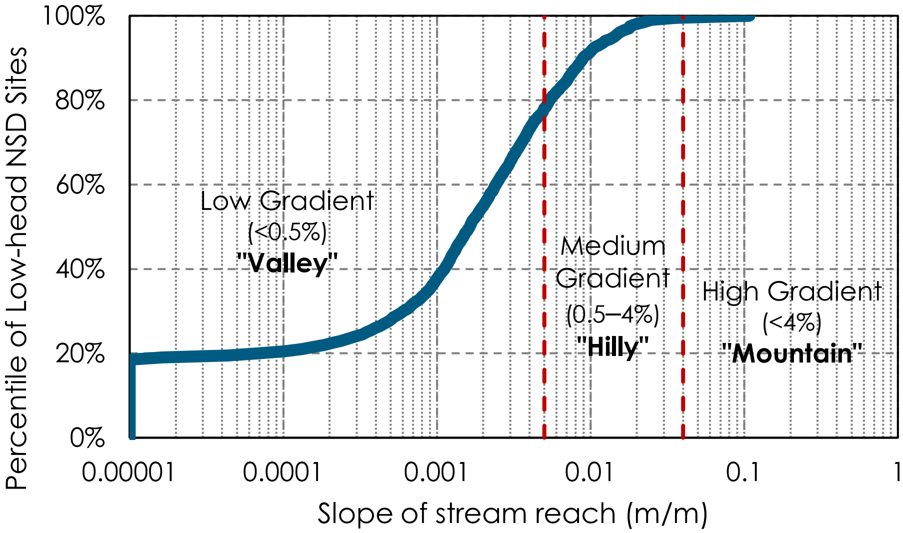

Figure 7. Distribution of stream gradients for low-head NSD sites by expected terrain class. Source: ORNL, using data based on NHDPlusV2[13] dataset (McKay et al. 2012) and stream gradient categories based on McManamay and DeRolph (2019).

In the third step, the expected soil deposition class for each site was determined using publicly available data. Figure 8 describes the distribution of the NSD population among soil classes by number of sites (i.e., count) and by cumulative power capacity. These data, adapted from the USGS Surficial Lithology maps (Cress et al. 2010), reflect the soil deposition environment at a relatively coarse scale surrounding a site. Although limited, these are the best available data to describe the potential instream soil environment. Most NSD sites contain alluvial or residual soils, which likely contain a mixture of well-graded silts, sands, clays, and gravels. Residual soils are likely to have different soil properties from alluvial soils because of the chemistry of lateritic soils; however, data concerning the site-specific soil composition are not available.

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[13] https://www.epa.gov/waterdata/learn-more (accessed August 10, 2020).

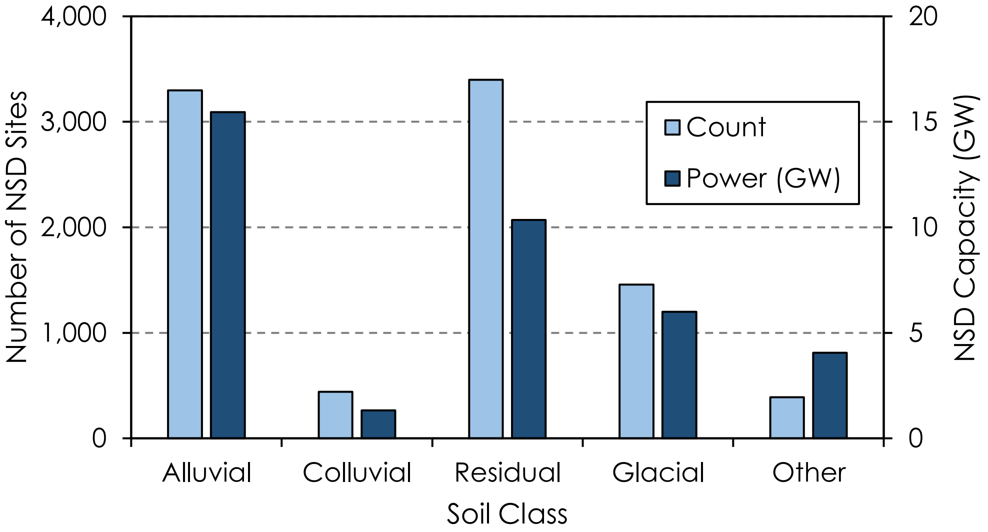

Figure 8. Distribution of low-head NSD sites among soil classes. Source: ORNL, based primarily on data from (Cress et al. 2010).

In the fourth step, the expected bedrock class for each site was determined using publicly available data. Figure 9 describes the distribution of the NSD sites in each bedrock class. Each site is classified based on the USGS State Geological Map Compilation (Horton, San Juan, and Stoeser, 2017), which is used here to describe the bulk lithology at a relatively coarse scale surrounding a site. Notably, bedrock formations are site-specific and may contain multiple rock types vertically or laterally. About half of the sites are classified as unconsolidated, meaning either that the bedrock is composed of broken or loose rock particles, or that the study was not deep enough to find bedrock, so the unconsolidated material represents soil.

Although these classes have distinct properties, various types of bedrock exist within each class, so considering engineering features in addition to these classes is important. Figure 10 describes the distribution of bedrock mean uniaxial compressive strength (UCS) in the catchment for the NSD population. According to the US Society of Dams (USSD) (2011), strengths above 70 MPa are considered high and strengths below 17 MPa are considered low. Given these thresholds, approximately 53% of sites have strong bedrock, whereas 24% have weak bedrock. Although compressive strength influences the competency of rock foundations, it is neither a sole nor a necessary determinant of foundation competency for low-head hydropower projects. A competent foundation could be provided by relatively weak rocks that are minimally weathered and lack unfavorable discontinuities. Conversely, a rock mass with high compressive strength but unfavorable discontinuities may not provide a competent foundation.

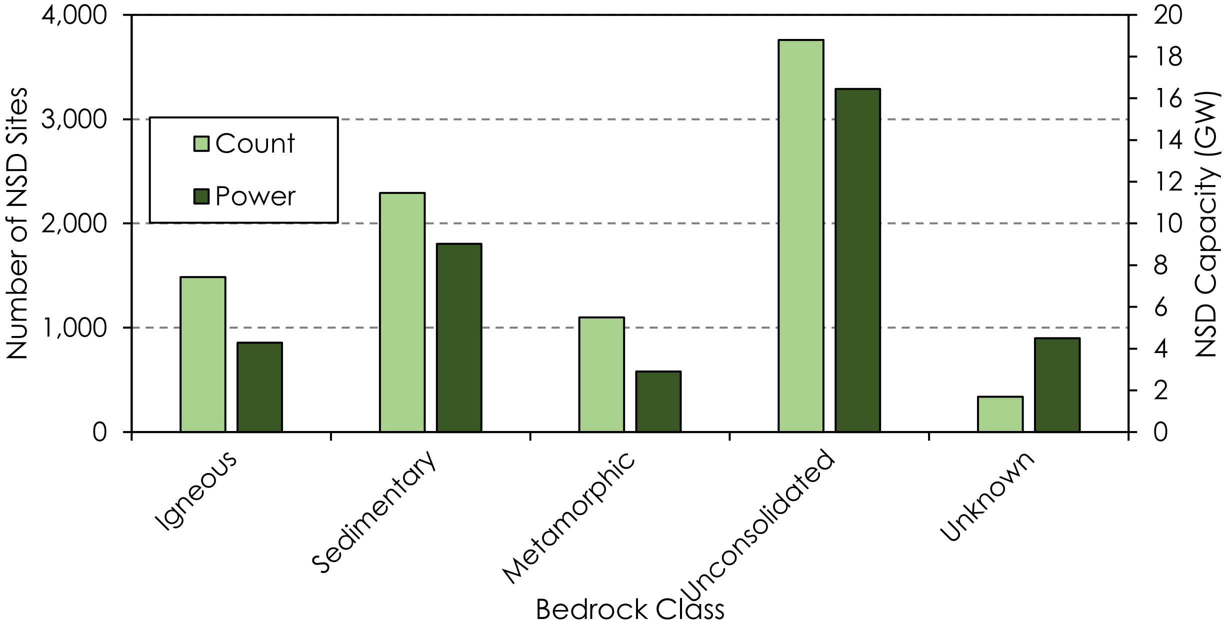

Figure 9. Distribution of low-head NSD sites among bedrock classes. Source: ORNL, based primarily on data from (Horton, San Juan, and Stoeser 2017).

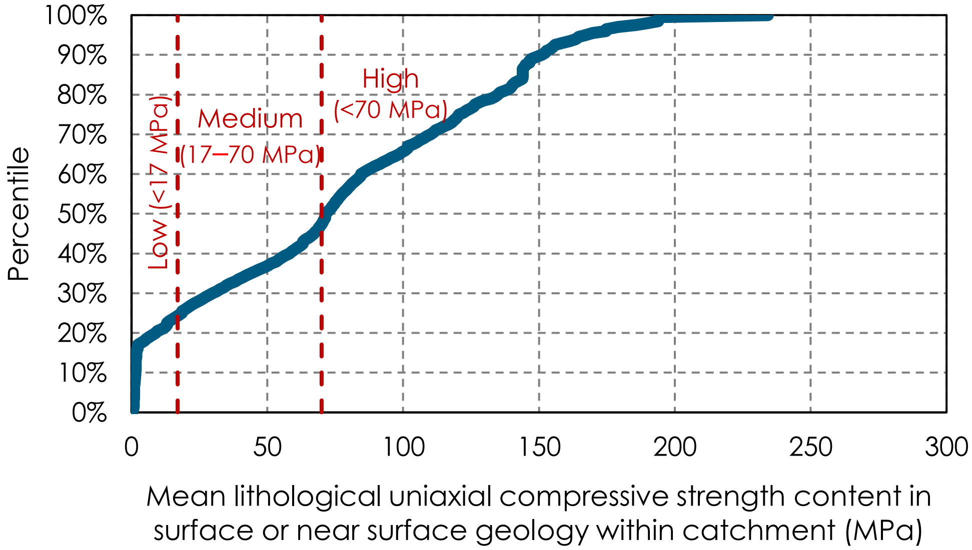

Figure 10. Distribution of bedrock compressive strength for low-head NSD sites. Source: ORNL, based primarily on data from(Hill et al. (2016). Compressive strength categories are based on USSD (2011).

Finally, the NSD sites were classified as either rock or soil beds to pair sites to the expected rock or soil class. Combining the aforementioned characteristics into a comprehensive classification of NSD sites requires numerous assumptions that can be verified only by nationwide site assessments. However, the following analysis is helpful for providing a high-level first look at the subsurface characteristics of the NSD population. Based on the available data and generalized sediment transport theory, the following conditions were selected to indicate where streams are more likely have a layer of overburden.

A site was classified as soil if any one of the following conditions was met:

- The site was located in a valley (i.e., stream slope less than 0.5%).
- (Or) the site was unconfined (4:1 valley-to-river width ratio along over half of the stream reach).
- (Or) the site's primary lithology was unconsolidated material.

Otherwise, the site was classified as rock.

The results of this classification are shown in Figure 11. These conditions imply that bedrock sites have medium to high stream gradients, at least moderate confinement, and shallow consolidated bedrock formations. Once identified, the sites were further classified by assigning the rock or soil class of the local catchment. Based on these results, 81% of low-head NSD developers will face a layer of alluvial, residual, or glacial soil overburden. These results agree with the data distribution available in the USACE NID 2018 data set,[10] which showed that 80% of low-head dam sites were built on soil foundations (15% rock and soil, 5% rock). The implications of these soil layers for foundation design and cost are discussed in Section 5.

As stated previously in Section 2.3, the designs of both the superstructure and foundation system are dependent upon subsurface conditions, the characteristics of which can be modified (to some degree) by foundation treatment to meet engineered design specifications. In addition, the way in which the foundation interface is designed and constructed depends on characteristics of both the superstructure and the subsurface. Thus, based on a site's subsurface conditions, the range of suitable superstructure classes can be determined. With this in mind, Section 0 presents additional information on superstructure characteristics and extends the analysis results presented in Figure 11 to approximate the suitability of various dam classes among low-head NSD sites based on subsurface class distribution.

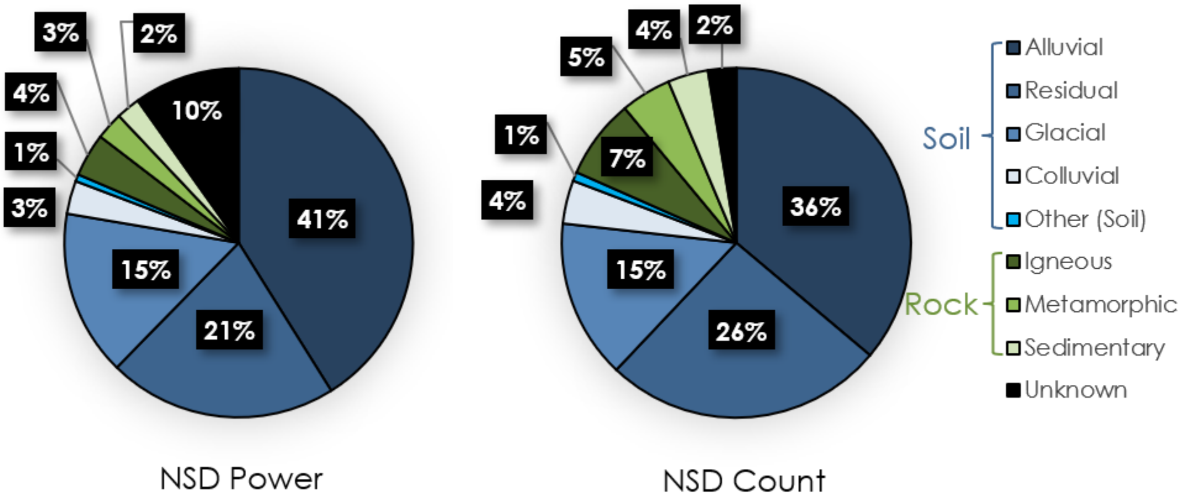

Figure 11. Distribution of low-head NSD site subsurface classes.

3.4 SUPERSTRUCTURE CHARACTERISTICS AND SUITABILITY ASSESSMENT

Superstructures may include dams, spillways, powerhouses, modular technologies, and other necessary civil works; as stated previously, among different hydropower facility superstructures, dams represent the primary challenge for hydropower foundations because of their size, external loads, and weight requirements. Consideration of the full superstructure system is important to foundation design because it determines the buoyant weight, live and dead loads, water action, and integration challenges for the foundation.

This section introduces conventional dam types, as well as modular technology for hydropower. Additional information on powerhouses and spillways is also provided. A suitability assessment is performed to identify which conventional dam construction types are most suitable among the low-head NSD sites, based on the subsurface classes identified in Section 3.3. The information in this section is presented at a high level; Section 4 further describes the engineering considerations among conventional dam types.

3.4.1 Dam Construction Types

A dam, defined by the Federal Emergency Management Agency (FEMA) (2004) as “an artificial barrier that has the ability to impound water, wastewater, or any liquid-borne material, for the purpose of storage or control of water,” can serve single or multiple purposes. FEMA (2004) defines a multipurpose project as

> a project designed for irrigation, power, flood control, municipal and industrial, recreation, and fish and wildlife benefits, in any combinations of two or more. Contrasted to single-purpose projects serving only one need.

Given their role in providing water retention and control, and the significant socioeconomic consequences should they fail, dams represent critical infrastructure. Hydropower dams serve an additional critical infrastructure role given their role in ensuring energy security.

Unlike most other civil infrastructure requiring a geotechnical foundation design, dams must maintain equilibrium under numerous static and dynamic hydraulic forces imparted by the upper and lower water bodies and any uplift pressure beneath the dam (Figure 12). Therefore, engineering design must carefully consider the full range of operational conditions expected (and regulated by responsible dam safety authorities) throughout the dam’s expected life (DeNeale et al., 2019). The complicated nature of hydropower foundation engineering analysis, relative to other geotechnical applications, is further complicated by the complexity of geologic materials and how they perform when saturated or exposed to water. Regardless of whether a hydropower facility design incorporates a conventional dam type (Section 3.4.1.1) or modular superstructure (Section 3.4.1.2), adequate foundation design and construction (covered in more detail in Section 4) is required to maintain functionality throughout all expected operational conditions.

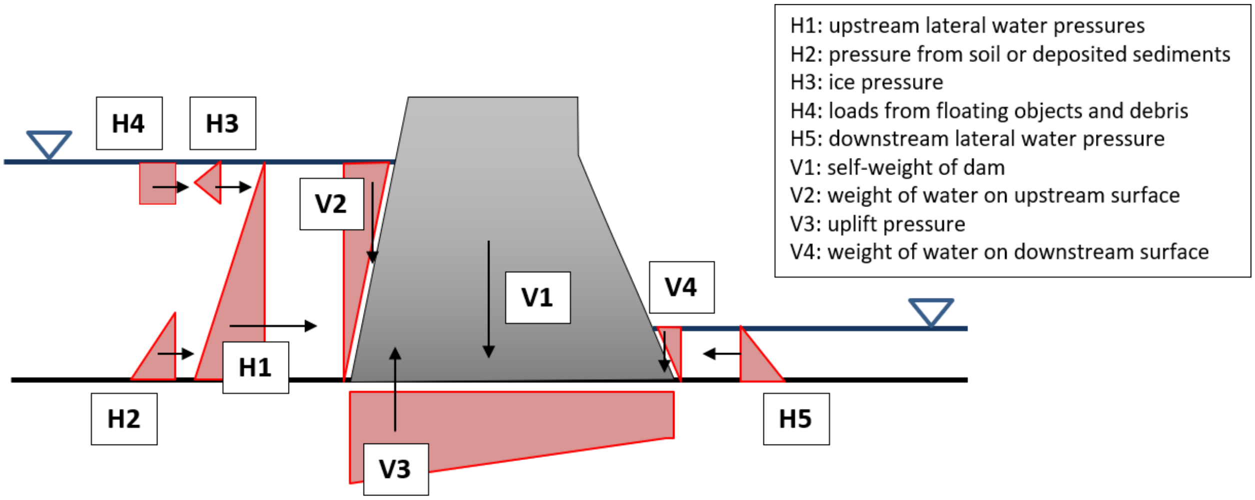

Figure 12. Common vertical and horizontal loads on a concrete gravity dam and foundation. Red triangles (not to scale) represent vertical and horizontal load distributions impacting the dam. [Source: (Smith et al. ,2017); adapted from the European Small Hydropower Association (ESHA, 2004)]

3.4.1.1 Conventional Dam Types

Dams are classified by construction material and general shape for engineering purposes, as shown in Figure 13. The primary classifications for existing dams are *earthfill*, *rockfill*, and *concrete*; a smaller number of the existing dam population are made of materials such as timber or masonry. Some dams use more than one construction material, depending on engineering and economic considerations. Most low-head dams are constructed as embankment, roller-compacted concrete (RCC), or concrete gravity dams.

Earthfill and rockfill dams are considered *embankment dams*, which use excavated natural materials (soil or rock) or man-made materials (e.g., geomembrane, concrete, or steel) to provide water retention. These dams use local materials to decrease transportation and material costs. Thus, the choice of material is primarily based on the availability and composition of borrow areas and on site subsurface conditions. However, multiple material types may be needed to form various layers of the embankment. Typically, embankment dams have a core zone that acts as an impervious barrier to limit water flow through the dam, and one or more filter zones to prevent piping of fine particles out of the dam core. Filters may also be necessary at the base of rip-rap used to mitigate erosion from wave action. A major disadvantage of embankment dams is that overtopping (flow over the dam) can erode the fill material and can lead to failure. Therefore, embankment dams must have adequate spillway capacity. In addition, flow through an embankment dam can result in piping, as discussed previously. Seepage control measures such as low-permeability zones and filters must be included in the design to mitigate this risk.

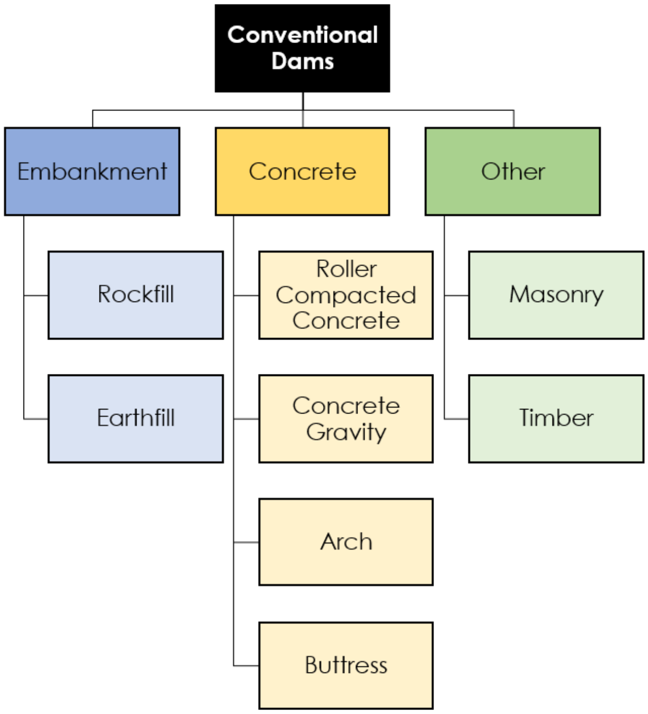

Figure 13. High-level hierarchy of conventional dam types by material type.

Embankment dams are classified as rockfill, as opposed to earthfill, when over half of the material in the maximum cross section consists of rock (Gulliver and Arndt 1991). Earthfill dams are the most common dam type in the United States, with about 90% of all dams in the USACE NID database being earthfill (Figure 14). Earthfill dams are often selected because they can be significantly cheaper to construct than concrete dams for low-head sites and can use a variety of available site soil types (DeNeale et al., 2019). Rockfill dams, on the other hand, are selected in locations with abundant sources of good rock and where long rainy seasons make construction difficult for finer soils. To account for the larger grain size, rockfill dams use an impervious liner to prevent seepage. To keep the membrane intact, dam designers must avoid foundation types that are pervious or subject to settlement.

Concrete dams, the other major class of construction, use reinforced or unreinforced concrete to create a barrier. These dams are typically more expensive to build than the others but can be designed with overflow spillways and other integrated outlet works. Designers may use sand and gravel from local borrow areas as concrete aggregate, so material availability is still an important consideration. These dams often require clean, stable rock foundations, so all alluvial overburden must be removed and the bedrock must be treated. RCC dams use lean concrete of a no-slump consistency that is compacted using vibratory rollers. The selection of mass concrete vs. RCC depends on the trade-offs between material and construction costs, structure size, and stability.

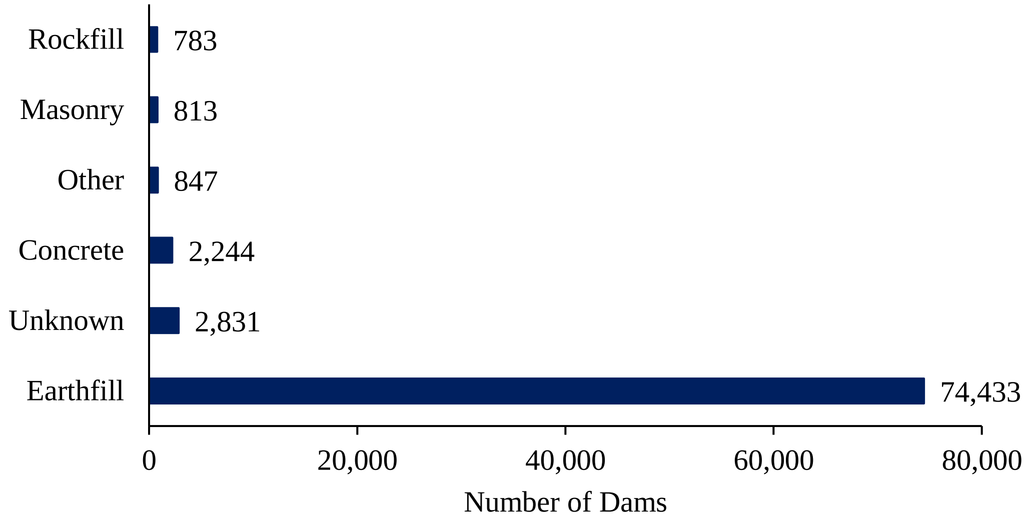

Figure 14. US existing low-head dam primary construction type. Source: ORNL, based on the USACE 2018 NID data set.

Concrete dams can be further classified as *gravity*, *arch*, and *buttress* types based on the support structures. Concrete gravity dams use their own weight for stability. Although rock foundations are preferable, small concrete gravity dams can be built on alluvium foundations if foundation treatment and cutoffs are designed to avoid overturning and seepage. Concrete arch dams use a curved face to transfer loads from the dam to the rock abutments. Thus, arch dams are preferable for narrow river valleys that have steep, competent rock abutments. Stiff soil, gravel, or cobblestone foundations prohibit the use of arch dams for structural reasons. Buttress dams use a series of buttresses, or counterforts, on the downstream side to stabilize the upstream wall of the dam. The buttresses can significantly decrease the amount of concrete required, at the expense of increased steel reinforcement and formwork costs. Arch and buttress dams are typically used for high-head sites (>30 ft), which are outside the scope of this analysis.

For low-head hydropower applications, earthfill, rockfill, and RCC dams are likely to be the most cost effective. In terms of engineering design, earthfill and rockfill dams may be thought of as *flexible* structures (more prone to consolidation, deformation, gradual motion, and seepage), whereas concrete dams may be thought of as *rigid* structures (definitive shape and structure acting as a solid body). The general engineering properties of different dam types are explored more in Section 4.

3.4.1.2 Standard Modular Hydropower Concepts

Beyond conventional dam construction types, modular hydropower design represents a promising but largely unproven paradigm for new hydropower development. The Standard Modular Hydropower (SMH) project,[14] led by ORNL with funding from DOE WPTO, aims to foster the development of environmentally compatible, cost-effective hydropower through modularization (i.e., the division of system components into distinct, readily transferable modules) and standardization (i.e., the development of universal details, guidelines, and specifications to maximize module replication and compatibility across multiple sites). In the SMH framework, standardized modules provide specific functions

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[14] Available from https://smh.ornl.gov/ (accessed August 10, 2020).

(foundation, generation, passage) and can be combined to form a hydropower facility while sustaining stream functionality (Smith et al., 2017). As illustrated in Figure 15, the module types include

- *Generation modules*, which transform incoming water flow into an energy output and outgoing water flow
- *Passage modules*, which transfer water, fish, sediment, or boats safely through a facility
- *Foundation modules*, which provide a stable platform that enables the foundation and other modules to maintain location, orientation, and stability

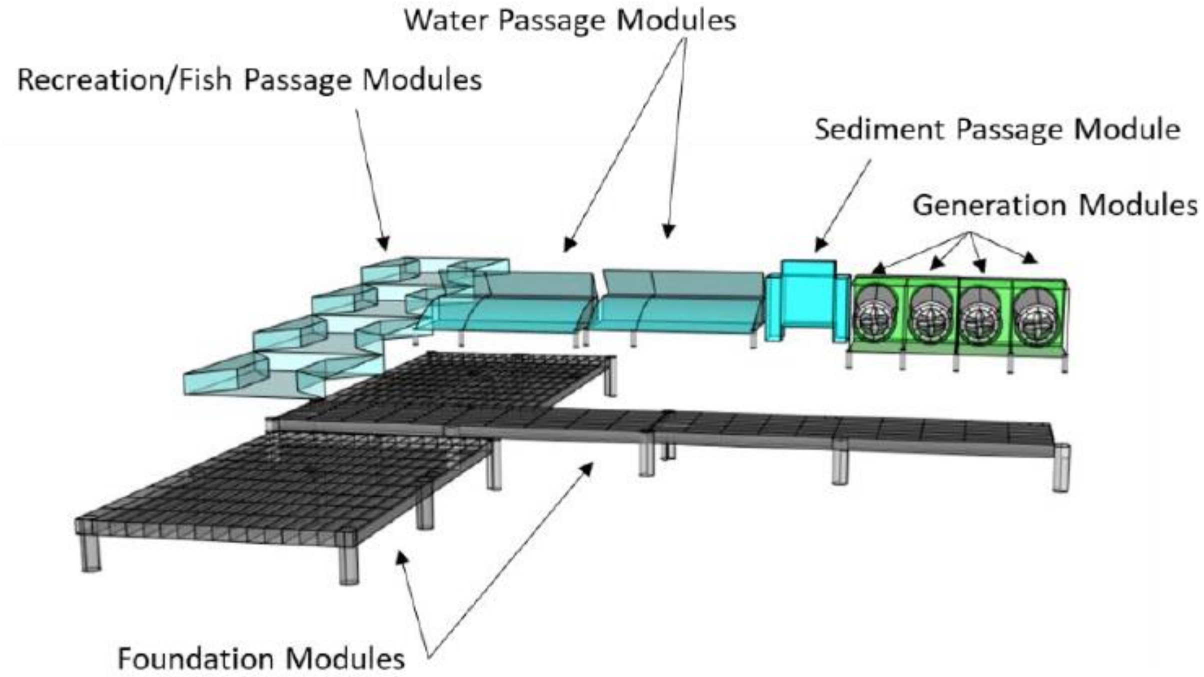

Figure 15. Conceptual schematic of an SMH facility consisting of functional passage, generation, and foundation modules.

Modularity enables economies of scale and is expected to reduce construction costs. For example, generation modules can be mass-produced at reduced costs and deployed across multiple projects that can scale generation by laterally stacking modules. Similarly, prefabricated modules can reduce costs by decreasing the need for custom-designed structures and accelerating construction timelines. Witt et al. (2017) details the various requirements and design specifications for successful implementation of SMH modules and facilities. To advance the SMH research concept, DOE WPTO has recently funded industry efforts to develop SMH innovative facility design concepts[15] and modular technologies for low-head hydropower applications.[16] The outcomes of these and other R&D efforts aim to motivate the types of transformative technologies and methods needed to support further hydropower growth.

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[15] Available from https://www.energy.gov/eere/articles/funding-selections-announced-innovative-design-concepts-standard-modular-hydropower (accessed August 10, 2020).

[16] Available from https://www.energy.gov/articles/doe-announces-249-million-funding-selections-advance-hydropower-and-water-technologies (accessed August 10, 2020).

Although all modules provide essential functions needed for the successful construction and operation of a hydropower facility, the foundation module is critical because it serves as the structural interface that anchors the generation module and passage modules to the stream bed. The role of the foundation module within the SMH concept is similar to that of the foundations of conventional hydropower facilities, whereas the design and construction processes require radical innovation to minimize costs and environmental disturbances associated with civil works and to economically justify the feasibility of a new hydropower project (Witt et al. 2017).

Modular superstructures are likely to be rigid structures that perform similarly to a concrete dam with respect to stability and watertightness. Engineering requirements for anchoring modular superstructures via foundation modules vary depending on subsurface and superstructure characteristics. In a truly modular facility, the generation and passage modules can be replaced throughout the life of the project. Therefore, foundation modules must also be able to adaptively connect and disconnect with the overlying modules. Although modular foundations are critical to modular facility design, previous R&D activities in this area are limited and such designs have not been deployed. Given this gap, modular foundation technologies and installation techniques represent a significant innovation opportunity, as discussed in Section 7.

3.4.2 Other Hydropower Facility Structures

Dams are often costly and difficult to design because they are constructed within the stream, and flowing water must be controlled and diverted while the dam is constructed. The foundations required for ancillary superstructures such as spillways and powerhouses have similar construction requirements. These structures enable proper operation of the hydropower facility and must be designed for normal (dry) operation, potential flooding, and seismic activity. The following sections describe the functionality and design requirements for both powerhouses and spillways. Proper grading and surface treatment is also needed for nearby structures such as switchyards, control rooms, parking lots, and recreational areas, but these structures are outside the scope of this report.

3.4.2.1 Powerhouse

The United States is home to more than 90,000 dams, approximately 2,500 of which are hydropower facilities (Hadjerioua, Wei, and Kao, 2012). Compared with NPDs, a hydropower project has an additional structure called a powerhouse, where powertrain (turbine-generator) and other equipment are housed. A powerhouses is located either at the toe of a dam (i.e., dam-toe scheme) or at the downstream end of the power conduit (for diversion facilities; DeNeale et al., 2019). For low-head facilities, the powerhouse may be constructed as part of the dam, so that the intake is integral with the powerhouse. Such powerhouses are conventionally constructed of concrete and have their own foundations integrated with the dam foundations. Similar to the dam, the integral intake powerhouse superstructure must be stable and watertight to form part of the reservoir impoundment.

A powerhouse enables the project to generate electricity, with the design flow limited to the operational characteristics of the installed generating equipment. Therefore, spillways are required to pass design flood flows in which significant volumes of water must be passed through the facility; other forms of bypasses (e.g., sluiceways) may also be installed to meet facility operational requirements. Besides the static gravitational forces of the powerhouse structure, operational conditions induce additional loads on the dam and foundation structures due to the movement of pressurized water flowing through the dam to the powerhouse.

3.4.2.2 Spillway

All dams, regardless of type, have some sort of spillway or bypass structure to transport stream or reservoir flows over, around, or through the impoundment structure. These flows can serve a variety of purposes, including flood control, navigation, recreation, water supply, and environmental conservation. The location and type of spillway or bypass can vary across sites, but they are commonly made from concrete or other non-erodible materials, or founded on rock to prevent weakening of the structure from relatively constant large flows (DeNeale et al., 2019). For instance, a spillway can be part of the dam or located on top of it, releasing water directly over the top; it can alternatively divert flow from the top of the dam via a bypass to release water further downstream. Typically, a spillways can draw water from a specific portion of the reservoir (i.e., usually the topmost layer), creating a consistent load on the dam and foundation structures when in use. Spillways can be divided into three main categories dependent on their usage—*service*, *auxiliary*, and *emergency*:

- *Service spillways* are regularly used to provide continuous or frequent releases. Accordingly, they are made from extremely damage-resistant materials. Examples include gated, morning glory, and stepped spillways (DeNeale et al., 2019).
- *Auxiliary spillways* are used in a secondary capacity to provide infrequent releases (e.g., to increase spilling capacity in flood events) and thus may be made of less damage-resistant materials than service spillways. Examples include cast-in-place reinforced concrete, riprap channel protection, and unarmored excavated channels (DeNeale et al., 2019).
- *Emergency spillways* are used in extreme circumstances to provide additional spilling capacity (e.g., when the service or auxiliary spillways are inoperable or in major flood events). Therefore, they consist of much lower-cost materials (e.g., some types of concrete, riprap, and unarmored materials) and will incur erosion damage if used frequently (DeNeale et al., 2019).

Across all three categories, spillways can be further defined by the types of flows they release, either controlled or uncontrolled. Controlled spillways can release precise volumes of water for specified periods of time using control systems such as gates, bulkheads, or stoplogs. Uncontrolled spillways do not have any of these control systems in place and therefore release water only when the upstream reservoir reaches a certain minimum elevation (DeNeale et al., 2019).

In addition to a dam, an impoundment includes the reservoir and other hydropower facility structures such as spillways and integral intake powerhouses. An overflow spillway can occupy a significant area in the center of a valley, and its foundation suitability would mirror that of a concrete dam. Service spillways or integral intakes generally occupy relatively small lengths across the development. Although these smaller structures must meet safety and performance requirements, their foundations are designed to be compatible with the more costly dam foundation.

3.4.3 Suitability Assessment for Conventional Dam Types

For stability and economic reasons, subsurface classes can preclude certain dam types. For example, building concrete dams on weak, compressible colluvial soils is difficult because of significant consolidation and low shear strength. Table 1 describes the feasibility relationships between the subsurface classes and the common, conventional dam types. Many other site-specific factors (discussed in Section 4.2) affect the selection of dam type, so Table 1 provides only high-level insights.

By combining the NSD subsurface classes shown in Figure 11 and the feasibility matrix shown in Table 1, the suitability of common dam types for the population of low-head NSD sites can be extrapolated.

Figure 16 presents the results for the three common dam types (earthfill, rockfill, and concrete gravity). Based on these results, rockfill and earthfill dams are likely suitable for more than half of the NSD sites, whereas concrete gravity dams are likely suitable for only 15% of the NSD sites.

Table 1. Suitability matrix for subsurface classes and dam types.

Foundation geology	Suitable dam type			Design considerations[17]
	Concrete gravity	Rockfill	Earthfill	
Igneous or metamorphic rock	Well-suited	Well-suited	Well-suited	Primary foundation design issue is often seepage through joints and fractures. Volcanic deposits sometimes are so permeable that they are not suitable
Sedimentary rock	Likely suitable	Likely suitable	Likely suitable	Suitability depends on rock type and discontinuity characteristics
Alluvial soil	Limited applicability	Requires careful study	Requires careful study	Issues include thickness, seepage susceptibility, and liquefaction
Colluvial soil	Not suited	Not suited	Requires careful study	Often contains weak compressible layers or landslide deposits
Glacial soil	Limited applicability	Likely suitable	Likely suitable	Foundation strength may control rockfill slopes; glacio-lacustrine clays may be a fatal flaw
Residual soil	Requires careful study	Likely suitable	Likely suitable	Depth and nature of weathering are key issues; may pose fatal flaw if parent rock weathers to unfavorable clay mineral (e.g., smectite)

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[17] The subsurface classes presented are high-level, and specific conditions may present fatal flaws for foundation engineering. For example, pyroclastic and airfall volcanic deposits (igneous) are less suitable for dam construction because they may contain highly variable material, be excessively permeable, or contain clays with unfavorable mineralogy. Specific conditions require additional site-specific geotechnical assessment beyond that in this report.

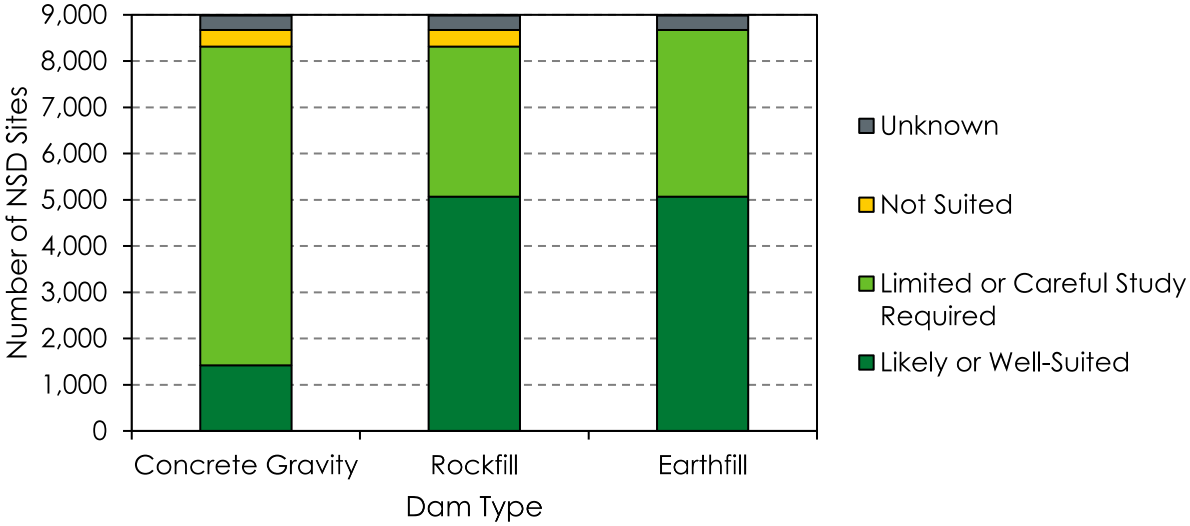

Figure 16. Suitability of common dam types for specific low-head NSD subsurface classes.

4. CURRENT STATE OF PRACTICE IN HYDROPOWER FOUNDATIONS

Hydropower foundation engineering practice involves three main development phases: geotechnical site assessment (described in Section 4.1), foundation design (described in Section 4.2), and foundation construction (described in Section 4.3). For the purposes of this report, *geotechnical site assessment*[5] is defined as activities performed to obtain information needed to design and construct a foundation system. *Foundation design* is defined as the process of using information from the site assessment to perform analyses and develop a cost-effective foundation system that meets the project design criteria. *Foundation construction* is defined as activities performed by the contractor, from mobilization through project commissioning, to fully develop the foundation system. These activities must integrate with overall project planning activities.

Geotechnical site assessment and foundation design are concurrent rather than sequential tasks, representing an iterative process to advance overall project design. Although projects may be organized in various ways, the common approach consists of three design stages—conceptual design, feasibility study, and detailed design. These stages are illustrated in Figure 17, which also indicates the approximate percentage of design completion reached at the end of each stage. Figure 18 also indicates the relative typical scheduling of a small hydropower project. Site assessment and foundation design are discussed in Sections 4.1 and 4.2, respectively, with this concept of project organization; the concepts are readily adopted to other forms of project organization as needed.

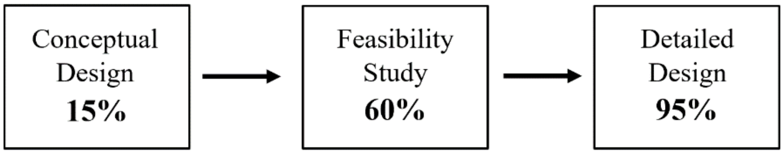

Figure 17. Typical staged approach to project design, showing the approximate percentage of design completion at the end of each stage.

Conventional hydropower foundations primarily support the structures that form the reservoir. These structures include, as a minimum, the dam, spillway, and power intake (independent or integral with the powerhouse). Additional structures such as fish passage facilities and low-level outlets may also be incorporated into the development. The dam is generally the largest and most complex structure, and its foundation requirements dominate the engineering activities. The foundations for the other structures are further developed to conform to the site conditions and the dam foundation. In this report, the terms “dam site” and “dam axis” refer collectively to the dam and appurtenant structures that form the reservoir.

Foundation and abutment design for dams and appurtenant structures is an engineering and scientific discipline process directed toward achieving an understanding of the stream bed (bedrock or soil). The stream bed includes the characterization of the subsurface conditions, identification of potential failure modes and risks, engineering analyses (e.g., slope stability, consolidation and settlement analyses, seismic performance), and consideration of treatment methods specific to each dam and appurtenant structure alternative considered based on site-specific requirements. Cost estimates, a risk register, and construction schedules are prepared at each phase of conceptual, feasibility, and detailed design. The project elements identified in conceptual design are optimized and further refined during each subsequent design phase. The primary geotechnical deliverable during detailed design is construction plans and specifications; a report is also typically prepared documenting previous site assessments and analyses performed before and during the detailed design phase. Key geotechnical assessments and activities are systematically conducted as a project advances through the conceptual design, feasibility study, and detailed design phases:

- Key results for **conceptual design** include selecting a site or sites that appear favorable, eliminating sites that have "fatal flaws" and are thus unsuitable, and selecting the type of dam most likely to be suitable for the project. Note that the term "fatal flaws" as used herein can indicate aspects of a site that would render a proposed project commercially unviable. Most of the work in this phase involves desktop studies that use existing data; however, field reconnaissance by experienced geotechnical engineers is invaluable to confirm that conditions visually apparent at the site are consistent with information developed from desktop studies.

- Once a site (and perhaps one or two alternate locations) has been identified, more detailed investigation and analyses are typically performed during the **feasibility study** phase to establish a practical geotechnical design as the basis for cost estimates, risk register, and project scheduling. The cost estimation is necessary to developers for gaining project approval from regulators and financial backers. At this stage, many engineering parameters needed for analyses may be estimated using experience or published data, and a site investigation determines site properties considered critical to project engineering and design (e.g., the thickness, density, and permeability of alluvial materials beneath the proposed dam).

- Finally, a **detailed design** phase study is conducted to enable construction, including preparation of plans and specifications.

During foundation construction (discussed in Section 4.3), additional site assessment may be necessary if conditions are encountered that appear inconsistent with design assumptions or previous geotechnical investigations (Fookes 1967). Depending on the evaluation of investigation results during construction, the design may need to be altered, in which case the design engineer should be involved. Such design and construction decisions are made based on technoeconomic analysis. They must (at a minimum) ensure up-to-date dam safety measures are applied to reduce risk to as low as reasonably practicable and to defend against potential foundation defects, stability failures or slides, overtopping dam or abutment erosion, piping, seepage, and other failure mechanisms.

The interrelation of and general timelines for the geotechnical site assessment, foundation design, and foundation construction are shown in Figure 18. The integral nature of these activities is represented by two-way arrows between site assessment and design/construction, and the shading of the site assessment box gradually fades from left to right, reflecting the relatively decreased activities needed to support foundation development as overall progress is made. Important reference materials describing design considerations and methodology include USBR (2006a; 2012); USACE (2004); Day (2010); Duncan, Wright, and Brandon (2014); and Fell et al. (2014). FERC's *Engineering Guidelines for the Evaluation of Hydropower Projects*[18] is a valuable resource containing 14 chapters that are updated by FERC, some as recently as 2018. Another source of reference material is numerous bulletins published by the International Commission on Large Dams.[19] Although focused on large dams that are higher than those within the scope of this document, the bulletins also provide necessary guidance applying to dams less than 50 ft tall.

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[18] Available from https://www.ferc.gov/industries-data/hydropower/dam-safety-and-inspections/eng-guidelines (accessed August 10, 2020).

[19] Available from https://www.icold-cigb.org/GB/publications/bulletins.asp (accessed August 10, 2020).

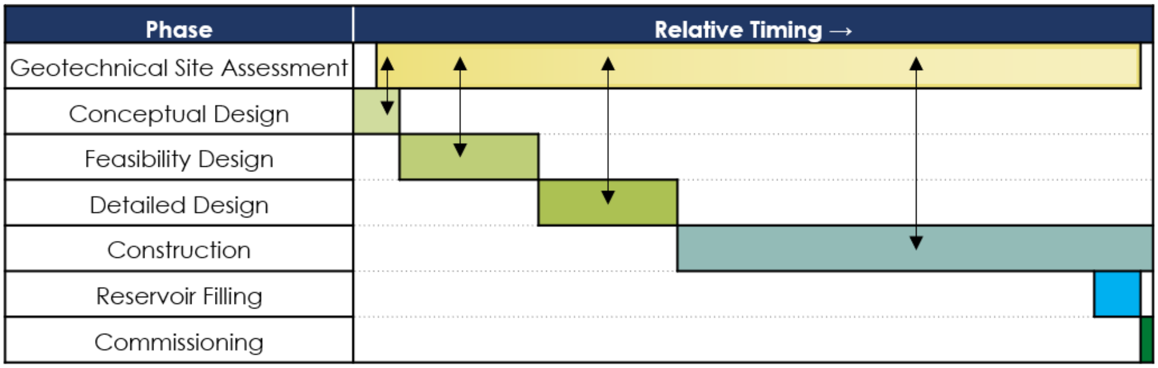

Figure 18. Representative sequence of principal phases for geotechnical site assessment, design, construction, and commissioning of small hydropower development.

4.1 GEOTECHNICAL SITE ASSESSMENT

As defined previously, geotechnical site assessment consists of the activities performed to obtain information needed to design and construct a foundation system. Some of the important watershed, stream, rock, and soil characteristics applicable to geotechnical site assessment are presented in Sections 3.1 and 3.2. The need to collect and evaluate these site-specific stream and subsurface characteristics forms the basis for collecting geotechnical site assessment information and conducting the requisite activities. Use of this geotechnical information is further combined with hydropower engineering design (of the superstructure and appurtenant works) to inform foundation design (described in Section 4.2).

Key objectives of geotechnical site assessment are to establish baseline information and a model of the subsurface geologic and hydrologic conditions and to evaluate engineering characteristics of subsurface materials. Activities typically completed to accomplish these objectives are

- Desktop geotechnical assessment of published information for the site
- Site reconnaissance and geologic mapping
- Subsurface investigation (including in situ testing)
- Laboratory testing
- Reporting (including geotechnical interpretation)

These activities should be planned to (1) obtain the information needed to identify whether potential fatal flaws exist in the foundation geology and (2) evaluate and develop designs that mitigate the risks of key geotechnical failure modes for dams (e.g., piping) and foundation or dam instability. These potential geotechnical failure modes are common to all dams and appurtenant structures, with varying degrees of likelihood. However, the conditions and events contributing to a potential failure differ significantly depending on site structure selection, site geology, and intensity of postulated site events resulting from seismic activity or floods.

Once the likely foundation conditions have been established, the site assessment can be planned to focus on gaining knowledge and documentation of expected hazards, soil or rock defects, or shortcomings, and on characterizing sources of local borrow material for construction. Various foundation investigation data are required to establish sources of construction materials for the design of embankments, concrete dams, and appurtenant structures, as discussed in detail in USBR (2006a; 1998; 2001; 2012).

Table D.2 in APPENDIX D provides key questions for each type of foundation that needs to be evaluated during the planning and design process and broadly describes the likely characteristics related to strength and watertightness. Although strength and watertightness characteristics are site-specific, understanding the site geology also provides important information needed to identify geologic and geotechnical hazards at a site Thus, during the conceptual evaluation, the likely site foundation conditions should be identified using published information and site reconnaissance.

Some geologic environments are more likely than others to result in high costs during foundation development. During each stage (as presented in Figure 18), the assessment of site foundation conditions must evaluate whether possible fatal flaws and significant development risks might exist, such as

- Karst topography
- Clay lenses
- Active or highly sheared faults
- Permeable volcanic deposits (e.g., lava tubes, columnar basalts)
- Liquefiable sands and gravels
- Thick openwork gravels
- Active or dormant landslides
- Collapsible soils (e.g., loess, mudflow deposits in arid environments)

In particular, foundations on clays frequently require expensive design measures to address low strength and compressibility and thus pose a significant development risk and potential fatal flaw. These challenges are particularly likely when the clay is highly plastic (often indicating clay minerals in the smectite family) or has a high water content and soft to medium-stiff consistency. Geologic environments where clays may occur include

- Altered pyroclastic environments and tuff
- Colluvial deposits
- Low-energy alluvial deposits (e.g., overbank and oxbow deposits)
- Some residual soils (depending on weathering of parent rock mineralogy)
- Glacio-lacustrine deposits
- Highly plastic clay shales (typically Cretaceous-era deposits in the United States)
- Fault gouge
- Lacustrine, estuarine, and marine deposits (not often encountered at suitable dam sites)

Because each site is unique and project objectives vary, the selection, planning, and implementation of a geotechnical site assessment requires both a well-trained and experienced geotechnical engineer and a geologist. The remainder of this section provides an overview of the process so that non-geotechnical engineers can interact effectively with these professionals.

4.1.1 Desktop Geotechnical Assessment

A desktop geotechnical assessment of subsurface conditions is the first step in the geotechnical conceptual design process. This desktop assessment involves evaluating existing information, including topographic, geologic, hydrologic, climatic, and seismic data. USBR (2006a) provides a useful list of potential information sources, which include topographic maps, regional geologic maps and studies, aerial photos, and agricultural soil maps. These data products are available through federal agencies such as

USGS, the National Oceanic and Atmospheric Administration, and the US Department of Agriculture, as well as state and local agencies. Google Earth provides a tool for preliminary assessment of potential sites using aerial imagery, although in some cases its topographic resolution is coarse or the imagery quality is low.

4.1.2 Site Reconnaissance and Geologic Mapping

As discussed previously, the design of dams and appurtenant structures is dependent on geologic conditions at the project site. Field reconnaissance is necessary to confirm topographic and geologic conditions at the site established during the desktop assessment. Published geologic maps are often unavailable, incorrect, or lacking resolution; in such cases, an experienced geologist is needed to produce a geologic map with geologic units, contacts, and locations of geologic features such as faults, shear zones, joints, and bedding. Foundation conditions can be studied through visual inspection of the geology in the site vicinity at locations such as rock outcrops, highway cuts, or erosional features. Detailed information about the fracture fabric (e.g., joint spacing, orientation) and compressive strength of the rock are all useful for an engineering characterization of a rock mass, which can be confirmed during site reconnaissance. Remote sensing techniques and data products derived from sources such as LiDAR,[20] photogrammetry, sonar, and SAR/InSAR[21] are increasingly used to supplement site knowledge and augment visual observations.

4.1.3 Subsurface Investigation

Although published information provides a useful starting point for conceptual design, site-specific information obtained through field investigation is almost always advisable and typically is essential for a feasibility-level study to establish whether a structure can be safely and economically built at the proposed site. The conceptual design may include a limited number of borings and test pits, as well as a focused geophysical study. During the feasibility phase, a more detailed investigation program is typically undertaken. Site-specific subsurface investigations may include geophysical exploration, subsurface exploration using test-pits and drill holes, and in situ testing. A site conceptual model is commonly developed and refined throughout an iterative process during the investigation phase. More than one drilling campaign may be needed to constrain uncertainties regarding site conditions.

4.1.3.1 Geophysical Exploration

Geophysical exploration is often used as one component of a field investigation of a dam site. It requires interaction between the geotechnical engineer and the geophysical professional; geophysical professionals are often specialized in a subset of available methods, so selecting an appropriate technique often requires consulting multiple geophysicists. Fell et al. (2014) provides a modern summary of geophysical exploration for dam design and identifies the following methods that may be useful, depending on site-specific issues:

- Seismic refraction
- Multi-channel analysis of surface waves
- Self-potential profiling
- Seismic selection
- Electromagnetic conductivity profiling (time-domain electromagnetics)

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[20] LiDAR—laser imaging, detection, and ranging

[21] SAR—synthetic aperture radar; InSAR— interferometric synthetic aperture radar

- Magnetic
- Microgravity measurements
- Ground-penetrating radar

These methods are useful because they obtain information along a two-dimensional (2D) plane, and sometimes in three-dimensional (3D) space, whereas drill holes provide information only along a vertical line. A network of boreholes (as discussed in more detail in Section 4.1.3.2) can be used to develop a 3D geologic model, but interpolation among boreholes may miss important site characteristics. As indicated by Fell et al. (2014), geophysical results may sometimes be misleading because of limitations and ambiguities in their ability to resolve certain features, or because of their interpretation. For example, they are not reliable for detecting and locating thin, weak seams that could pose significant failure risks for any dam type, especially concrete gravity dams. Geophysical interpretations should be confirmed using bore holes with continuous core sampling or test pits.

USACE (1995) provides greater detail regarding geophysical testing. However, the document is not recent, and geophysical technology is continuously progressing and improving; experts in the area must stay aware of new developments.

4.1.3.2 Subsurface Exploration and In Situ Testing

Subsurface exploration is required to characterize subsurface material (i.e., the bedrock and soils), identify potential anomalies or discontinuities in the subsurface, determine the depth to bedrock at the site, and collect samples for field and laboratory tests. An experienced geotechnical engineer should plan, manage, and interpret these investigative exploration measures. The Naval Facilities Engineering Command (NAVFAC, 1986) and USACE (2001) provide more information on common field investigation methods.

Trenches are useful for shallow subsurface exploration of the dam site to characterize the uppermost material, and for paleoseismic studies of potentially weak or active faults that may impact the study site because they either pass through the planned dam footprint or are in close proximity to the site. Test pits can reveal subsurface conditions and allow visual inspection, logging, sampling, and testing of foundational and embankment construction material, as well as potential borrow material sources. Excavations to depths of up to 30 ft may be achieved, depending on the foundation soil strength and available equipment. Safe work procedures must be established by qualified personnel.

To collect information on subsurface material below the depth limits of trenches and test pits, additional exploration measures may be needed. Common methods include drilling and cone penetrometers. Other, less frequently used methods, such as self-boring pressure meters, are not discussed in this report.

Borehole drilling is performed using methods such as augers, rotary wash, percussive drilling, or coring; several methods allow samples to be obtained. Relatively undisturbed soil samples of cohesive deposits can be obtained using Shelby tubes or piston samplers, but samples must be handled with care to minimize disturbance. For claystones and tills, a vibratory (sonic) rig may be needed; this method provides continuous samples through materials that may be extremely difficult to penetrate using traditional rotary auger methods. Rock samples can be obtained with wire-line coring. Soil samples (disturbed and undisturbed) should be collected and visually classified in the field according to the USCS (ASTM, 2017), a standardized method of describing and classifying soils. As a rule of thumb, boreholes are located along the proposed dam axis with a depth at least equal to the proposed dam height (although some states require more), and along at least one section perpendicular to the dam axis (more than one may be required if the valley is wide or the geology varies substantially). To better understand seepage and pore pressure regimes, the depth to groundwater should be determined at a number of times throughout the year. The hydraulic conductivity of the subsurface materials should be measured via packer testing, or through aquifer tests such as a pump-out test.

In situ testing is often performed to measure properties when sample disturbance is a significant concern. For example, the density and strength of cohesionless deposits cannot be routinely measured except using in situ tests such as the standard penetration test (SPT) or the cone penetration test (CPT). The SPT is a relatively crude but extremely common in situ test, performed by measuring blows of a standard weighted hammer required to drive a standard sampler to a depth of 12 inches; a significantly disturbed sample is also obtained that can be visually classified. The CPT uses an electronically instrumented probe; it is generally more repeatable than the SPT and can be correlated to a variety of soil behaviors. However, it does not provide samples for visual classification or laboratory testing and will not penetrate gravelly layers or rock.

For rock foundations, wire-line coring is the most common form of subsurface exploration. Drill cores should be logged for geotechnical characteristics according to the rock mass rating criteria presented in Bieniawski (1989) or the Hoek–Brown failure criterion (Hoek and Brown, 1980). These criteria include an assessment of the overall rock mass characteristics, including

- UCS
- Rock quality designation
- Joint condition rating
- Fracture spacing
- Groundwater condition

The UCS of the rock mass can be assessed through on-site point load testing (PLT) and direct laboratory testing of the UCS. Samples of intact cores should be subjected to PLT at the core rig during drilling on a target frequency of one PLT per core run (typically 5 ft) to obtain a semicontinuous log of rock strength. Core samples should be collected during drilling operations and carefully transported to the laboratory for testing according to ASTM (2014), as discussed in Section 4.1.4.

Core drilling in rock foundations should also include an assessment of the orientations of discontinuities within the rock mass. The orientations of geologic discontinuities can be measured using core orientation techniques, such as the Reflex ACT core orientation tool (the preferred method for core analysis), or via downhole measurements of discontinuity orientation, such as an optical and/or acoustic televiewer survey (or similar). Other techniques for assessing the orientations and qualities of discontinuities exist, and should also be considered, but are outside the scope of this document.

4.1.3.3 Pore Pressure Evaluation and Permeability Testing

Both rock coring and soil boring approaches should include instrumentation for measuring pore pressures in the dam foundation. This is typically accomplished by installing vibrating wire piezometers or open standpipe piezometers upon completion of the corehole or borehole. Grouted-in vibrating wire piezometers are the preferred method for evaluating pore pressures within the dam foundation footprint, but they do not allow for groundwater sampling.

Downhole permeability testing should be considered if the permeability of the embankment foundation material is a key design consideration. This testing can be performed using packer testing or falling head testing depending on materials present (rock or soils, respectively). Packer testing is the preferred method of assessing the permeability of dam foundations and for grouting design.

4.1.4 Laboratory Testing

Soil laboratory testing is necessary to confirm classification; identify undesirable properties such as dispersivity or corrosivity; and establish engineering properties such as strength, volumetric and shear stress-strain relationships, stress history, and hydraulic conductivity. Common laboratory tests used to characterize geotechnical properties (e.g., structural, dynamic, and compacted soil properties) of a soil are listed below. Additional information is available from NAVFAC (1986) or USACE (1991) and is summarized in Table D.3 in APPENDIX D. Soil properties (some of which were introduced in Section 3.2.2) measured through common laboratory testing include the following.

- Natural moisture content and natural density
- Specific gravity
- Atterberg limits (liquid limit and plastic limit)
- Particle size distributions (sieve analysis and hydrometer analysis)
- Corrosivity (pH, sulfate, and electroconductivity)
- Flexible-wall permeability test
- Consolidation
- Swell/collapse potential
- Shear strength
- Compaction (vibratory, or standard or modified Proctor test)

Rock laboratory testing is typically conducted to evaluate the shear strength and compressibility characteristics of the rock mass. Testing should include an assessment of intact rock strength as well as the shear strength of rock discontinuities. Intact rock strength is typically measured using UCS testing according to ASTM (2014). The laboratory UCS testing should also include elastic properties measurements (Young's modulus and Poisson's ratio) for use in foundation compressibility and settlement analyses. The shear strength characteristics of rock discontinuities are typically tested using small-scale direct shear testing according to ASTM (2016). Selection of normal stresses during small-scale direct shear testing is an important consideration and should be based on the range of normal stresses expected within the dam foundation. Other tests may also be appropriate depending on the rock encountered and the conceptual design of the dam

4.1.5 Reporting

The key outputs from the site assessment activities are a geologic model for the site and the engineering characteristics of the site. One approach to documenting these outputs is to (1) prepare a report describing the geologic model developed during the conceptual study phase, which is updated based on results of the site investigation, and (2) prepare a data report during the feasibility study that provides information needed to perform analyses and prepare construction drawings and specifications. Maps, diagrams, and borehole logs from all exploration investigations should be included, as well as the results of field and laboratory tests. Geotechnical professionals should interpret the field findings and testing results.

4.2 FOUNDATION DESIGN AND TECHNOLOGY

This section summarizes foundation design for hydropower dams and appurtenant works that form the impoundment (Section 4.2.1) and other civil infrastructure (Section 4.2.2). Although commonalities exist in the design for these elements, the differences are important to consider, so they are covered in separate sections.

4.2.1 Foundation Design of Dams and Appurtenant Works

Each site has unique characteristics that the designer must consider in developing a design solution. Foundations are designed to be compatible with the structures they support. Technical performance requirements for the principal structures (modules) include the following.

- All principal structures (modules) forming the impoundment must hold back the impounded water and/or pass water downstream in accordance with operational and safety requirements.
- Concrete structures must be essentially impermeable and (1) be safe against overturning, sliding, and uplift; (2) resist imposed loads under normal and extraordinary operating conditions, including floods and earthquakes; and (3) experience negligible or minimum settlement.
- Earthfill and rockfill structures generally are permeable and incorporate an internal core or drain to minimize or control the phreatic surface through the structure. An exception is a concrete-face rockfill dam (CFRD), which incorporates an upstream impermeable layer to eliminate the phreatic surface in the rockfill.
- Seepage must be controlled to address the risk of internal erosion and so that high pore pressures do not induce foundation or embankment instability.
- Earthfill and rockfill structures must have stable slopes under normal and extraordinary operating conditions, including flood, earthquake, and reservoir drawdown. The strength of both the foundation and the embankment must be considered in analyzing stability and sliding.
- Settlement of the structure must be within specified design tolerances during and after construction.

The primary objective of the foundation design is to satisfy these listed technical performance requirements. Doing so requires evaluation and assessment of foundation conditions using site investigations, laboratory testing, and geotechnical analyses. Depending upon the geotechnical conditions encountered, the foundation design may include special treatments such as grouting and cutoff trenches to address identified potential subsurface defects. Shear and compressive strength and compressibility characteristics of the foundation materials must be determined to understand the foundation response to applied loading during and after construction. The permeability of the dam and foundation is evaluated to understand and estimate pore pressure in the dam and its foundation. Pore pressure is a key consideration for overall structure stability and sliding resistance. Strain compatibility between the various foundation elements is also an important consideration.

Key outcomes of the foundation design process are

- Site selection and characterization
- Selection of dam type and arrangement of appurtenant works along the dam axis
- Identification of potential failure modes and possible fatal flaws based on the site geotechnical characterization and selected dam type
- Listing of perceived risks into a risk register
- Identification and analyses of foundation treatment measures to reduce risks associated with the identified potential failure modes

- A plan for instrumentation, monitoring, and surveillance of the dam to manage remaining residual risk
- Construction drawings, specifications, and quality assurance and control plans

Interactions among the dam superstructure, the constructed foundation elements, and the subsurface must be considered. As an example of the importance of this consideration, the existence of open fractures in the foundation of Teton Dam and the use of a highly erodible silt embankment material were both factors contributing to the dam’s catastrophic and tragic failure in 1976.

4.2.1.1 Site Characterization and Selection

Geologic and geotechnical characterization of a potential project site according to the approaches outlined in Section 4.1 is an important activity in the dam site selection activity process. Geologic considerations during site selection are summarized in Table D.2 in APPENDIX D and include the following.

- Minimally weathered igneous and metamorphic rock usually have high bearing capacity and negligible permeability and thus are preferred foundations that readily support dams with a structural height of 50 ft or less, because treatment requirements are often minimal and the risk of unanticipated construction costs is lower than for more challenging geologic environments. Measures to limit foundation seepage may be considered. Some volcanic deposits are an exception, as they may be highly permeable or include weak clay deposits.

- Moderately weathered igneous and metamorphic rock and many sedimentary rocks are also suitable for structures less than 50 ft tall, but they are less desirable than minimally weathered igneous and metamorphic rock because foundation treatment is usually more extensive.

- A soil foundation is suitable for many projects, but fatal flaws are more prevalent, development risks can be significant, and treatment costs are higher on average than for bedrock sites. For example, organic deposits (e.g., peat) and soft-to-medium stiff or high-plastic clays are considered unsuitable foundations as they have low resistance to shear forces and may experience excessive settlement.

- Sand and gravel with low fines content (USCS Soil Classification GW, GP, SP, and SW[22]) often provide suitable foundations because of their predictable settlement behavior and ability to resist shear forces, but they must be treated to control seepage. Such soil foundations can generally support earthfill and rockfill embankment dams less than 50 ft tall.

- Soils comprising sand with silt (USCS Soil Classification SM[23]) are usually more compressible than clean coarse-grain soils but can often support low structures, provided that adequate and possibly costly foundation treatment measures are implemented.

- Sites where aerial photographs and topographic maps indicate evidence of significant slope failure in valley walls are less desirable.

- Sites upstream of a waterfall can be attractive for hydropower development. High-velocity flows upstream of the falls frequently scour the stream bed to bedrock, where it is partially exposed during low-flow season. A small concrete overflow dam with a hydraulic height of less than 30 ft is often suitable. The dam site should be located far enough upstream of the falls to avoid a possible foundation instability. Where falls are present, fish passage facilities are typically unnecessary, and

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[22] GW—well-graded gravel; GP—poorly-graded gravel; SP—poorly-graded sand; SW—well-graded sand. (ASTM, 2017)

[23] SM—silty sand. (ASTM, 2017)

falls naturally preclude recreational boating. The power intake at the dam can convey water to a penstock extending below the falls, allowing for a larger hydraulic head to generate increased power and energy, improving project economics.

Non-geotechnical issues that may impact site selection (but are not addressed in this section) include the following.

- Valley topography—narrow valleys are preferred because dam volumes are smaller than for wide valleys. Wide U-shape valleys often have thick permeable alluvial deposits that require foundation treatment, rendering the project uneconomical.
- Site access for construction, operation, and power transmission.
- Environmental impacts.
- Cultural resources and issues.
- Regulatory environment.

4.2.1.2 Selection of Dam Type and Appurtenant Structures

The selection of dam type is influenced by site topography, geology, availability and quality of construction materials, spillway design flood considerations, and the arrangement of the passage modules, including an integral intake and powerhouse or separate power intake. Foundation geology often varies across a valley or along a dam axis. Initial selection of a dam type, and the general arrangement of the impounding structures, require geologic and geotechnical judgements related to the foundation, including rock and soil type and depth to rock. For low-head application, earthfill, rockfill, and concrete gravity dams may be suitable.

The selection of the spillway arrangement is undertaken concurrently with selection of the dam type. A concrete dam normally has a concrete overflow spillway. A CFRD could have an overflow spillway section. Earthfill and rockfill dams more frequently have an overflow spillway located in an abutment. Spillways, whether gated and ungated, are sized to pass the design flood and conform to the site topographic and geologic conditions. The width of the spillway along the dam axis is selected based on an economic comparison of spillway surcharge level vs. cost, including the cost of the dam (non-overflow sections). Additionally, consideration can be given to designing for dam overtopping without dam failure.

Table 2 describes common dam types based on characteristics of the structure material and compatible foundation material. Figure D.1, Figure D.2, and Figure D.3 in APPENDIX D provide graphical illustrations of these dam types, showing conventional foundation measures used to control seepage or enhance watertightness. Both gated and ungated concrete spillways are also shown in Table 2.

Concrete gravity and rockfill dams can be considered for rock foundations, and for dense sand and gravel foundations where practical foundation seepage control measures (such as cutoff trenches) are feasible. The selection between concrete and rockfill is often a cost-based decision; concrete is more expensive per unit of volume than rockfill but requires less total volume. Soil embankment dams may be preferable where offsite sources of concrete are distant and limited, or where no rock is locally available. Filter sand and drain gravel typically are high-cost elements of embankment dams. For sites where foundation conditions dictate relatively flat slopes, the choice between soil and rockfill is often determined based on availability and cost. Concrete gravity and rockfill dams can be designed for overtopping, while embankment dams cannot. Thus, where design storms require passing very large flows, the former two dam types offer advantages for spillway design.

Table 2. Common foundation designs based on dam type and foundation material.

Primary construction	ID	Dam type	Foundation material
Earthfill	E1	Homogeneous earthfill with internal drain	Impervious soil
	E2	Central or inclined core, zoned earthfill	Impervious rock
	E3	Homogeneous earthfill with internal drain	Pervious soil (or highly weathered rock or regolith)
	E4	Central core, zoned earthfill	Pervious soil (or highly weathered rock or regolith)
	E5	Zoned earthfill with upstream impervious zone	Pervious soil (or highly weathered rock or regolith)
Rockfill	R1	Rockfill with central or inclined core	Sound rock, treated as necessary for low permeability below core
	R2	Rockfill with upstream membrane (assumed CFRD)	Sound, impervious rock
Concrete Gravity	C1	Concrete hydraulic structure (e.g., non-overflow section, overflow section, power intake)	Sound, impervious rock
	C2	Concrete hydraulic structure (e.g., non-overflow section, overflow section, power intake)	Pervious competent soil (or highly weathered rock or regolith)

Overflow spillways for concrete dams are designed similarly to the concrete dam but with additional loading cases associated with flood passage. Concrete overflow spillways located in abutments, retaining walls, side walls, and their foundations must meet the structural stability and foundation hydraulic conductivity requirements. For low dams in permeable foundations, concrete spillways would require measures to elongate the seepage path to avoid internal erosion of the foundation, as shown in Table 2.

Other passage and generation modules also fit into the general arrangement across the valley. These generally are concrete structures that comply with the technical performance requirements outlined in Section 4.2.1 and have foundation treatment measures as shown in Table 2.

In summary, across the dam axis, the structures are compatible with their specific foundation. The dam and appurtenant works and their foundations are analyzed in three dimensions to demonstrate that they meet all technical performance requirements. Special attention is given to contact surfaces between different structures and/or different material zones.

The selection of dam type is the most important element to be considered and greatly influences the arrangement of structures across the valley. The dam site selection is closely followed by the selection of the spillway and other appurtenant works. A flow chart conceptually showing the process for selecting dam types most suitable for a site is shown in Figure 19; the applicable dam type (shown in gray boxes) is consistent with the identification code (labeled as ID) provided in Table 2. The decision process shown begins by appropriately characterizing the geologic environment. Next, the likely strength and seepage characteristics of the foundation are determined based on the geologic environment. A foundation with low compressibility and relatively high shear strength is necessary if a concrete dam is to be considered. The seepage characteristics influence the selection of foundation treatment technology and the geometry of earthfill and rockfill dams. Site-specific information may be needed for these characteristics to be established with reasonable confidence. The economics of dam construction material must then be evaluated. Again, this is likely to be site-specific and dependent on such factors as locally available material and costs to either purchase or produce concrete. Although outside the scope of foundation design, the availability or scarcity of low-permeability borrow material, filter sand, and drain material or construction of the core of a rockfill or earthfill dam often influences the selection of dam type.

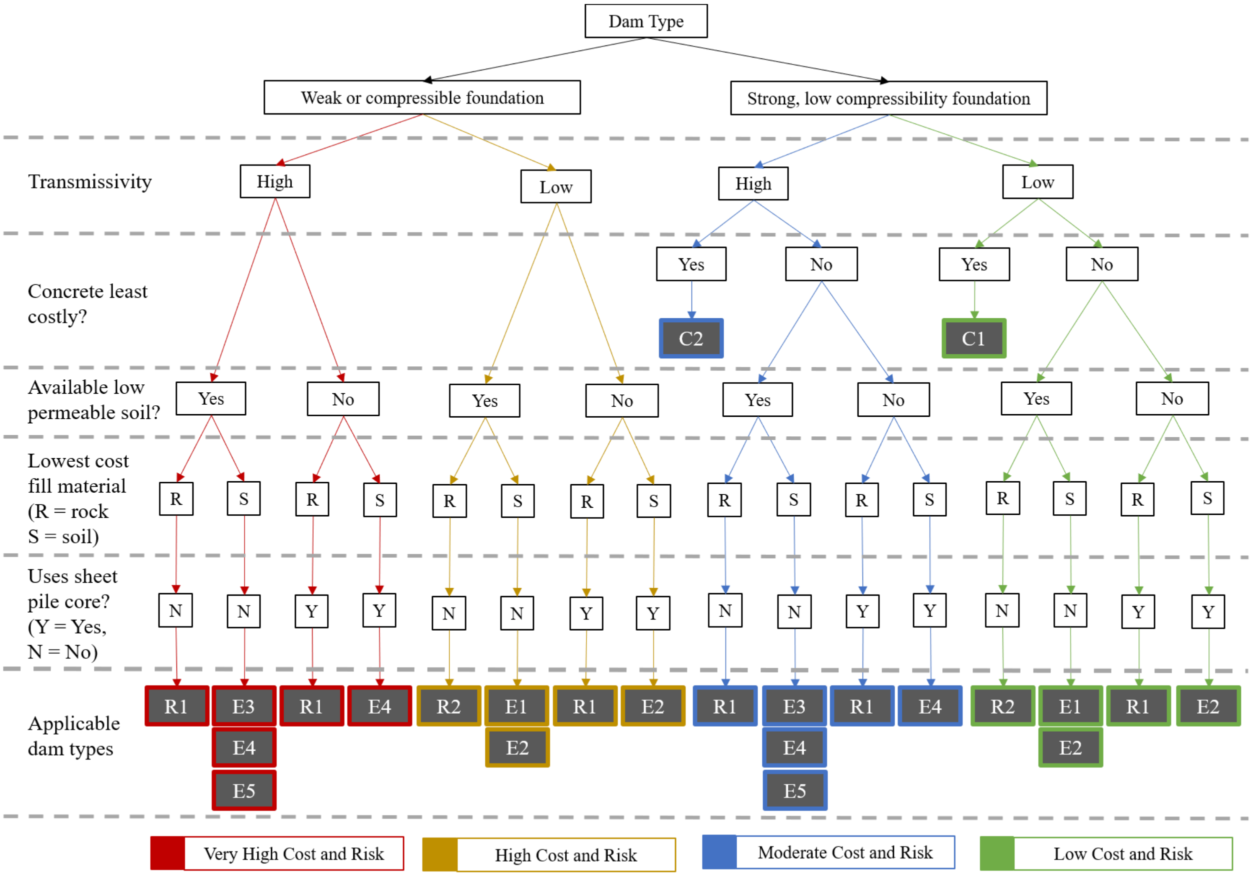

Figure 19. Conceptual dam type selection process flow diagram.

4.2.1.3 Risk Assessment and Management

Geotechnical engineering differs from many other engineering disciplines in that it involves geologic materials (soil and rock) created by natural processes with ranges of material and mechanical properties, rather than engineered materials with predictable pre-engineered properties. In many disciplines, an engineer can establish the engineering properties of a metal or plastic accurately by specifying the type and grade of material (e.g., ASTM A36 steel). An engineer can specify the shape (geometry) of a metal or plastic component for the purposes of design. However, with geologic and soil materials, geologic characteristics, distribution, and the properties of the soil or rock must be determined rather than specified. This uncertainty is further increased by the complexity of geologic materials and how they perform when saturated or exposed to water, which can vary as a result of prior geologic events including stress history and exposure to weathering and groundwater seepage.

A geotechnical engineer must address inherently larger material property uncertainty than do engineers in other disciplines. Although the application of formal and quantitative probabilistic analysis has progressed, the results of such analyses are limited when predicting observed behavior. Tools used to assess risk are summarized in Section 4.2. A modern document describing current best practices for dam risk management has been prepared jointly by the USBR and the USACE (USBR and USACE, 2019), although the level of effort to fully implement the method described may not be appropriate for low-head hydro projects. Nevertheless, it remains necessary for the geotechnical engineer to use judgment in developing design criteria and managing the associated risk and uncertainty. Industrial practice and related judgment is developed based on knowledge and on experience with previous dam designs in similar geologic settings. In short, the effective and well-managed development of dam design criteria requires specialized training and experience.

One strategy the project developer can employ to manage geologic and soil risk is to perform high-quality investigation and analyses to reduce uncertainty; Silva, Lambe, and Marr (2008) provide an example for slope stability. In their example, the engineer identifies engineering characteristics and shows that "state of the practice" design may reduce the probability of failure by two orders of magnitude compared with projects designed with the same criteria but using "routine" investigation and design methods. Although the additional cost associated with more thorough design and investigation may not be justified for some projects, the public risk and nature of the consequences of a dam failure is such that the design must reduce perceived risk to low levels to meet societal expectations. Selecting an appropriate scope level for site investigation and analyses is necessary to understand and reduce project risks.

Throughout the design process, two approaches exist for dealing with geotechnical uncertainty. The first is to make conservative assumptions throughout the design process (e.g., choosing reasonable lower bounds from laboratory strength test results). However, this approach may result in a costly design. A second is to use Terzaghi's observational method. Peck (1969) describes the process as follows:

> *(a) Exploration sufficient to establish at least the general nature, pattern and properties of the deposits, but not necessarily in detail.*
>
> *(b) Assessment of the most probable conditions and the most unfavorable conceivable deviations from these conditions. In this assessment geology often plays a major role.*
>
> *(c) Establishment of the design based on the working hypothesis of behavior anticipated under the most probable conditions.*
>
> *(d) Selection of quantities to be observed as construction proceeds and calculation of their anticipated values on the basis of the working hypothesis.*
>
> *(e) Calculation of values of the same quantities under the most unfavorable conditions compatible with the available data concerning the subsurface conditions.*
>
> *(f) Selection in advance of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis.*
>
> *(g) Measurement of quantities to be observed and evaluation of actual conditions.*
>
> *(h) Modification of design to suit actual conditions.*

The observational method typically requires more performance monitoring and more involvement of the design engineer during construction, but it often reduces overall earthwork costs. However, the method is not applicable for all (sudden) failure modes.

Once the dam site subsurface has been characterized, a potential failure modes analysis (PFMA) should be performed to identify and plan for the mitigation of risks inherent to the dam and its foundation (USBR and USACE, 2019). A formal PFMA is typically required and used in the dam design process. A PFMA often consists of a workshop ranging in duration from a half day to several days attended by experts in the design, construction, and operation of dams. The purpose is to identify the potential failure modes for the dam structure of interest. The probability of possible failure events occurring is determined. Expert elicitation is used for a PMFA. This process involves disciplines outside the expertise of the designer and facilitates "cold-eyes" review. Where risk (defined by the probability of a series of events and the consequence if the events occur) is not tolerable, the design might be altered, monitoring and mitigation strategies may be identified, or rarely, the project could be abandoned.

4.2.1.4 Foundation System Design

Once one or more viable options for dam type have been identified the geotechnical engineer must next

- Identify potential failure modes.
- Choose design features and criteria so that the probability of identified potential failure modes is acceptably low.
- Plan an investigation to gather data necessary to assess and analyze the failure modes, and select engineering parameters to analyze proposed design features.
- Perform the analyses and modify the design if needed to meet criteria.
- Identify residual risks associated with the design, concepts for mitigation that could be implemented if adverse performance is observed, and a monitoring program.

Geotechnical engineering during the design process is focused on developing defenses against probable dam failure modes. Of historical failure modes, as shown in Figure 20, the fundamental concerns of a geotechnical engineer are (1) foundation defects (or subsurface defects, using the terminology of this report); (2) slides (which may or may not extend through the superstructure into the subsurface); and (3) piping or seepage. Whereas Figure 20 indicates foundation defects and slides are responsible for 10% of dam failures internationally, the Association Society of State Dam Safety Officials (ASDSO)[24] reports them to be a cause of 30% of dam failures in the United States. Similarly, Figure 20 reports piping and seepage as the cause of 40% of international dam failures, while ASDSO indicates them as a cause of 20% of dam failures in the United States. (The differences are in part explainable by different definitions.) Seismic loading and surface erosion also often require consideration during design. Susceptibility of earthen spillways to erosion is another design issue that requires geotechnical input on some projects. Other important but non-geotechnical modes are overtopping and structural failure of control structures (e.g., gates and spillways).

Once potential failure modes have been characterized, each identified mode is analyzed to determine whether foundation treatment is necessary to mitigate the risk and select appropriate foundation treatments. Foundations for water retaining structures must be designed and built to incorporate measures to minimize or effectively manage foundation seepage (also called "underseepage"). As the various structures are arranged across the valley, each must incorporate a foundation that considers foundation seepage measures that are compatible with the structure that it supports. Foundations of granular material and highly jointed or fractured rock are highly permeable and require treatment of the foundation. Conventional foundation treatment measures to achieve these design objectives have been extensively documented by the USBR (2006a; 2012).

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[24] Available from https://damsafety.org/dam-failures (accessed August 10, 2020).

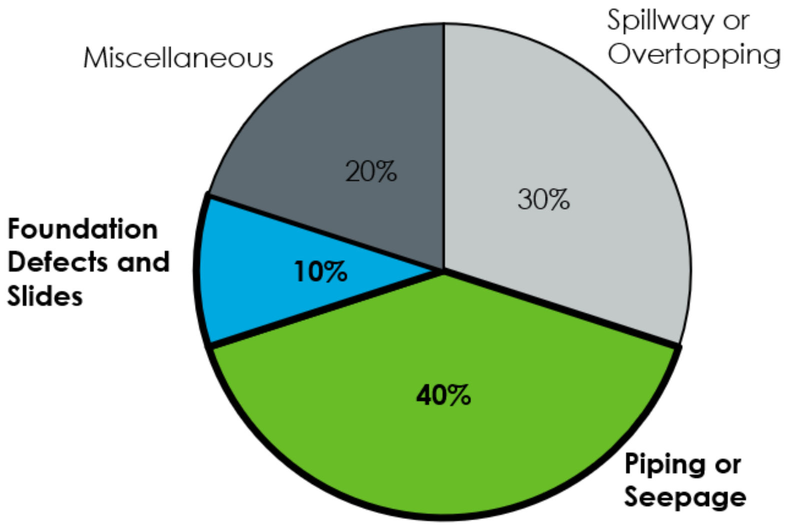

Figure 20. Approximate fraction of international dam failures by proximate cause. Piping or seepage along with foundation defects and slides are highlighted as potentially foundation-related failure modes. Source: After DeNeale et al. (2019), as modified from Baecher, Paté, and de Neufville (1980).

Treatments that may be applied for a dam foundation are listed in Table 3, with additional information on procedure provided in Table D.5 in APPENDIX D. Such treatments also apply to spillways and other appurtenant works and include

- Excavation of weak or permeable material
- Placement of dental concrete or low-permeability material on the foundation surface
- Anchors (typically for concrete gravity dams, spillways, and stilling basins)
- Cutoff trenches, such as these:
    - A clay-filled cutoff trench, for an earth and rockfill dam with central clay core, where the clay core is extended to a rock foundation
    - A cement slurry trench—a trench is excavated to a required depth and backfilled with a cement slurry
- Grout curtains
- Grout blankets
- Walls (e.g., slurry, sheet pile, or concrete)
- Relief wells
- Any combination of the above to respond to the conditions encountered in the field

Upstream impermeable blankets, comprising clay blankets, geotextiles, or concrete aprons. Elements that are part of the superstructure (and thus are not considered part of the foundation) include

- Filters and drains
- Geotextile membranes/blankets
- Embankment and concrete dam structures
- Core

Typical design measures to improve performance of the superstructure include

- Flattening slopes
- Constructing berms
- Excavating shear keys
- Adding drainage elements in the embankment to lower the phreatic surface within the embankment
- Employing granular drains and filters as a key defense to piping (internal erosion)

Table 3. Applicability of common dam foundation treatments by dam and foundation type. Source: Modified from Fell et al. (2014). Green check boxes indicate applicability; red ×'s indicate non-applicability.

Treatment	Foundation type	Applicability		
		Concrete dam	Rockfill dam	Earthfill dam
General foundation excavation	Rock	☑	☑	☑
	Soil	☑	☑	☑
Foundation cutoff excavation	Rock	☑	☑	☑
	Soil	☑	☑	☑
Cutoff foundation wall	Rock	☑	☑	☑
	Soil	☑	☑	☑
Curtain grouting	Rock	☑	☑	☑
	Soil	×	×	×
Consolidation grouting, also called blanket or stitch grouting	Rock	☑	☑	☑
	Soil	×	×	×
Rock anchors[25]	Rock	☑	×	×
	Soil	×	×	×
Ground improvement	Rock	×	×	×
	Soil	☑	☑	☑
Relief wells	Rock	×	×	×
	Soil	☑	☑	☑
Upstream impermeable blanket or concrete apron	Rock	×	×	×
	Soil	☑	☑	☑

Common watertightness considerations for foundation treatment are listed in Table D.4 in APPENDIX D for specific dam and spillway types, with references to the typical sections shown in Figure D.1, Figure D.2, and Figure D.3 in APPENDIX D. Once a preliminary design is established, the embankment and foundation are evaluated to check stability and analyze seepage, and to compare the predicted level of performance if more than one dam type is under consideration. Typical calculations that are useful in foundation design include settlement and consolidation analysis, seepage analysis, and stability analysis (see Figure 12), as summarized in Table 4. Formal training is necessary to perform the work. Results from these geotechnical calculations will guide the selection of both foundation treatment and specific dam components such as zones, trenches, and the core.

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[25] Rock anchors are often used for spillways and stilling basins, regardless of dam type.

Table 4. Typical calculations for design of dams and appurtenant works.

Analyses	Purpose	Description
Elastic settlement and consolidation analyses	Determine immediate and time-dependent vertical deformation due to loads from embankments and structures	Standard one-dimensional consolidation analyses using elastic stress distributions as described by numerous fundamental geotechnical textbooks. When needed, 2D or 3D analyses are performed using finite element analysis
Seepage analysis	Calculate location of phreatic surface, pore pressure distribution, and seepage quantities	Typically performed using finite element analyses
Stability analysis	Confirm that proposed design has an adequate factor of safety for the structure and foundation.	Usually performed with software implementing limit equilibrium analyses—see Duncan, Wright, and Brandon (2014). Numerical methods (e.g., finite element or finite difference analyses) also employed when deformation prediction is important

4.2.1.5 Foundation Design for Construction and Operation

An important task for the designer is to develop a monitoring plan to be implemented during construction and operation. Adhering to best practices for dam design will result in an acceptably low probability of failure, although residual risk remains during construction because of the following possibilities:

- Important subsurface conditions may be discovered during construction even after a well-planned design investigation.
- Errors may occur during design that are not detected in the review process.
- Mistakes or changes may occur during construction.
- The dam and appurtenant structures may not be commissioned, operated, or maintained properly.
- Unforeseen loads may act on the structure (updates in seismic or hydrologic loading).
- An unknown condition may exist that could adversely impact dam performance.

For this reason, best practice is to implement a construction and operations surveillance and monitoring program using both documented visual inspections and geotechnical instrumentation. Designers are well-suited to developing such a program. Within the United States, nonfederal dam projects frequently rely on requirements provided by FERC for these types of programs (FERC, 2017). Typical instrumentation could include monitors for water level wells, water and earth pressure, temperature, internal and surface movements, joint/crack displacement, strain in concrete structures, relative motions of benchmarks, and motion from earthquake shaking.

Small dams generally do not have inspection galleries that house extensive instrumentation and facilitate internal visual inspection. Small dams in undeveloped reaches in rural areas would generally be classified as low-hazard dams, and their instrumentation requirements are usually guided by state dam safety regulations. Larger dams and small dams with a significant-/high-hazard classification require instrumentation to monitor the structure and the foundation system.

Instrumentation for foundations is generally directed at specific issues or concerns such as foundation seepage, weak foundation zones, confirmation of foundation design parameters, and response to seismic loadings. Table 5 presents typical types of foundation instrumentation.

Table 5. Instrumentation for foundation systems.

Problem, concern, or issue	Typical instrumentation for the foundation system
Foundation seepage under the dam or through the abutments	• Collection channels and measurement weirs, possibly with a float and continuous recorder • Open standpipe piezometers screened at specific depths in the downstream areas
Foundation seepage in the abutment areas	• Collection channel and measurement weir, possibly with a float and continuous recorder • Open standpipe piezometers screened at specific depths in the downstream areas • Groundwater observation wells downstream from the abutments
Uplift pressure and pore pressure in the foundation	• Vibrating wire piezometers
Foundation deformation or settlement	• Piezometers, inclinometers and extensometers
Seismic loadings in high risk zones	• Seismograph (accelerograph)

4.2.2 Civil Infrastructure Foundation Design

Other hydropower project structures are associated with project development but can fall outside of the foundation footprint of the dam and appurtenant works, including

- Aqueducts (e.g., canals, penstocks)
- Powerhouses (not integral with the dam)
- Retaining walls
- Transmission towers

Infrastructure foundations are typically classified either as shallow (e.g., spread or strip footings and mat foundations) or deep (pile foundations). Experience has shown that deep foundations, mats, and shallow foundations on rock are less susceptible to construction defects and locally variable soil conditions than are shallow foundations on soil. Many designers avoid shallow foundations on soil for expensive or critical structures for which high reliability is essential. Many types of deep foundations are available; selection depends upon capacity required, local availability of materials and contractors, and installation considerations (e.g., presence of large cobbles and boulders).

The objective of civil infrastructure foundation design is to establish the foundation type (e.g., spread footings or piles) and dimensions for infrastructure that will safely and adequately transfer loads from a structure to the ground (soil, rock, or both) and undergo post-construction settlement of the foundation units within tolerable limits. The fundamentals of design methodology applicable for low-head hydropower projects are contained within numerous geotechnical textbooks. AASHTO (2010) provides relatively recent design standards using the Load Resistance and Factored Design (LRFD) method, which may be applicable for hydropower foundations. Many other useful publications providing specialized foundation design procedures that are generally applicable for hydropower projects in addition to transportation infrastructure are available from the Federal Highway Works Administration's online library.[26] Selected relevant USACE design manuals are listed in Table 6. The Canadian Foundation Engineering Manual provides another relatively recent and comprehensive guide to foundation design for infrastructure.

Table 6. Selected USACE foundation design manuals.

Pub number [27]	Title	Pub date	Citation
EM 1110-1-1904	Settlement Analysis	9/30/1990	USACE (1990)
EM 1110-1-1905	Bearing Capacity of Soils	10/30/1992	USACE (1992)
EM 1110-1-2908	Rock Foundations	11/30/1994	USACE (1994b)
EM 1110-2-2504	Design of Sheet Pile Walls	3/31/1994	USACE (1994a)
EM 1110-2-2906	Design of Pile Foundations	1/15/1991	USACE (1991)

Becker (1996a; 1996b) summarizes the components of the civil infrastructure foundation design process, which are also appropriate for dam civil infrastructure. The following are important considerations for the process:

- Other types of infrastructure foundations (besides dams and appurtenant structures) included in the development are much less likely to pose a fatal design flaw or result in large cost overruns than are the dam and appurtenant structure foundation.
- A primary purpose of analyses is to confirm adequate bearing capacity and acceptable settlements.
- Infrastructure design relies more heavily on code of practice (including building codes) than does dam design.
- Establishing design criteria requires effective interaction between geotechnical and structural engineers; design criteria should be established based on realistic performance requirements rather than arbitrary standards (e.g., less than 1 inch of settlement) to avoid unnecessary conservatism in the design.
- The importance of site investigation and establishing an appropriate geologic model for the site is similar to the importance of design of dam and appurtenant structure foundations.

In most instances, foundation loads associated with other infrastructure are smaller and less complex than those imposed by a dam. Dam designs must address seepage, a wider variety of geologic environments and soil conditions, rock bearing and sliding capacity, and foundation potential settlement. Special conditions such as liquefiable sands and gravels, soft to medium-stiff or expansive clays, and karst topography are examples of dam foundation conditions that may result in excessively high construction costs or may be considered fatal flaws.

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[26] Available from https://www.fhwa.dot.gov/engineering/geotech/library_listing.cfm (accessed August 10, 2020).
[27] Available from https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/u43544q/666F756E646174696F6E/?udt_43544_param_orderby=Pub_x0020_Number&udt_43544_param_direction=descending (accessed August 10, 2020).

4.3 FOUNDATION CONSTRUCTION

This section summarizes foundation construction considerations, including pre-excavation activities, excavation activities, and foundation treatments.

4.3.1 Pre-Excavation Activities

4.3.1.1 Contractor's General Obligations

The entity contracted to construct the dam and appurtenant structures and their foundations must comply with the applicable codes, permits, laws and regulations from any applicable state, regional, or federal authorities. During foundation construction, the contractor is obligated to incorporate measures related to environmental protection (e.g., general environmental best management practices [BMPs]), fish and wildlife protection (e.g., prohibition of hunting and fishing), erosion control (e.g., implementation of riprap), preservation of archeological resources (e.g., stop work and recover artifacts, if found), public safety (e.g., signage and limits to site access), and worker safety (e.g., personal protection equipment and safety plan).

4.3.1.2 General Mobilization and Site Preparation

The foundation contractor will mobilize the required construction equipment. This could include trucks (haul and water), excavators, bulldozers, motor graders, cranes, pile drivers, trench diggers, vibrating rollers, mobile compressors, diesel generators, and drilling and grouting equipment.

Site preparation includes execution of provisions for the equipment yard, fuel depot, construction access roads, and designation of areas for placement of excavated material. Initially, the foundation surface is exposed after the area is cleared and grubbed of vegetation and the topsoil is removed. Excavated topsoil is often stored for later site restoration efforts.

4.3.1.3 River Diversion and Care of Water

Dam and appurtenant structure foundations are constructed "in the dry." The contractor executes a river diversion to provide relatively dry work areas to allow operation of construction equipment and implementation of foundation treatment measures. Care-of-water and river diversion works can be incorporated as permanent features.

Most river diversion works are initiated at the beginning of the dry season and typically include cofferdams, canals, culverts, and pipes to pass flows around a work front. The work area is often protected from high flows (typically a 10- or 20-year flood) by dikes, cofferdams, or sandbag walls. Figure 21 shows an example of construction activities occurring within a protected foundation work site.

In deep excavations, groundwater may be present and can flood excavated areas. To maintain a dry work area, the contractor can pump seepage water within the excavation area. The contractor may also implement measures to limit groundwater infiltration. Such measures include driving sheet piles or grouting around the perimeter of the work area. Additionally, to lower the local groundwater table, the contractor may establish a perimeter well point system. Such care-of-water measures can be expensive considering that they frequently extend throughout the construction period.

Figure 21. Chickamauga Lock replacement project[28] in Chattanooga, Tennessee, showing foundation excavation and treatment within the dewatered/coffer dammed work site. Image courtesy of Scott DeNeale.

4.3.1.4 Environmental Best Management Practices

The contractor will adhere to environmental BMPs, which will ultimately have cost and schedule impacts. With regard to small hydropower development, BMPs pertain to work conducted in-river or in riparian environments. This includes test pits dug during site investigations as well as river diversion and flood management during construction.

BMPs include structural, vegetative, or managerial practices used to treat, prevent, or reduce water pollution. Structural BMPs use structures to control flooding and flow diversion. Vegetative BMPs use landscaping practices, such as grassed swales, to reduce erosion. Managerial practices include regular maintenance of structural and vegetative BMPs, spill prevention, and waste reduction practices.

Many BMPs remove pollutants from the water. Some of the water quality benefits are reduced soil erosion, lower contaminant loadings, and cleaner bottom sediments. Another benefit of BMPs is reduction of flooding. Temporarily detaining a large portion of runoff volume and releasing it at a slow rate limits flooding.

4.3.2 Excavation Activities Including Care of Water

The principal structures (dam, spillway, powerhouse, fish passage, and low-level outlets) are sited to conform to the topographic and geologic conditions at the site. The design establishes foundation levels of the proposed structures based on the engineering interpretations and judgements of the expected subsurface conditions. The contractor executes the works in accordance with the engineer’s drawings for construction and specifications. Foundation excavation and subsequent dam construction are planned and executed in close coordination with diversion and care of water.

Final excavation levels are normally established, assessed, and treated in the field. The foundation levels and treatment measures may vary from those shown on the construction drawings. The construction

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[28] For recent information about the Chickamauga Lock replacement project, see https://www.waterwaysjournal.net/2020/05/01/new-chickamauga-lock-could-open-as-soon-as-2023/ (accessed August 10, 2020).

contract generally includes language pertaining to the liberties afforded to the contractor, such as proceeding with placing fill, concrete, or other material with the approval of the resident engineer. The resident engineer may require further excavation or other measures. Field tests may be required to confirm compliance with the anticipated foundation conditions.

4.3.2.1 Excavation and Surface Preparation of Soil Foundations

Soil in the dam foundation that is unsuitable or is needed as processing sand and aggregate for concrete production is readily excavated and hauled away by excavators and haul trucks. Material is hauled to spoil areas or staging areas for processing. In situ soil in riverine areas is generally well compacted. Once excavated, the soil exhibits a bulk-up, over the original in situ volume, on the order of 10% to 20% depending upon the soil type.

Before soil, rock, or concrete is placed over a soil foundation, the surface is prepared to achieve the desired foundation requirements between the foundation and the structure that it supports. Such surface treatments may include

- Adding a thin layer of selected gravel, mixing the gravel into the underlying material using a tilling machine, and compacting the soil using a vibratory roller
- An application of a layer soil-cement
- Using a vibratory roller to prepare the surface and adding gravel, as necessary, to achieve a reasonably flat working area for placing the initial layer of concrete or fill

If any over-excavation in the field occurs, the contractor is required to backfill such areas with structural fill, as approved by the resident engineer.

4.3.2.2 Excavation and Surface Preparation of Rock Foundations

Rock excavation is readily accomplished by a variety of construction methods, such as

- Employing bulldozers to rip the rock and a front-end loader to load the material into the haul trucks.
- Employing excavators and haul trucks.
- For confined excavation, such as a deep setting of a draft tube, employing drill and blast or mechanical methods. Rock debris is removed by an excavator with haul trucks.

Material is hauled to spoil areas or to staging areas for processing. Excavated rock exhibits a bulk-up over the original in situ volume, on the order of 25% to 40%.

When a cutoff trench for an earth and rockfill dam with a clay core is used, it is generally founded on rock to limit seepage. Before clay or concrete is placed over a rock foundation, the surface is prepared to achieve the desired foundation shape and the bond between the foundation and the structure that it supports. Such surface treatments may include

- Shape and trim exposed rock surfaces that may give rise to localized stress fractures in a concrete structure.
- Remove loose rock and soil material that is present in rock joints or fractures. Backfill such areas with rock-replacement concrete.

- Perform shallow consolidation grouting or stitch grouting to enhance the consistency and competency of the rock foundation.

- Before placing the first layer of clay or concrete, clean the foundation with water jets and apply broom-swept slush grout to the rock surface.

These treatment measures can be costly, and it may be preferable to deepen the overall excavation to reduce surface treatment requirements. If any over-excavation of rock due to uncontrolled blasting occurs, the contractor would be required to fill such areas with backfill lean concrete, as approved by the resident engineer.

4.3.3 Foundation Treatment Below the Excavated Level

Foundation treatment below the excavated foundation can be performed on the in situ rock and soils to, most frequently, minimize or reduce foundation seepage. This foundation treatment requires specialized construction equipment.

In rock foundations, pressure grouting is performed to fill the deeper joints, cracks, and crevices that are not treated by the shallow consolidation grouting. Pressure grouting involves drilling grout holes and pumping a grout mixture that fills rock voids. Water pressure testing is frequently performed to confirm that the desired hydraulic conductivity is achieved. Grout curtains are employed under most embankment dams, rockfill dams with central cores, and concrete-faced rockfill dams. They are also employed under most concrete dams.

In soil foundations, treatment measures are performed to reduce hydraulic conductivity or elongate the seepage path. Pressure grouting is infrequently performed, as the soil foundation has high permeability and would “take” excessive quantities of grout. To provide a largely impermeable wall within the soil, the contractor could drive sheet piles or construct a concrete cutoff wall that reaches the desired depth into the soil foundation.

5. REPRESENTATIVE COSTS AND TIMELINES FOR HYDROPOWER FOUNDATIONS

This section assesses representative costs and timelines of foundation geotechnical site assessment, design, and construction for conventional, low-head hydropower facilities. These foundation costs and timelines inherently incorporate the evaluation of risks at every stage along the development process. This section builds on information presented previously in Sections 3 and 4, including the representative structures, their compatible foundations, and conventional foundation treatment measures. References are noted herein from the USBR, USACE, USSD, Association for the Advancement of Cost Engineering (AACE), and others. Cost and timeline information is primarily derived from a wide range of prior project experience.

5.1 ANALYSIS FRAMEWORK

In the process of estimating costs and timelines for a hydropower project foundation, the dam type and general arrangement of the spillway and other structures (modules) must be initially established. Figures D.1, D.2, and D.3 in APPENDIX D introduce six typical earthfill dams, three typical rockfill dams, and six typical sections for concrete dams and spillways, respectively. Table D.4 presents characteristics of the structural material, compatible foundation material, and conventional measures to enhance watertightness. This analysis considers the foundation footprint along the dam axis including appurtenant structures.

The analysis considers a maximum structural height of 50 ft (refer to Figure 1) and a minimum of 15 ft for NSD sites. This range is selected as representative of most low-head hydropower developments in the United States that are likely to be economical. Little economy of scale, either in time or cost, exists over this range of structural heights.

For purposes of estimating foundation timelines and costs, the general terrain at the dam site, type of foundation, and type of dam and appurtenant structures are considered. General terrain is classified in three types: mountain, hill, and valley, as initially presented in Section 3.1. Table 7 presents the suitability of the dam structures and their foundations to each terrain; the information covers the four principal dam types (and their corresponding foundations) that are judged likely to be prevalent in future hydropower development. The four dam types are previously introduced in Section 4 along with other dams that are variations of these four types. Conventional concrete hydraulic structures, both overflow and non-overflow structures that assist the dam in impounding the reservoir, are also included in Table 7. As shown, suitability is classified as either “conventional” or “special situation,” indicating whether a particular dam type is likely to be suitable or require more detailed consideration, respectively, based on the terrain class.

Drainage basin areas (catchments) are larger in the valley than in the mountains. Hydropower developments in the mountains would allow exploitation of the higher hydraulic head available, but less water would be available for hydropower generation. The opposite applies to a development in the valley, where more water is available, but with less exploitable hydraulic head. In a hilly terrain, there may be a balance between exploitable water and hydraulic head.

The depth of excavation required to achieve a suitable foundation level is a key parameter for consideration of costs and timelines. Typical ranges of required excavations are highly variable and would vary across the dam axis. The ranges indicated in Table 7 may be suitable for a small hydropower development. If required excavation depths significantly exceed the upper value of the ranges shown, the development may be considered uneconomical.

Table 7. Suitability of dam types and foundation based on terrain class.

		Terrain class		
		Mountain	**Hill**	**Valley**
Typical cost-effective range of excavation depth (ft)		2 to 6	3 to 10	6 to 15
Type of dam and associated foundation	Homogeneous earthfill on impermeable foundation (soil or rock)	Special situation	Conventional	Conventional
	Zoned earthfill and rockfill dam on permeable soil (or highly weathered rock or regolith) foundation	Special situation	Conventional	Conventional
	CFRD with plinth on impermeable rock foundation and rockfill on permeable soil (or highly weathered soil or regolith) or impermeable rock foundation	Conventional	Conventional	Special situation
	Concrete gravity dam non-overflow section on impermeable rock foundation	Conventional	Conventional	Special situation
Type of spillway/ impounding structure and associated foundation	Concrete overflow or non-overflow impounding structure on an impermeable rock foundation	Conventional	Conventional	Conventional
	Concrete overflow or non-overflow impounding structure on a permeable soil foundation	Special situation	Conventional	Conventional

For each dam type or spillway/impounding structure and compatible foundation, there is an indication of their suitability in different terrains, along the lines presented in Table 1 of Section 3. The designation of "Conventional" in Table 7 indicates that such development would be considered within current industry practice. The designation of "Special Situation" indicates that the development would be outside of current industry practice and thus generally considered cost-prohibitive.

5.2 STANDARDS FOR COST ESTIMATION

Standards for cost estimating are promulgated by various institutions, including ASTM International (ASTM, 2019), AACE International (AACE, 2019), USACE (USACE, 2016), USSD (USSD, 2012), and USBR.[29] The ASTM standard and the AACE standard are nearly identical. USSD (2012) specifically addresses dams and spillways and presents detailed templates for cost estimation, including foundation costs. Such templates are detailed for an embankment dam and a concrete gravity dam (RCC placement method).

The AACE provides for five classes of estimates (AACE, 2019), as shown in Table 8. The AACE classes refer to the level of project definition, its end use, typical estimating methodology, and expected range of contingency.

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[29] Available from https://www.usbr.gov/tsc/techreferences/cost.html (accessed August 10, 2020).

Table 8. AACE classification of cost estimates. Source: Modified from AACE, 2019.

Estimate class	Primary characteristic	Secondary characteristic		
	Maturity level of project definition deliverables Expressed as % of complete definition	End use: Typical purpose of estimate	Methodology: Typical estimating method	*Expected accuracy range: Typical variation in low and high ranges
Class 5	0% to 2%	Concept screening	Capacity factored, parametric models, judgement, or analogy	L: −20% to −50% H: +30% to +100%
Class 4	1% to 15%	Study of feasibility	Equipment factored or parametric models	L: −15% to −30% H: +20% to +50%
Class 3	10% to 40%	Budget authorization or control	Semi-detailed unit costs with assembly level line items	L: −10% to −20% H: +10% to +30%
Class 2	30% to 75%	Control or bid/tender	Detailed unit cost with forced detailed take-off	L: −5% to −15% H: +5% to +20%
Class 1	65% to 100%	Check estimate or bid/tender	Detailed unit cost with detailed take-off	L: −3% to −10% H: +3% to +15%

*The state of process technology, availability of applicable reference cost data, and many other risks affect the range markedly. The ± value represents typical percentage variation of actual costs from the cost estimate after application of contingency (typically at 50% level of confidence) for given scope.

Class 2 to 5 estimates are generally prepared by engineering consultants who are participating in the geotechnical engineering, including preparation of bid documents. Contractors generally provide Class 1 and 2 estimates as budgetary or firm offers to execute construction. As shown in Table 8, the contingencies are very high for Classes 3 to 5, reflecting the lack of project definition.

The estimate of costs is from the standpoint of the owner. In general terms, the cost of construction is also the price offered by the construction contractor. The owner has other costs associated with the project such as permitting, engineering, management, and environmental mitigation.

5.3 WORK BREAKDOWN STRUCTURE

Defining the scope of the foundation system is fundamental to providing useful cost and timeline representations. The work breakdown structure (WBS) divides the foundation system into preconstruction (geotechnical site assessment and design) and construction activities that foster construction planning and sequencing (PMI 2017). Table 9 presents the WBS for the foundation component of hydropower projects for a variety of subsurface conditions. This breakdown essentially represents a generalized version of the USSD guidelines (USSD, 2012).

Foundation system costs are those costs associated with the nine major items presented in Table 9. Items 100 and 200 refer to the site assessment and design efforts prior to construction, whereas items 300–900 refer to the construction.

Table 9. Typical foundation work breakdown structure.

Activity area	WBS Dictionary	Work item description
Site assessment	**100**	**Field investigations and testing**
	101	Initial and preliminary investigations
	102	Feasibility investigations
	103	Final design for construction (detailed design)
Design	**200**	**Planning and design**
	201	Desktop study, screening, and preliminary study
	202	Feasibility study and basic design
	203	Final design, specifications, and drawings for construction
Construction	**300**	**Owner's quality assurance oversight during construction**
	301	Owner's quality assurance oversight
	400	**Excavation and care of water**
	401	Clearing and grubbing, including removal of trees
	402	Stripping and stockpiling of organic soil layer
	403	Diversion works and care of water for foundation construction
	404	Excavation of granular soil, highly weathered rock, or regolith (transport to fill, aggregate plant, stockpile or spoil area)
	405	Excavation of rippable rock by machine (transport to fill, rock crusher, stockpile or spoil area)
	406	Excavation of rock using controlled blasting (transport to fill, rock crusher, stockpile or spoil area)
	500	**Surface treatment of soil foundations for embankment fill**
	501	Surface shaping and preparation of permeable soil foundation, including tilling and compaction
	502	Surface shaping and preparation of impermeable soil foundation
	600	**Surface treatment of a rock foundation for embankment fill**
	601	Surface shaping and preparation
	602	Shallow consolidation grouting or stich grouting
	603	Foundation cleaning and placement of broomed slush grout (for clay core only)
	700	**Surface treatment of rock foundations for concrete structures**
	701	Remove highly jointed and fractured rock and backfill with dental concrete
	702	Shaping rock surface using dental concrete or shallow consolidation grouting
	703	Foundation cleaning and placement of broomed slush grout
	800	**Subsurface treatment measures for the excavated foundation for permeable foundations (may be combined with piles)**
	801	Slurry trench
	802	Sheet pile cutoff wall
	803	Concrete cutoff wall
	900	**Subsurface treatment measures for the excavated foundation for impervious rock foundations**
	901	Grouting

5.4 OVERVIEW OF FOUNDATION TIMELINES, COSTS, AND RISKS

Timelines, costs, and risks are highly interdependent in all phases of project development. The phasing of the project development is established to arrive at decision points regarding whether the proposed development merits further site investigation and design. In the early planning stages, readily available maps, imagery, and published information are gathered and evaluated. Initial efforts may include a site reconnaissance visit focused on identifying potential fatal flaws in the seismic and geologic setting. Such fatal flaws may include active faults, unfavorable terrain features, high variability and solubility in local geology, instability in valley side slopes, and the expectation of a need for excessively deep excavations or other costly foundation treatment measures. The existence of such unfavorable characteristics would likely produce increased costs, timelines, and risks, thereby eliminating the project from further consideration.

Table 10 presents the timeline, cost, and risk breakdown of the previously identified structures, each with its assumed compatible foundation system. The compatible foundation system refers to the as-built foundation excavation level with required surface and subsurface treatment.

Table 10. Foundation system timeline, cost, and risk breakdown. Based on unpublished work performed by Knight Piésold Consulting.

Category	Structural material and assumed foundation system	Typical cost-effective depth of overburden removal for <30 ft of hydraulic head (ft)	Relative cost of foundation system	Relative time duration	Relative risk of changed geologic conditions during construction	Foundation-related constraints to successful development	Principal cost drivers	Principal work breakdown makeup
Earthfill or rockfill dam	Homogeneous earthfill on impermeable soil foundation	<5	Low	Moderate	Low	Terrain, soil strength, and liquefaction potential, depth of required excavation	Local geology, foundation footprint	Excavation volume, foundation surface preparation
	Homogeneous earthfill on impermeable rock foundation	<5 to 8	Low	Moderate	Low	Terrain, rock quality, depth of required excavation	Local geology, foundation footprint, degree of rock fracturing	Excavation volume, foundation surface preparation, grouting
	Zoned earthfill and rockfill dam on permeable soil foundation	<5 to 8 for dam shoulders and <15 for plinths (upstream toe slab)	High	Long	Moderate	Terrain, soil strength, and liquefaction potential, depth of required excavation, groundwater level	Local geology, dewatering and care of water, foundation level and footprint	Excavation volume, foundation surface preparation, grouting
	CFRD with plinth on impermeable rock foundation and rockfill on permeable soil or impermeable rock foundation	<5 for dam should and <10 to 15 for plinths (upstream toe slab)	High	Long	Moderate	Terrain, soil strength, and liquefaction potential, rock quality, depth of required excavation, groundwater level, soil permeability	Local geology, depth of plinth foundation	Excavation and foundation treatment of plinth

Table 10. Foundation system timeline, cost, and risk breakdown (continued). Based on unpublished work performed by Knight Piésold Consulting.

Category	Structural material and assumed foundation system	Typical cost-effective depth of overburden removal for <30 ft of hydraulic head (ft)	Relative cost of foundation system	Relative time duration	Relative risk of changed geologic conditions during construction	Foundation-related constraints to successful development	Principal cost drivers	Principal work breakdown makeup
Concrete structure (overflow or non-overflow)	Concrete gravity dam, non-overflow section on impermeable rock foundation	<5 to 8	Low	Moderate	Low	Terrain, rock quality, depth of required excavation	Foundation footprint and degree of rock fracturing	Foundation grouting and surface preparation
	Concrete overflow or non-overflow impounding structure on impermeable rock foundation	<5 to 8	Low	Moderate	Low	Terrain, rock quality, depth of required excavation	Foundation grouting and surface preparation	Foundation grouting and surface preparation
	Concrete overflow or non-overflow impounding structure on permeable soil foundation	<8 to 10 (or use piles)	High	Long	Low	Terrain, soil strength and liquefaction potential, depth of required excavation, groundwater level, soil permeability	Dewatering and care of water, cutoff trenches and walls	Excavation volume and cutoff walls
Investigation	All	N/A	Low	Short	Low	Local studies and subsurface geology complexity or unsuitability	Foundation footprint, depth of boreholes, number of laboratory and field tests	Field exploration progress, laboratory testing, reporting

Table 10. Foundation system timeline, cost, and risk breakdown (continued). Based on unpublished work performed by Knight Piésold Consulting.

Category	Structural material and assumed foundation system	Typical cost-effective depth of overburden removal for <30 ft of hydraulic head (ft)	Relative cost of foundation system	Relative time duration	Relative risk of changed geologic conditions during construction	Foundation-related constraints to successful development	Principal cost drivers	Principal work breakdown makeup
Engineering	All	N/A	Low	Short	Low	Local studies and subsurface geology complexity or unsuitability	Types of structures and their foundations, complexity of design, special situations, modeling	Foundation planning and design, reporting

5.5 FOUNDATION SYSTEM COSTS

Foundation site assessment, design, and construction are specific to the dam site. The foundation type and required treatment are planned in conjunction with the type and arrangement of the dam and appurtenant structures. The generalized foundation system costing information presented herein is intended to inform DOE and hydropower stakeholders about typical foundation cost considerations, including cost drivers and challenges associated with the development process.

The level and detail of the cost estimating coincide with the data available and the stage of development of the potential hydropower project. Section 5.5.1 presents representative cost breakdowns of foundation system costs. Further insight into the cost drivers and risks associated with foundation engineering and river diversion are presented in Sections 5.5.2 and 5.5.3, respectively.

Foundation system costs are specific to the site conditions. Costs are correlated to the quality of the subsurface foundation material within the initial 2 to 8 ft below the surface (assumed final excavation level along the development profile). Material quality for foundation systems is broadly represented by shear strength and hydraulic conductivity, with a preference for high shear strength and low hydraulic conductivity. Figure 22 shows the relative increase in foundation system costs over a range of materials from competent rock to weak soils or karst formations.

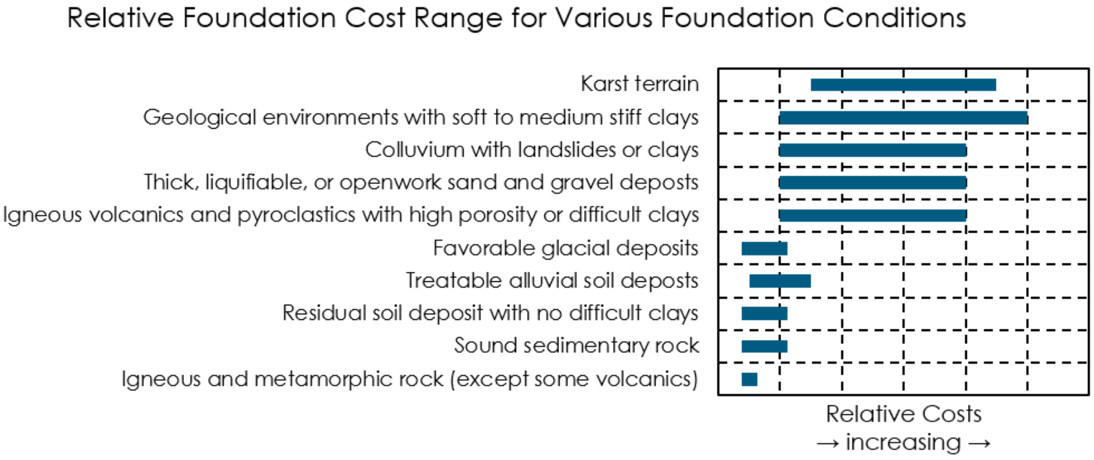


Figure 22. Qualitative relative foundation costs. Based on unpublished work performed by Knight Piésold Consulting.

5.5.1 Representative Cost Breakdown of Foundation System Costs

As presented in Section 5.3, nine principal cost categories are used for a foundation system (Table 9). The magnitude and distribution of these costs depend upon the cost drivers shown in Table 10, which are highly dependent on (a) site geology and its complexity and (b) the types of structures that form the impoundment and their general arrangement.

To illustrate general cost breakdowns, three representative project types (rock foundation in mountain terrain, rock and permeable soil foundation in hilly terrain, and permeable soil foundation in valley terrain) were considered as characterized in Table 11; the information is applicable for low-head (15 to 30 ft of head) new hydropower development. Main cost drivers are the size of the foundation footprint, the depth of excavation, and the extent of subsurface treatments. The cost drivers are minimized for a rock foundation in mountain terrain. The size of the foundation footprint and depth of excavation are significantly larger for hill and valley terrains. Additionally, a main cost driver for soil foundations in valley terrain is the extensive measures to control underseepage, such as upstream impermeable blankets and cutoff walls.

Table 11. Reference foundation characteristics for representative project types. Based on standard industry practices complied from multiple sources (e.g., USBR and USACE).

Feature	Reference foundation characteristic		
	Rock foundation in mountain terrain	**Rock and permeable soil foundation in hilly terrain**	**Permeable soil foundation in valley terrain**
Principal dam type and spillway	Concrete gravity dam and overflow spillway	Zoned earth and rockfill dam and concrete overflow spillway	Gated concrete barrage
Other structures forming the impoundment	Power intake, sediment passage, and so on	Power intake, sediment passage, and so on	Earthfill dikes, integral intake powerplant, fish passage
Relative maximum height of the non-overflow section	High	Medium to high	Low
Relative depth of excavation to final elevation	Low	High for clay core; low for dam shoulders and concrete structures	Medium
Relative size of foundation system footprint	Small	Medium	Large
Surface preparation measures at the excavated foundation level (in addition to cleaning)	Stich grouting, dental concrete	Compaction on soil foundations and stitch grouting and dental concrete on rock foundation	Compaction
Subsurface treatment below the excavated foundation level	Minimal pressure grouting in highly fractured areas	Grouting under clay core and concrete structures	Slurry trench, sheet-pile or concrete foundation cutoff wall

Representative foundation system component cost breakdowns are provided in Table 12 and are shown as a percentage of total foundation system costs; representative foundation system costs (as a percentage of total ICC) are also provided in Table 12. The breakdowns indicate the following:

- Mountainous terrains have lower total foundation system costs than hill or valley terrains.
- Site assessment costs are lowest for mountainous terrain, as the foundation footprint is relatively small.
- Excavation, surface treatment, engineering, and owner’s quality assurance oversight costs are proportionally higher for mountainous terrain, because the total foundation system cost is very low.
- Subsurface treatment is particularly costly in valley terrains, where there may be additional challenges associated with controlling underseepage in soil foundations.

Graphical representations of the information from Table 12 are provided in Figure 23.

Table 12. Typical foundation system component cost breakdown for representative project types. Based on actual industry project experience (unpublished).

Development phase	Cost component (WBS no.)	Component cost (% of total foundation system cost) for predominant terrain and typical foundation system		
		Rock foundation in mountain terrain	Rock and permeable soil foundation in hilly terrain	Permeable soil foundation in valley terrain
Site assessment	Initial and preliminary investigations (101)	2%	2%	2%
	Feasibility investigation (102)	8%	8%	8%
	Detailed design (103)	5%	10%	10%
Design	Desktop study, screening, and preliminary study (201)	3%	3%	3%
	Feasibility study and basic design (202)	7%	7%	7%
	Final design (203)	20%	15%	10%
Construction	Owner's quality assurance oversight (301)	20%	15%	15%
	Excavation and care of water (400)	20%	15%	10%
	Surface treatment of excavated foundation (500, 600, and 700)	5%	10%	5%
	Subsurface treatment below the excavated foundation level (800 and 900)	10%	15%	30%
	TOTAL	**100%**	**100%**	**100%**
	Representative foundation system cost (as % of total ICC)	4 to 8%	6 to 10%	8 to 15%

Small hydropower developments are economically viable only when the total cost of the foundation system makes up a relatively small portion of the total project cost (also referred to as ICC). For purposes of this report, the ICC represents the costs to perform the site assessment, design, and construction of a small hydropower project. The costs of the impoundment structures, water conductors, powerhouse, and generating equipment are necessarily a large majority of the ICC. The total foundation system costs, for an economical small hydropower project, would likely range from 4 to 15% of ICC, as indicated in Table 12 for the three representative projects. The lower value corresponds to rock foundations in mountain terrain, whereas the higher value corresponds to pervious foundations in valley terrain.

Care-of-water precautions, including river diversion works, are integral to the foundation system and are included in the cost breakdown shown in Figure 23 as related to excavation activities. Economically viable small hydropower developments require cost-effective measures for and sequencing of river diversion and care of water. The representative total cost allocation for river diversion would vary from 2 to 5% of ICC. The lower value would correspond to impervious rock foundations in mountain terrain with a relatively small foundation footprint and lower construction-period floods. The upper value would correspond to permeable foundations in valley terrain with a relatively large footprint and higher construction-period floods. These issues are further discussed in Section 5.5.3.

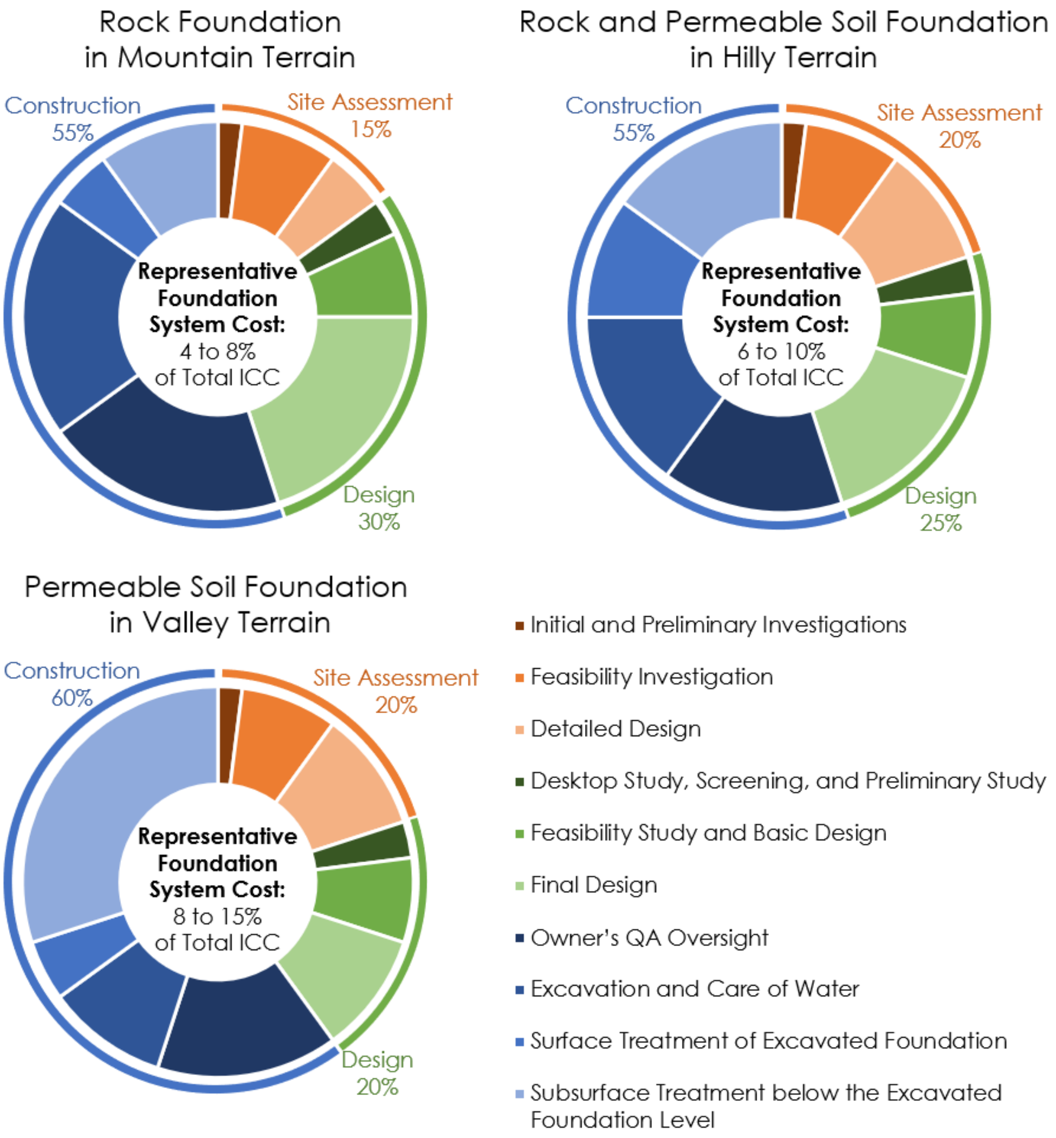


Figure 23. Representative foundation system cost breakdown by project type. Based on actual industry project experience (unpublished).

Many projects have experienced cost overruns attributable to foundation difficulties or surprises during construction. These overruns may have been due to inadequate investigations, lack of adequate engineering effort to tailor the structures to the site geology and topography, and/or contractual terms, among other considerations.

Based on industry practitioners’ prior experience with challenging foundation conditions and associated cost overruns, foundation costs are often viewed as very high. However, this perception of high cost largely stems from a lack of knowledge of the site-specific subsurface. Section 4 addresses the planning process to balance initial investigation and engineering efforts so as to screen and pursue only the most attractive opportunities for development. Early identification of fatal flaws is paramount in the development process. Combining sound site selection processes with innovation (Section 7) shows promise in identifying many potential small hydropower developments.

5.5.2 Overview of Relative Costs, Timelines, and Risks of Investigations and Engineering

Previous report sections have addressed the roles of investigations and engineering in the development process, along with cost and timeline perspectives. Project structures require engineered foundation systems that meet safety and performance requirements, including stability and controlled or negligible underseepage. Investigations vary according to both the type of structure the foundation will support and the foundation material below the final excavated level. Costs of foundation investigations are dependent on the size of the foundation footprint, depth of the subsurface to be explored, types of investigations, and number of tests.

Consideration of a potential site begins with an appreciation of the surface features, with respect to topography, geology, and vegetative cover. Excavation of the surface materials, to a suitable foundation level, is an important cost component within the foundation system. Cost trade-offs can be evaluated by comparing the cost of excavation vs. treatment of the subsurface materials, along with impacts on the timeline and risks. The types and properties of the surface and subsurface materials require investigation, in both the field and laboratory.

Table 13 presents the relative cost and complexity of the development phase and foundation system material. The extent of geotechnical testing and engineering required is lowest for rock foundations and increases as foundation materials become progressively weaker.

Table 13. Relative cost and complexity of development phase by foundation material type. Based on a combination of published and unpublished information (synthesized). Proprietary industry knowledge.

Foundation material	Concept	Feasibility	Design	Construction
Dispersive/weak clays	Low	Med/high	Med/high	High
Compacted granular soils	Low	Med	Med/high	Med/high
Rock	Low	Med*	Med	Med/high

Increasing Tests →

Increasing risk →

*Heightened cost due to requirements for continuous core sampling

Along the development phases, geotechnical engineering and evaluations of rock mechanics proceed in response to the increase in data and the results from the expansion of field and laboratory investigations. Engineering studies are undertaken to arrive at a detailed design for the foundation system and its compatibility with the structures it supports. Table 14 presents the relative time required, relative cost, implied risk, and constraints of the various project phases/studies.

Table 14. Relative time, cost, and risk for geotechnical foundation activities. Based on a combination of published and unpublished information (synthesized). Proprietary industry knowledge.

Project phase	Time required	Relative cost	Risk implication	Constraints
Conceptual siting	Low	Low	Low	Data availability
Desktop study (geologic background)	Low	Low	Low	Data availability
Field reconnaissance	Low	Low	Med	Site access, skilled/experienced field personnel

Table 14. Relative time, cost, and risk for geotechnical foundation activities (continued). Based on a combination of published and unpublished information (synthesized). Proprietary industry knowledge.

Project phase	Time required	Relative cost	Risk implication	Constraints
Geotechnical study design	Low	Low	Med-high	Skilled/experienced field personnel, scheduling, access design, sufficient for regulatory requirements
Geotechnical field campaign	Med-high	Med-high	High	Site access, skilled/experienced field personnel, scheduling, sufficient for regulatory requirements
Hydrogeological in situ testing	Low*	Low*	High	Site access, skilled/experienced field personnel, scheduling, sufficient for regulatory requirements
Geotechnical lab testing	Low-med	Low-med	High	Trusted lab, number of samples and test types sufficient for regulatory requirements and design engineers
Hazards study (seismic/slopes)	Low	Low	High	Data quality/availability, skilled/experienced field personnel, sufficient for regulatory requirements and design engineers
Foundation type determination	High**	High**	High	Sufficient high-quality data, trust in geologic/hydrologic model
Construction	High	High	Critical	Includes every previous item plus funding, quality assurance/quality control, communication

*Time and cost shared with geotechnical field campaign (these are concurrent activities).
**Every previous item is required for competent foundation type determinations; "High" expresses the cumulative time and cost.

5.5.3 Cost Drivers and Flood Risk for Care of Water Including River Diversion

River diversion was introduced in Section 4.3. The construction timeline is highly dependent on how the contractor manages the river during the construction period. The timelines for river diversion are addressed in Section 5.6.

River diversion is frequently the sole responsibility of the contractor. The considerations associated with balancing the risk between the contactor and owner is addressed in Section 4 and Section 6.

River diversion works are generally considered temporary works, including excavated channels, bypass culverts/pipes, and cofferdams. Sometimes, permanent facilities are incorporated into the river diversion plan. A river diversion plan is usually developed in detail during the feasibility study. The costs of these temporary works are included in the construction costs and financial analyses. The river diversion plan is unique to the river and site and considers the following:

- Owner's, state, or federal guidelines and lender's requirements for acceptable flood risk
- River flood hydrology and seasonal flows
- River hydraulics and flood levels (preconstruction and during construction)
- Construction period flood risk, including seasonal considerations
- Site topography and geology
- Proposed structures and foundation systems

- Protection of work fronts and partly completed structures. Overall target schedule and assumed calendar month or quarter to initiate the river diversion works

Small hydropower projects are challenged by economy of scale. For economic viability, a project would typically exclude deep foundation excavations and long construction periods. Deep foundations expose the contractor to groundwater intrusion in the excavated foundation and require a longer construction period. Longer construction periods also expose the contractor to multiple flood seasons. An extraordinary construction-period flood could overtop a cofferdam and require reconstruction of permanent works and the cofferdam. Such risks are assessed by the contractor and included in its risk premium, as previously outlined in Section 4.3.

As discussed in Section 5.1, the cost-effective maximum depth of overburden removal is between 5 and 15 ft for a wide variety of foundation types. If the foundation overburden is over 15 ft, the project is likely to be cost prohibitive. If the cofferdam is over 15 ft high, the project is likely to be cost prohibitive. Hence, excavation depths are relatively shallow, and overall project construction periods are relatively short, on the order of 2 to 3 years. Rivers normally have one main flood period per calendar year, and their durations are influenced by rainfall periods and, in northern latitudes, snowmelt. The foundation construction would generally be exposed to floods only over one or two main flood periods. Table 15 presents relative costs, project construction times, and relative risks, depending on the terrain.

Table 15. Relative costs for river diversion during construction. Based on a combination of published and unpublished information (synthesized). Proprietary industry knowledge.

Terrain	No. of flood periods exposed to damage to the foundation system	Construction period length and susceptibility to damage from construction period floods	Relative cost of river diversion works	Cost drivers for river diversion works
Mountain	1	Low	Low	Return period of construction period flood, size of foundation footprint, cofferdam height
Hill	1 or 2	Med	Med-high	
Valley	1 or 2	Med	Med-high	

5.6 FOUNDATION SYSTEM TIMELINES

Duration is a major cost driver in the execution of geotechnical site assessment, design, and construction for hydropower foundation systems. The initial timeline is generally established before estimating costs. In the execution of services, including construction services, adhering to the timeline is paramount to meeting the cost objectives.

Reasonable timelines foster a balance in resource allocation, including labor, equipment, and materials. Overly aggressive timelines can lead to over-allocation of resources, downtime, and/or inefficient sequencing of work activities, which may increase the risk of having to redo work. In economic analyses of small hydropower developments, the target timeline must reflect a balance between timeline-sensitive costs and the date of commissioning.

Table 10 includes a general overview of the relative time durations of site assessment, design, and construction of foundations for a wide variety of earthfill and rockfill and concrete structures. Section 5.5.2 and Section 5.5.3 also include information on cost and timeline drivers related to (a) investigations and engineering and (b) river diversion works.

Cost drivers include the care of water, foundation footprint size, subsurface characteristics (in particular, foundation material strength, site geologic complexity, hydraulic conductivity), excavation depth, and foundation treatment extent. As previously outlined, mountain terrains are likely to allow rock foundations, whereas valley terrains are likely to allow only soil foundations. Hilly terrain could present both rock and soil foundations. Rock foundations have greater strength, less required excavation, less hydraulic conductivity, and smaller footprints than soil foundations.

Foundation system timelines are presented in two parts:

- Investigations and engineering of foundation systems
- Foundation system construction, including river diversion

5.6.1 Timelines for Investigations and Engineering of Foundation Systems

Investigations and engineering are undertaken concurrently and generally comprise three distinct phases: initial studies, feasibility studies, and detailed design. Figure 24 presents a typical timeline for investigations and engineering for each of the three phases and three terrains.

The timeline shows representative durations for the principal activities within each phase. The timeline varies from 12 to 18 months for mountain terrain and valley terrain, respectively. Three “hold” periods are shown, which represent the time allotted for the developer to commit to a prefeasibility study, feasibility study, and detailed design. The hold periods are for an as yet undetermined duration in which the developer is considering other aspects of the development, including financing, permitting, and environmental mitigation. Essentially, the developer decides whether the project and site under consideration are sufficiently attractive to continue with development. The durations of the hold periods will depend on the policies of the developer, the quality and quantity of information, and the internal risk assessments.

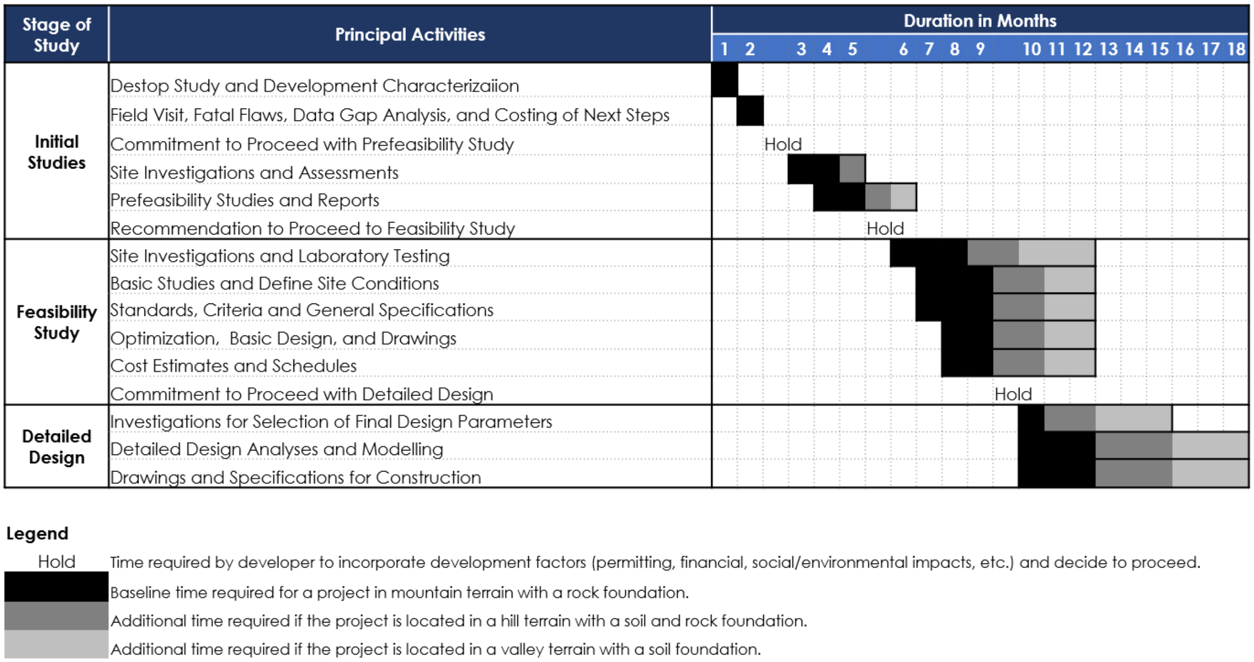


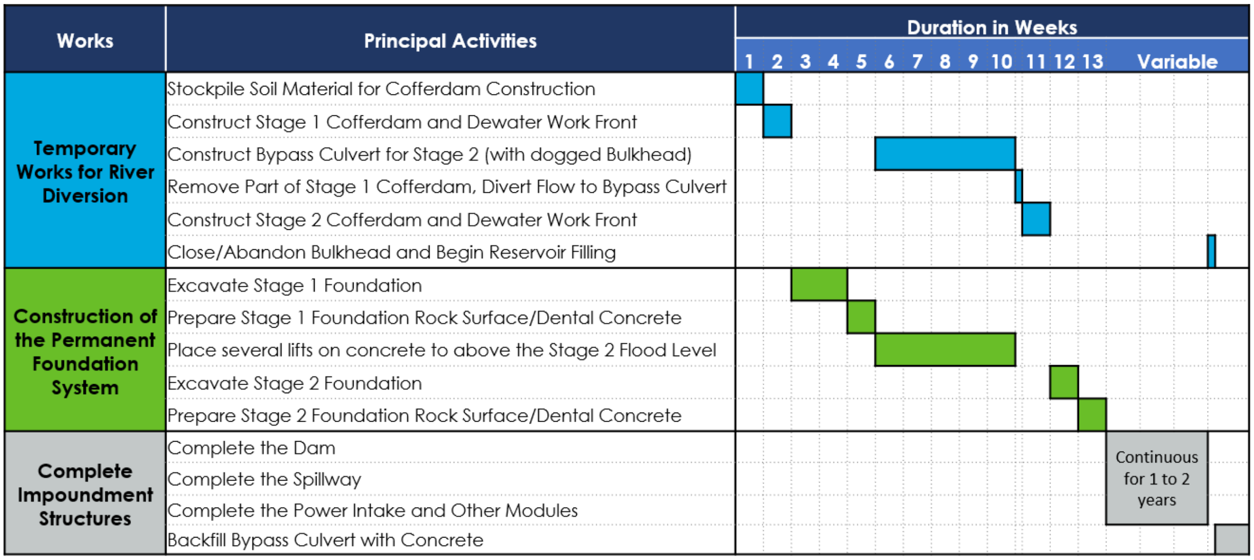
Figure 24. Representative schedule for geotechnical engineering (site assessment and design) of foundation systems. Based on a combination of published and unpublished information (synthesized). Proprietary industry knowledge.

5.6.2 Timelines for Foundation System Construction Including Care of Water

Foundation system construction is undertaken concurrently with river diversion. Initial activities of the contractor are dominated by the forecasted river flows and water levels and how they affect the work fronts within the riverine area, including the management and control of water and sediments to comply with federal and state regulations.

The principal considerations in planning river diversion (outlined in Section 5.5.3, Care of Water), including river diversion cost drivers, present similar challenges for the construction timeline. The contractor generally views river diversion as risky, as rainfall and snowmelt are highly variable. Also, in higher altitudes or latitudes, the contractor may not be able to execute river diversion or foundation system works under cold weather conditions. Contractors place a high priority on meeting river diversion milestones.

A representative timeline of foundation system construction (green activity boxes) with river diversion (blue activity boxes) is shown in Figure 25. The timeline corresponds to a concrete dam on a rock foundation in mountain terrain and indicates the subsequent impoundment structure construction activities (gray activity boxes) that follow foundation construction.



Works	Principal Activities	Duration in Weeks													
		1	2	3	4	5	6	7	8	9	10	11	12	13	Variable
Temporary Works for River Diversion	Stockpile Soil Material for Cofferdam Construction	🟦													
	Construct Stage 1 Cofferdam and Dewater Work Front		🟦												
	Construct Bypass Culvert for Stage 2 (with dogged Bulkhead)						🟦	🟦	🟦	🟦	🟦				
	Remove Part of Stage 1 Cofferdam, Divert Flow to Bypass Culvert											🟦			
	Construct Stage 2 Cofferdam and Dewater Work Front											🟦			
	Close/Abandon Bulkhead and Begin Reservoir Filling														🟦
Construction of the Permanent Foundation System	Excavate Stage 1 Foundation			🟩	🟩										
	Prepare Stage 1 Foundation Rock Surface/Dental Concrete					🟩									
	Place several lifts on concrete to above the Stage 2 Flood Level						🟩	🟩	🟩	🟩	🟩				
	Excavate Stage 2 Foundation												🟩		
	Prepare Stage 2 Foundation Rock Surface/Dental Concrete													🟩	
Complete Impoundment Structures	Complete the Dam														Continuous for 1 to 2 years
	Complete the Spillway														
	Complete the Power Intake and Other Modules														
	Backfill Bypass Culvert with Concrete														▨

Figure 25. Representative schedule for foundation system construction, including care of water (river diversion), for a rock foundation in mountainous terrain. Based on a combination of published and unpublished information (synthesized). Proprietary industry knowledge.

As shown in Figure 25, the care of water, inclusive of river diversion works, is managed in two stages:

1. Stage 1 includes using a cofferdam to isolate one-half of the riverine area within the foundation footprint. This area is dewatered by pumping. The foundation is excavated. The foundation surface is prepared for concrete placement. A diversion culvert is constructed, along with the lower portion of the dam to the specified Stage 2 flood level. The diversion culvert is equipped with a closure bulkhead gate, dogged in position for deployment to initiate reservoir filling.

2. Stage 2 includes removing the Stage 1 cofferdam and diverting the flows through the diversion culvert. The Stage 2 cofferdam is placed to isolate the other half of the riverine area. This area is dewatered by pumping. The remainder of the works are completed to form the impoundment.

Foundation systems and river diversion are minimal for sites with rock foundations. Footprints and construction-period floods are generally smaller for rock foundations because of the smaller drainage basin. Figure 25 indicates that under such favorable conditions, Stages 1 and 2 and the foundation system can be completed within 3 months.

Under ideal conditions (as shown in Figure 25), the works would be exposed to only one flood season. Water diversion and cofferdams are expensive and risky. Developments in hilly or valley terrains could be exposed to more than one flood season, as footprints are larger there and diversion and foundation works would likely require more time. A construction timeline that encompasses three flood seasons might be a fatal flaw, as diversion and foundation costs could amount to 20% or more of the ICC.

6. KEY CHALLENGES FOR HYDROPOWER FOUNDATIONS

Each project phase of hydropower foundation development has key challenges that can affect either the cost of the project, the time required to complete the project, and/or the associated risks. These three metrics (cost, time, risk) are all closely related and are dependent on one another. Reducing risk frequently requires spending more time during design and construction phases, and therefore raises the overall project cost. Costs may be reduced by selecting cheaper construction materials or by rushing certain phases of project development, which in turn may increase long-term project risk. Particular challenges related to specific phases of project development may appear to be most closely related to one of the three project performance metrics, but ultimately they are related to all three.

Desirable goals to reduce project performance metrics (cost, time, risk) include

- **Reduce construction costs** (i.e., time and materials). One possibility for doing so is to consider cost/scale relationships for certain solutions (i.e., feasible at a small but not large scale, or vice versa)
- **Reduce overall construction times**, perhaps by increasing the efficiency and applicability of foundation construction or by installing standard modular designs.
- **Reduce uncertainty** related to foundation treatment costs, structure stability, and risk of failure.
- **Minimize ground excavation**. Methods of minimizing the excavation needs include prioritizing sites where excavation is minimal or creating systems that require less excavation to avoid seepage, such as grout curtains, lined reservoirs, and low-head systems.
- **Minimize disturbances in river connectivity** during installation, operation, and maintenance. Where feasible, the use of cofferdams could be avoided by using channel restriction, installing passage and fish-ladder modules first, working during only low-flow conditions, and reducing installation times.

The SMH approach of designing and constructing individual, interchangeable modules represents a significant leap forward in efforts to optimize project performance. Using optimized and highly repeatable, reliable components would benefit any project with respect to the three metrics of cost, time, and risk. However, the modular, repeatable, “one-size-fits-all” approach lacks broad adoption among the hydropower community and remains unproven, given the lack of prototype deployment. Certain standard approaches and recognized construction methods are suitable for some river and stream settings and unsuitable for others. However, every hydropower facility foundation has a site-specific geologic setting and geotechnical requirements related to the soil materials present and project designs being implemented. This in itself is a challenge in developing standard or modular foundation solutions that perform well. A better understanding of the general challenges and opportunities associated with foundation development will ultimately benefit the creation of a flexible approach to hydropower project development.

The following sections provide a summary of key challenges related to the three specific phases of project development, presented in terms of the metrics of cost, time, and risk. The development of hydropower projects is divided into two primary phases: feasibility and construction. Feasibility can be further subdivided into two subphases: planning and investigation, with planning occurring iteratively before, during, and after investigation to inform optimal project construction.

6.1 KEY CHALLENGES FOR HYDROPOWER GEOTECHNICAL SITE ASSESSMENT

At a high level, the greatest challenge associated with geotechnical site assessment is balancing the need to collect usable and accurate site data with the high investment costs. Time and costs related to geotechnical site assessment make strategic assessment a necessity. Good judgement based on experience and data interpretation and interpolation is required to reach a conclusion about the site conditions and the design information required. The risk of undercharacterizing a site (e.g., potentially missing a fatal flaw) could be grave, so a reasonable and thorough investigation must be completed. Likewise, a point exists at which additional boreholes are unlikely to provide any more vital data necessary for the design. The following are some key challenges for foundation geotechnical site assessment:

- **Site access difficulties**, particularly for drilling equipment, can be costly, especially in early project stages when roads are poor or nonexistent. Drilling to obtain samples for geotechnical assessment is of utmost importance; so if access is an issue at a given site, specialized machinery (e.g., helicopters, all-terrain vehicles or track rigs with stabilizers, or even animal or hand-carried sampling rigs) must be used, or an access road must be built prior to sampling. Either of these options will impose higher costs on the sampling exercise. Choosing to undersample a site because access is difficult also brings inherent risks.

- **Regulatory approval timelines** needed to obtain required permits (typically required for test pits and drilling performed in riparian zones) may not be trivial and should be considered in project scheduling. In some cases access to sites is seasonally limited, which can effectively push a project schedule back for as much as a year if a narrow investigation window is missed.

- **High-resolution satellite and/or aerial imagery** (via remote sensing) is often not available. A lack of the useful information they can provide decreases the quality of remote mapping of potential or probable site conditions (e.g., photolineament analysis, landslide identification) during the pre-feasibility phase, thus increasing the costs of assessing multiple sites. Satellite imagery and digital topography coverage within the United States is highly variable in terms of quality. Depending on where a potential site is located, the available satellite or high-altitude aerial imagery or digital topography may not be of sufficient resolution or recent enough to be useful. Drone imagery has recently become a viable option for acquiring imagery and associated data. Although these initial assessments require confirmation with boreholes, they expedite site selection and reduce total exploration costs.

- **Geophysical exploration limitations** exist at some sites; and although the results of traditional methods such as seismic refraction profiles typically provide information along a 2D section rather than at a single point, they are not always definitive. Their interpretation may require calibration or confirmation with boreholes. Depending on site conditions, surveys such as seismic refraction may be costly and difficult to complete. However, where large areas need to be assessed quickly and boreholes are either too costly or too time-consuming to cover the area, these surveys can save time and provide rapid results to refine the selection of an area for detailed investigation if multiple areas are under consideration.

- **Soil and rock sampling reliability** challenges exist. Physical disturbance of field samples and limitations of laboratory testing methods may create discrepancies between behavior measured in the lab and actual field performance. This risk should be minimized by methods designed to minimally disturb samples and/or by in situ testing of mechanical properties where possible (which requires specialized equipment in some cases). In addition, rock discontinuities can only be measured either in surface exposures or from borehole core-samples, limiting the ability to reliably identify important subsurface features. Hydraulic properties of rock masses can be assessed via in situ testing (which requires special equipment), but values associated with these properties can vary spatially and in some cases over time. Care in interpreting and extrapolating these values must be taken, and possible discrepancies or scaling effects between field and laboratory testing results should be considered.

- **Rock joint strength** is difficult to reliably measure in situ because of the various types of strength metrics (e.g., shear vs. tensile) that may play a role in engineering decisions. Because of the complicated nature of establishing these parameters in situ, these types of measurements (e.g., via geophysical testing or subsurface exploration methods) may be difficult to justify in terms of time and cost, especially for moderate-size projects typical of low-head hydropower.

- **Site material erosion** by high-velocity flows poses a serious risk to dam foundations and abutments (and spillways), particularly those impoundment structures sited on soil foundations or those that employ overflow structures constructed with natural materials. Surficial erosion (in the case of overtopping or high-velocity spillway flows, which may occur on or near critical abutment structures) can result and historically has resulted in the catastrophic failure of impoundment structures. Similarly, internal erosion (e.g., piping)—which results from high seepage velocities related to improperly designed foundations, improperly characterized ground conditions in the area of structural foundations, or improperly constructed impoundments—can result and historically has resulted in the catastrophic failure of impoundment structures. Care must be exercised during the site assessment phase to appropriately evaluate the susceptibility of site materials to both surficial and internal erosion, and to evaluate the structural stability of foundation and abutment materials in response to conditions that may lead to surficial and/or internal erosion.

- **Modeling limitations** relate to the uncertainty associated with subsurface properties and characteristics. Hydropower geotechnical investigations could be improved through better 3D geologic models that convey subsurface data and uncertainty, or numerical models to predict performance, among other objectives. Current practice is currently limited to characterizing relatively small sections of the overall foundation footprint, which leaves openings for unexpected conditions to remain unidentified even as the foundation is being constructed and completed. Unexpected geologic and subsurface conditions present significant risks to hydropower project development.

6.2 KEY CHALLENGES FOR HYDROPOWER FOUNDATION DESIGN

At a high level, the greatest challenge in hydropower foundation design is the risk associated with imperfect knowledge of subsurface conditions. Overestimating the ability of subsurface materials to resist the applied loads, or to act as a barrier to seepage, can result in a number of adverse outcomes, including shortened service life, structural damage, loss of reservoir capacity, or even failure of the dam. Other possible consequences of incomplete or inadequate subsurface condition assessments include significant costs accrued before abandoning a site, unexpected construction costs, and contract disputes over changed conditions. Risk mitigation strategies are used to decrease risk, cost, and time in the conventional design process. The following are some key challenges for foundation design:

- **Unexpected site conditions** can be encountered. Thus, careful site selection is necessary to reduce the potential that adverse or fatal flaw conditions will be discovered only during design and construction. In addition, site investigations should be conducted thoroughly to reduce (but not eliminate) the potential for that unanticipated conditions or behavior will be revealed during construction or operation. Communication between the designers and the geotechnical engineers should occur early during the site selection process, and throughout the geotechnical investigation, to maximize the likelihood that the data necessary for design will be collected.

- **Structural stability, strength, and seepage calculations** (e.g., grouting, cutoff trenches) are important and challenging steps in the design process. These calculations are performed based on geotechnical characterizations, and they require detailed engineering across the foundation–superstructure system to ensure the facility's mechanical properties and safe operations. Although these calculations are difficult (and sometimes uncertain) for conventional designs, the design and engineering calculations required for modular superstructures present an even greater challenge, given the relative lack of in situ modular design demonstrations and deployment.

6.3 KEY CHALLENGES FOR HYDROPOWER FOUNDATION CONSTRUCTION

Construction challenges include the cost and risk drivers related to the logistics of construction, and the physical processes during construction. Geologic and geotechnical risks are inherent in construction of the foundation. As the site is excavated, developers may discover "changed geologic conditions," which include geologic features not identified during site assessments and which may significantly increase costs or timelines. As described in Section 4, foundation construction is executed based on a contract between an owner/developer and a contractor. A key challenge for hydropower projects during the construction phase is balancing the risks between the owner/developer and contractor. When presenting a bid, the contractor aims to keep its total bid low, while carefully assessing or seeking to share the foundation risks involved in executing the project, and assigning a risk premium to the bid. Risk sharing is a technique often employed by developers and contractors as a way of controlling or lowering cost and limiting contingency. During the construction phase, the contractor attempts to minimize its costs and risk while complying with its contractual obligations. Key challenges for foundation construction include the following:

- **Risk quantification and communication** between the contractor and the developer are important in arriving at an acceptable, contracted construction cost. The developer must share all available geologic data, results of investigations, and engineering judgements. This information allows the contractor to confidently include the appropriate level of risk in its pricing. In certain situations in which a gap exists in subsurface conditions, the contractor and developer can arrive at an equitable cost-sharing arrangement. In the tunneling industry, the use of geotechnical baseline reports has proved useful in anticipating and mitigating contract risks (USACE 2007).

- **Unexpected geologic and subsurface conditions** can lead to significant cost and schedule overruns and require adaptive solutions. Changed geologic conditions may include a previously unrecognized need for deep foundation excavation, deep-seated geologic instabilities close to or within the footprint of the foundation, excessive grout take (which indicates the likely presence of voids, karst, or highly transmissive fracture networks), higher than expected porosities in permeable foundations, and high groundwater levels.

- **Construction scheduling delays** can occur as a result of the unpredictable timelines associated with project development, including licensing and other activities.

- **Water diversion system (dewatering and cofferdam) installation costs and mitigation** can present significant cost challenges for construction. Water diversion during construction determines river connectivity, which includes the disruption of natural sediment flows and turbidity, fish passage, and hydrologic regime. These patterns additionally impact the health of the habitat and wildlife in the surrounding ecosystem.

- **Performance monitoring availability**, using both visual surveillance and geotechnical instrumentation, is essential for detecting unanticipated behavior or conditions during construction and operation.

The key challenges for hydropower foundation presented in this section are further explored as areas of opportunity in Section 7.

7. OPPORTUNITIES FOR INNOVATIVE HYDROPOWER FOUNDATION TECHNOLOGIES

As discussed throughout this report, foundations play a central role in hydropower site assessment, design, and construction; therefore, innovations in hydropower foundation technologies can be useful for future development. To improve the cost, time, and risk performance of future projects, opportunity areas are identified that are likely to benefit from new and emerging technologies. Investment in these areas could improve hydropower performance, feasibility, and safety. In searching for technological and logistical solutions to these challenges, other industries across the inland and aquatic spheres can potentially offer relevant insights. Section 7.1 (and the literature review summarized in APPENDIX E) provides a review of recent advancements in non-hydropower industries, and Section 7.2 outlines the major opportunity areas with examples.

7.1 ADVANCES IN NON-HYDROPOWER INDUSTRIES

Hydropower foundations experience unique conditions unlike those associated with other aquatic and inland industries, which are typically driven by isostatic conditions. The conditions include resisting and supporting loads imposed by the surrounding hydrologic environment and operating under dynamic hydraulic conditions and pressure gradients throughout the entire structure. Accordingly, hydropower developers are typically concerned with structural stability and seepage control in designing and constructing foundations, whereas non-hydropower industries are primarily interested in structural stability, with an interest in the performance aspects of foundations in relation to various superstructures. Foundation site assessment, design, and construction technologies and methodologies used in other industries (including the transportation, offshore wind energy, marine and hydrokinetic [MHK] energy, and residential/commercial building industries) *may* have some relevance in advancing the structural stability and performance aspects of hydropower foundations. Innovations in these other industries could offer transferability and help guide hydropower R&D efforts. Additionally, technologies such as instrumentation and autonomous equipment used in the mining industry could have relevance to hydropower technology R&D and advancement.

Based on literature reviews of various non-hydropower foundation and supporting technologies, a key advancement across multiple industries (e.g., offshore wind, MHK, commercial and residential building) has been the use of prefabrication (i.e., modularization and standardization). For example, certain types of offshore wind turbine foundations can be grouped into a few key components to simplify the manufacturing, transportation, and construction aspects of development and thus reduce timelines and costs. Additionally, improvements in overall construction logistics help increase time and cost efficiency, as they maximize the amount of work that can be performed at any one time. Moreover, advancements in materials that increase strength, ductility, and other structural properties may make them more economical, sustainable, and robust than traditional concretes and steels. Other supporting technologies that may prove beneficial to hydropower foundation design and construction are autonomous equipment, instrumentation (e.g., sensors and analytical software), and scouring protection. Reducing the need for human labor makes operation safer and more economical; and sensors could be useful in detecting early signs of damage to the foundation from seismic activity, extreme weather events, or regular wear and tear to prevent future dam/facility failure. Although not necessarily centric to the foundation, scouring protection is useful for structures such as facility spillways and tailraces that are prone to hydraulic stresses which, if left untreated, could lead to future facility failure.

A literature review of foundation technologies and methods used in other non-hydropower industries is provided in APPENDIX E.

7.2 OPPORTUNITY AREAS FOR HYDROPOWER GEOTECHNICAL FOUNDATIONS

Because geotechnical foundations represent a major cost driver for many hydropower projects (Fang, 1991; O'Connor et al., 2015a), technology innovations and other opportunities have the potential to improve overall hydropower project feasibility with respect to via risk, cost, and/or timeline reductions. The uncertainties and hazards associated with subsurface conditions with respect to siting, exploration, and design are significant; and improvements in those processes could help reduce risk and construction timelines. DOE initiatives to improve construction costs and overall construction times could advance the use of techniques and technologies focused on the major aspects of foundation development.

These challenges range from the early stages of planning and reconnaissance to the final stages of construction. As discussed in Section 6, the interdependency among cost, time, and risk plays a critical role within a project and is typically associated with the level of uncertainty regarding conditions associated with each stage of a foundation project.

Uncertainty affects many aspects of the site assessment, design, and construction processes (McMahon, 1989). It is related primarily to the extent to which site conditions can be accurately characterized and understood, and to the ability to predict and respond to changing and unexpected conditions as a project progresses. The varying levels of uncertainty are reconciled through trade-offs among cost, time, and risk of the project, as agreed upon between the owner and the contractor.

Based on the key challenges presented in Section 6, areas that offer unique opportunities to address cost, time, and risk are site investigation/assessment, planning/design, and the expectations and logistics of the construction phase. Therefore, the distinctive opportunity areas for improvement lie in (1) geotechnical site assessment, (2) foundation design and materials, and (3) construction methods and technology.

Given the co-dependency among these areas (e.g., any knowledge gaps, uncertainties, or other complexities involving geotechnical site assessments and foundation design could carry weight throughout the foundation development phases), it is misleading to prioritize one over the other. For example, the capital costs associated with construction are the largest among the representative, direct foundation-related costs, as presented in Section 5.5.1. However, many hydropower development projects have experienced cost overruns attributable to uncertainties experienced during construction, which might have been reduced through earlier and more thorough assessment and design considerations

These three opportunity areas are described in the following sections. Opportunity subcategories are also presented for each opportunity area, with examples (for demonstration purposes only) provided in Table 16, Table 17, and Table 18. Notably, innovation opportunities may not be limited to a single area, given the integral and often reciprocal nature of site assessment, foundation design, and construction. **Opportunity areas are <u>not</u> mutually exclusive** but are presented to reflect key domains for innovation.

7.2.1 Opportunity Area 1: Geotechnical Site Assessment

Geotechnical site assessment focuses on advancements in both physical on-site and offsite assessment. Example opportunities (Table 16) generally include geophysical methods of data acquisition and processing, recognition and analysis techniques to improve certainty in characterizing subsurface conditions, identification and prediction of potential failure mechanisms, and refinement of testing area selection.

The practice of gathering geophysical data for subsurface investigations is well developed. Geophysical investigations are focused around both passive and active condition measurements, whereby sensitive instruments measure either steady-state conditions (e.g., gravity) or induced conditions and/or responses to external inputs (e.g., electrical resistivity, seismic refraction, ground-penetrating radar). Currently, there appears to be little room for innovation in the practice of active source generation (i.e., investigators have already used all currently known and readily measurable types and wavelengths of acoustic, gravimetric, radiometric, and electromagnetic energies to gather information about material properties of earth materials).

Table 16. Example opportunities for hydropower geotechnical site assessment.

Offsite (desktop) geotechnical assessment
Improved remote and/or aerial imaging, sensing, and collection technologies (e.g., LiDAR, sonar, SAR/InSAR, photogrammetry)
Advancement of geophysical methods and data processing techniques and methods (including AI) to improve efficiency of surface and subsurface characterizations
More accurate desktop assessments to quantity takeoffs for borrow areas, site access, and excavation
Development, incorporation, and use of extensive database of existing dams and construction techniques, paired with on-site characterization serving as a predictive and/or guidance tool for improved siting
Advanced techniques for testing area selection, which could include automatic recognition of fractures, ground-penetrating radar, processing of data using decision-based AI techniques based on neural network applications of historical projects, and improved data visualization. Such solutions could be related to (1) data mining of existing data sets, (2) novel data acquisition techniques such as remote sensing/geophysics or improved sensors, and (3) data processing using AI or other technological approaches like traditional remote sensing analyses, among others.
On-site geotechnical assessment
Advancements in the use of condition monitoring and control systems for real-time dam foundation hazard monitoring and longer-range forecasting and mitigation
Nascent technologies for minimally invasive subsurface site investigation (includes minimization or replacement of boring/drilling studies applications, accurate determination of the depths to competent rock, nondestructive analysis or other possible approaches to appropriately characterize and improve confidence in bearing strength of foundation materials and identification of potential failure mechanisms)

New advances in the fields of remote sensing and analysis are trending toward novel techniques in data processing, resolution, and pattern recognition. Advanced methods of signal processing and/or automated pattern recognition and feature extraction are at the forefront of mathematical and artificial intelligence (AI) research fields today. Improved resolution of feature detail from both active and passive source remote sensing has been achieved across the fields of microscopy, astrophysics, biology, and geophysics; and this work will continue to provide improved resolution of difficult-to-access (e.g., subsurface) targets.

Automated feature recognition via AI approaches (including machine learning or deep learning, among others), in particular, stands to contribute to projects focusing on the built world. It will eventually be broadly extended to interpretations of the natural world. Already, private industry ventures and academic institutions are developing and using these approaches to automatically identify, quantitatively assess, and catalog fractures in concrete and steel infrastructure from 3D photogrammetric models created from drone and/or manually acquired imagery. Extending such methods to high-resolution imagery of potential dam sites could drastically improve the remote assessment of potential hydropower sites (particularly in bedrock-dominated areas) by providing information about bedrock fracture network density, and potentially tying it to foundation seepage conditions at potential sites at the desktop study level.

Consideration of advances in data acquisition and processing methods may greatly benefit remote studies, reconnaissance-level studies, and geophysical surveys of potential development sites, depending on site conditions and settings. More work in developing these methods and applying them to remote sensing and geophysical surveys is needed.

7.2.2 Opportunity Area 2: Foundation Design and Materials

This opportunity area focuses on innovations for foundation design and materials. Examples of design-related opportunities are briefly listed in Table 17. Notably, this opportunity area includes modular foundation structures, which could be a significant innovation in this field, and material and treatment technologies to improve strength and reduce seepage.

Table 17. Example opportunities for hydropower foundation design and materials.

Foundation design
Integration and use of prefabricated and modular applications (e.g., foundation components, drainage components, concrete forms)
Innovations that incorporate typically temporary structures (e.g., cofferdams, forms, scaffolding) for permanent use and subsequent function for the hydropower facility
Custom foundation design based on existing site terrain and stream features (facilitated by advanced sonar, underwater LiDAR, or other surveying techniques)
Approaches for adaptively modifying design on-site based on in situ conditions and configurations
Materials
Improvements in concrete-to-rock bonding agents, slurries, and other materials that improve seepage control performance or facilitate adequate and safe drainage
Development of geotextile materials for *subsurface* stabilization and seepage applications
Improved and cost-effective applications of high-flow grout and environmentally friendly compounds for treatment of seepage
Use of ultrahigh–performance concrete

The use of advanced composite materials should be considered for both foundation and modular unit treatments, as well as potentially for reservoir lining treatments for projects sufficiently small in size. Geotextiles have frequently been employed in special foundation systems to stabilize slopes and control or filter seepage. Composite geotextiles comprise strong, lightweight fabrics treated with sprayable water-impermeable coatings to provide high–tensile-strength waterproof linings for a variety of earth-stabilizing and water-handling issues. These types of practices may eventually be extended to treatments of subsurface settings necessary to control sub-foundation seepage or reservoir stability in certain settings. Improvements in material engineering, manufacturing processes, and specifications have led to many applications. Use of geotextiles can shorten project construction timelines and lessen environmental impacts. For example, using a geotextile membrane in zoned-embankment construction can reduce the construction schedule and mitigate the impact to the environment associated with the exploitation of natural construction materials. It remains a challenge to advance geomembrane improvements, enhance standardization, and broaden their acceptability within the dam design–construction sectors.

Grouting has been employed in special foundation systems to enhance watertightness. Conventional grout mixes include water, cement, sand, and admixtures. Admixtures have been improved in recent decades, which has led to the use of specialized chemical grouts with non-shrink, strong, and lubricating properties. Additional advancements in admixtures and pressurized delivery have been made recently in the oil and gas industry, particularly in applications involving hydrofracturing. In certain settings, traditional grout curtains or methods of cutoff wall excavation may be cost-prohibitive in small hydropower applications; the use of novel formulations of high-flow grout or other novel environmentally safe water-impermeable compounds to treat foundation seepage may benefit these types of projects. The challenge remains to cost-effectively incorporate the advances into the dam design–construction sectors.

Potential concepts for standard, modular design include the use of large-scale 3D printing stages. If this technology proves to be sufficient for these types of projects, advanced materials and design techniques could be prioritized to decrease material and time requirements in the field. Currently, several organizations are developing large-scale stage and central-pivot 3D cement “printers” to construct small buildings within 24 hours. Development of large-scale additive metal printing technologies and/or the use of advanced materials such as ultrahigh-performance concrete, especially within a single hybrid printing unit, could greatly improve design and production aspects of small hydropower project development.

Although hydropower foundations must be customized to individual site conditions, the use of advanced manufacturing technology to accurately measure, and perhaps custom-print, a foundation section to be bonded or installed into a precut section of footing material, might be considered. Currently, advancements in underwater LiDAR applications allow for high-precision 3D surveys of ocean floor conditions for the deep-water hydrocarbon production industry. These types of surveys might be suitable for certain rock-foundation applications in which a custom-printed foundation module could be printed to precisely fit into place (with the use of suitable anchors and seepage treatments).

7.2.3 Opportunity Area 3: Construction Methods and Technology

This opportunity area focuses on novel and improved construction methods and technology, some of which could support examples identified in the prior opportunity areas. Examples of construction-related opportunities are briefly listed in Table 18. Strategies for reducing owner and developer risk, methods of incorporating knowledge-based results for better-defined and less conservative agreements (i.e., using improved certainty regarding unknown conditions to decrease risks), and communication techniques for describing and quantifying risk are introduced as key challenges in Section 6. These contractual-related items, though important, are nontechnical and are not the focus of this section.

Table 18. Example opportunities for hydropower foundation construction methods and technology.

Construction methods
Improved methods for rating geologic complexities to improve communication and shared understanding of uncertainties to decrease owner/contractor overall perceived risks and costs
Improved environmental BMPs and mitigation techniques for foundation site investigation and construction, such as minimizing or eliminating the use of cofferdams
Advanced bedrock anchoring techniques for rigid structures (e.g., concrete or modular components)
Techniques for the application and use of 3D underwater concrete printing of a foundation component
Construction technology
Advanced sensing/monitoring technologies to enable real-time quality control of on-site concrete, material, and other placement efforts
Technologies for underwater equipment applications that may limit need for cofferdams
Deployment of self-operating equipment in open pit excavations, mixing and placement of mass concrete, and placement of embankment fill for continuous 24-hour operation
Other applications for self-operating, potentially autonomous technologies, such as for excavation, soil compaction, or various treatments

The contractor develops its method of construction to provide a constructed product that conforms to the construction drawings and specifications, and incorporates measures to facilitate acceptance testing. Continued advancements in instrumentation and testing devices, including automation, will allow for construction time and cost reductions.

Prefabricated concrete elements or pre-engineered steel structures, while not particularly applicable to foundations, may have applications in river diversion activities that are closely allied to foundation construction. Prefabricated concrete elements are generally heavy; site access, working space, and crane lifting capacity may limit their use.

There are many large construction equipment manufacturers. They produce tailored construction equipment that is used in a variety of industrial sectors, including heavy civil works (e.g., tunneling), mining, agriculture, power, water supply, and oil and gas. These manufacturers respond to the needs of contractors and have developed versatile equipment that allow a contractor to tailor its equipment for maximum utility. Areas of customization include size, horsepower, wheels/tracks, operating elements and options, lift capacities, dashboard instrumentation, and automation. The manufacturing industry will continue to respond to the needs of its customers.

Contractors frequently improvise during construction. They have engineering departments that design their temporary works so that temporary access roads and work fronts are stable, equipment limits are respected, and the entire site is a safe working environment. In incorporating small hydropower schemes into existing dams, contractors have used barges and floating bulkheads to assist in the placement of permanent operating equipment, powerhouse elements, and so on.

Environmental BMPs, as they relate to foundation site investigation and construction, could also be evaluated to understand how their cost and schedule impacts could be further minimized while they meet their objectives of minimizing erosion and increasing flood control. In addition, there is interest in reducing the costs and timelines associated with river diversion and related environmental protection measures, specifically the use of cofferdams. Opportunities exist for the construction industry to develop the means and methods necessary to construct a foundation without the use of cofferdams. Such methods would require improvised equipment and accessories, for example, a dewatering dome to facilitate concrete placement as water flows around the dome. The dome could be equipped for dewatering, surface preparation, remote viewing inspection, concrete placement, and rapid concrete hardening. Measures would also have to include in situ or laboratory testing of the bond between the rock foundation and the first layer of concrete.

8. REFERENCES

Abhyankar, Vivek, and N. Subramanian. 2018. “Innovation in Bridges Components and Materials.” *NBM&CW,* 2018.

American Association of State Highway and Transportation Officials (AASHTO). 2010. *AASHTO LRFD Bridge Design Specifications*. 5th ed. Washington, D.C., USA: AASHTO.

American Society of Civil Engineers (ASCE). 2008. *Sedimentation Engineering: Processes, Measurements, Modeling, and Practice*. https://doi.org/10.5772/intechopen.68509.

Association for the Advancement of Cost Engineering (AACE) International. 2019. “Cost Estimate Classification System - As Applied in Engineering, Procurement, and Construction for the Process Industries.” *Recommended Practice 18R-97*.

ASTM International. 2011. “Standard Terminology Relating to Soil , Rock , and Contained Fluids.” *ASTM D653-11*. West Conshohocken, PA. https://doi.org/10.1520/D0653-11.2.

———. 2014. “Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures.” *ASTM D7012*. West Conshohocken, PA.

———. 2016. “Standard Test Method for Performing Laboratory Direct Shear Strength Tests of Rock Specimens Under Constant Normal Force.” *ASTM D5607*. West Conshohocken, PA.

———. 2017. “Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System).” *ASTM D2487*. West Conshohocken, PA.

———. 2019. “Standard Classification for Cost Estimate Classification System.” *ASTM E2516-11*. West Conshohocken, PA.

Baecher, Gregory B., M. Elisabeth Paté, and Richard de Neufville. 1980. “Risk of Dam Failure in Benefit-Cost Analysis.” *Water Resources Research* 16 (3): 449–56. https://doi.org/10.1029/WR016i003p00449.

Becker, Dennis E. 1996a. “Eighteenth Canadian Geotechnical Colloquium: Limit States Design For Foundations. Part I. An Overview of the Foundation Design Process.” *Canadian Geotechnical Journal* 33 (6): 956–83. https://doi.org/10.1139/t96-124.

———. 1996b. “Eighteenth Canadian Geotechnical Colloquium: Limit States Design For Foundations. Part II. Development for the National Building Code of Canada.” *Canadian Geotechnical Journal* 33 (6): 984–1007.

Bieniawski, Z.T. 1989. *Engineering Rock Mass Classifications*. John Wiley & Sons, Inc.

Brady, B. H. G., and E. T. Brown. 2004. *Rock Mechanics for Underground Mining*. 3rd ed. Springer. https://doi.org/10.1016/B0-12-369396-9/00224-0.

Chen, Long, and Wei-Haur Lam. 2014. “Methods for Predicting Seabed Scour around Marine Current Turbine.” *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2013.08.105.

Comiti, Francesco, and Luca Mao. 2012. “Recent Advances in the Dynamics of Steep Channels.” *Gravel-Bed Rivers: Processes, Tools, Environments,* 351–77. https://doi.org/10.1002/9781119952497.ch26.

Cress, Jill, David Soller, Roger Sayre, Patrick Comer, and Warner Harumi. 2010. “Terrestrial Ecosystems: Surficial Lithology of the Conterminous United States.” *U.S. Geological Survey Scientific Investigations Map 3126, Scale 1:5,000,000, 1 Sheet*.

Day, Robert W. 2010. *Foundation Engineering Handbook*. 2nd ed. McGraw-Hill, Inc.

Deneale, Scott T., Gregory B. Baecher, Kevin M. Stewart, Ellen D. Smith, and David B. Watson. 2019. “Current State-of-Practice in Dam Safety Risk Assessment.” *Oak Ridge National Laboratory*. Oak Ridge, TN, USA.

Duncan, J. Michael, Stephen G. Wright, and Thomas L. Brandon. 2014. *Soil Strength and Slope Stability*. 2nd ed. John Wiley & Sons, Inc.

Esteban, M. D., J. S. López-Gutiérrez, J. J. Diez, and V. Negro. 2011. “Methodology for the Design of Offshore Wind Farms.” *Journal of Coastal Research* Special Is (64): 496–500.

Esteban, M. Dolores, José Santos López-Gutiérrez, and Vicente Negro. 2019. “Gravity-Based Foundations in the Offshore Wind Sector.” *Journal of Marine Science and Engineering* 7 (64): 14. https://doi.org/10.3390/jmse7030064.

European Small Hydropower Association (ESHA). 2004. “Guide on How to Develop a Small Hydropower Plant.”

Fang, Hsai-yang. 1991. *Foundation Engineering Handbook*. 2nd ed. Chapman & Hall.

Federal Emergency Management Agency (FEMA). 2004. “Federal Guidelines for Dam Safety.” Washington, D.C.

Federal Energy Regulatory Commission (FERC). 2017. “Chapter 14 Dam Safety Performance Monitoring Program.” In *Engineering Guidelines for the Evaluation of Hydropower Projects*, 188.

Fell, Robin, Patrick MacGregor, David Stapledon, Graeme Bell, and Mark Foster. 2014. *Geotechnical Engineering of Dams*.

Fookes, Peter G. 1967. “Planning and Stages of Site Investigation.” *Engineering Geology* 2 (2): 81–106. https://doi.org/https://doi.org/10.1016/0013-7952(67)90026-9.

Gulliver, John S., and Roger E. A. Arndt. 1991. *Hydropower Engineering Handbook*. McGraw-Hill, Inc.

Hadjerioua, Boualem, Yaxing Wei, and Shih Chieh Kao. 2012. “An Assessment of Energy Potential at Non-Powered Dams in the United States.” *Oak Ridge National Laboratory*. Oak Ridge, TN, TN, USA.

Heath, Jason, Richard Jensen, Jose Jr Arguello, Diana Bull, Sam Weller, Jon Hardwick, and Lars Johanning. 2014. “Specific Requirements for MRE Foundation Analysis. Deliverable 4.2 of the DTOcean Project.”

Hill, Ryan A., Marc H. Weber, Scott G. Leibowitz, Anthony R. Olsen, and Darren J. Thornbrugh. 2016. “The Stream-Catchment (StreamCat) Dataset: A Database of Watershed Metrics for the Conterminous United States.” *Journal of the American Water Resources Association* 52 (1): 120–28. https://doi.org/10.1111/1752-1688.12372.

Hoek, Evert, and E. T. Brown. 1980. *Underground Excavations in Rock*. London : The Institution of Mining and Metallurgy.

Horton, John D., Carma A. San Juan, and Douglas B. Stoeser. 2017. “The State Geologic Map Compilation (SGMC) Geodatabase of the Conterminous United States.” https://doi.org/https://doi.org/10.5066/F7WH2N65.

International Renewable Energy Agency (IRENA). 2016. “Floating Foundations: A Game Changer for Offshore Wind Power.”

Iowa Highway Research Board (IHRB). 2006. “An Illustrated Guide for Monitoring and Protecting Bridge Waterways against Scour.” *Project TR-515*.

Kao, Shih-Chieh, Ryan A. McManamay, Kevin M. Stewart, Nicole M. Samu, Boualem Hadjerioua, Scott

T. DeNeale, Dilruba Yeasmin, M Fayzul K. Pasha, Abdoul A. Oubeidillah, and Brennan T. Smith. 2014. "New Stream-Reach Development: A Comprehensive Assessment of Hydropower Energy Potential in the United States." *Oak Ridge National Laboratory*. Oak Ridge, TN, USA.

Leopold, Luna B., and M. Gordon Wolman. 1957. "River Channel Patterns: Braided, Meandering, and Straight." *Physiographic and Hydraulic Studies of Rivers*. Washington, D.C., USA. https://doi.org/10.1007/978-1-349-15382-4_8.

Locsin, Jean Louis Z., Heather B. Scranton, Alec D. Smith, Mary Vittoria-Bertrant, and Mark S. Greenleaf. 2015. "Foundation Innovations Ensure Successful Bridge Replacement." *Deep Foundations*, no. Jan/Feb: 12–16.

McKay, L., T. Bondelid, T. Dewald, J. Johnston, R. Moore, and A. Rea. 2012. "NHDPlus Version 2: User Guide (Data Model Version 2.1)."

McMahon, B K. 1989. "Geotechnical Design in the Face of Uncertainty: Australian Geomechanics Society E.H. Davis Memorial Lecture." *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 26 (2): 74. https://doi.org/10.1016/0148-9062(89)90194-0.

McManamay, Ryan A., and Christopher R. Derolph. 2019. "Data Descriptor: A Stream Classification System for the Conterminous United States." *Scientific Data* 6: 1–18. https://doi.org/10.1038/sdata.2019.17.

Naval Facilities Engineering Command (NAVFAC). 1986. "Soil Mechanics Design Manual 7.01."

O'Connor, Patrick, Katherine Zhang, Scott T Deneale, Dol Raj Chalise, and Emma Centurion. 2015. "Hydropower Baseline Cost Modeling, Version 2." *Oak Ridge National Laboratory*. Oak Ridge, TN, USA. https://doi.org/10.2172/1185882.

Peck, Ralph B. 1969. "Advantages and Limitations of the Observational Method in Applied Soil Mechanics." *Geotechnique* 19 (2): 171–87.

PMI. 2017. *PMBOK Guide - A Guide to the Project Management Body of Knowledge*. Sixth Edit. Project Management Institution.

Renard, K. G., G. R. Foster, G. A. Weesies, and D. K. McCool. 1997. "Predicting Soil Erosion by Water: A Guide to Conversation Water Planning with the Revised Universal Soil Loss Equation (RUSLE)." *Agriculture Handbook No. 703*. Washington, D.C., USA.

Rosgen, David L. 1994. "A Classification of Natural Rivers." *Catena* 22 (3): 169–99. https://doi.org/10.1016/0341-8162(94)90001-9.

Schaefer, Vernon R., James K. Mitchell, Ryan R. Berg, George M. Filz, and S. Caleb Douglas. 2012. "Ground Improvement in the 21st Century: A Comprehensive Web-Based Information System." *Geotechnical Special Publication*, no. 226 GSP: 272–93. https://doi.org/10.1061/9780784412138.0011.

Schumm, Stanley A. 1977. *The Fluvial System*. Caldwell, NJ, USA: The Blackburn Press.

Silva, Francisco, T. William Lambe, and W. Allen Marr. 2008. "Probability and Risk of Slope Failure." *Journal of Geotechnical and Geoenvironmental Engineering* 134 (12).

Smith, Brennan T., Adam Witt, Kevin M. Stewart, Kyutae Lee, Scott DeNeale, and Mark Bevelhimer. 2017. "A Multi-Year Plan for Research, Development , and Prototype Testing of Standard Modular Hydropower Technology." *Oak Ridge National Laboratory*. Oak Ridge, TN, USA.

Teodosio, Bertrand, Shanaka Kristombu Baduge, Tuan Duc Ngo, Priyan Mendis, Maral Tecer, and David Heath. 2018. "A Feasibility Review of Innovative Prefabricated Footing Systems for Residential Structures." *Preprint*. https://doi.org/10.20944/preprints201807.0441.v1.

Terzaghi, Karl, and Ralph B. Peck. 1948. *Soil Mechanics in Engineering Practice*. New York: John Wiley & Sons, Inc.

Uria-Martinez, Rocio, Megan Johnson, and Patrick O'connor. 2018. "2017 Hydropower Market Report." *Oak Ridge National Laboratory*. Oak Ridge, TN, USA.

US Army Corps of Engineers (USACE). 1990. "Settlement Analysis." *Engineer Manual 1110-1-1904*.

———. 1991. "Design of Pile Foundation." *Engineering Manual 1110-2-2906*.

———. 1992. "Bearing Capacity of Soils." *Engineer Manual 1110-1-1905*.

———. 1994a. "Design of Sheet Pile Walls." *Engineer Manual 1110-2-2504*.

———. 1994b. "Rock Foundations." *Engineer Manual 1110-1-2908*.

———. 1995. "Geophysical Exploration for Engineering and Environmental Investigations."

———. 2001. "Geotechnical Investigations."

———. 2004. "General Design and Construction Considerations for Earth and Rock-Fill Dams."

———. 2007. *Geotechnical Baseline Reports for Construction: Suggested Guidelines. Technical Committee on Geotechnical Reports of the Underground Technology Research Council. Reston, VA: American Society of Civil Engineers*. Books. American Society of Civil Engineering. https://doi.org/https://doi.org/10.1061/9780784409305.

———. 2016. "Civil Works Cost Engineering." *Engineer Manual 1110-2-1302*.

US Bureau of Reclamation (USBR), and US Army Corps of Engineers (USACE). 2019. "Best Practices in Dam and Levee Safety Risk Analysis."

US Department of Energy (DOE). 2016. "Hydropower Vision A New Chapter for America's 1st Renewable Electricity Source." Washington, D.C. https://doi.org/10.2172/1502612.

US Department of the Interior Bureau of Reclamation (USBR). 1998a. "Earth Manual." Denver, CO, USA.

———. 1998b. *Engineering Geology Field Manual Volume 1*. 2nd ed. Vol. I.

———. 2001. *Engineering Geology Field Manual Volume 2*. Second Edi.

———. 2006. *Design of Small Dams*. 3rd ed. New Delhi, India: SBS Publishers & Distributors Pvt. Ltd. New Delhi, India.

———. 2012. "Chapter 12: Foundation and Earth Materials Investigation." In *Design Standards No. 13 Embankment Dams*, 111.

US Federal Highway Administration (FHWA). 2013. "Characterization of Bridge Foundations Workshop Report." *FHWA-HRT-13-101*.

US Society of Dams (USSD). 2011. "Materials for Embankment Dams." Denver, CO, USA.

———. 2012. *Guidelines for Construction Cost Estimating for Dam Engineers and Owners*.

Wischmeier, Walter H., and Dwight D. Smith. 1965. "Predicting Rainfall-Erosion Losses from Cropland East of the Rocky Mountains: Guide for Selection of Practices for Soil and Water Conservation." *Agriculture Handbook No. 282*. Washington, D.C., USA.

———. 1978. "Predicting Rainfall Erosion Losses: A Guide to Conservation Planning." *Agriculture Handbook No. 537*. Washington, D.C., USA.

Wisconson Department of Transporation (WDOT). 2017. "Chapter 7.2 Foundation Types." In

Geotechnical Manual, 4.

Witt, Adam, Brennan T. Smith, Achilleas Tsakiris, Thanos Papanicolaou, Kyutae Lee, and Kevin M. Stewart. 2017. “Exemplary Design Envelope Specification for Standard Modular Hydropower Technology.” Oak Ridge, TN, USA.

APPENDIX A. KEY TERMINOLOGY

Hydropower terminology often varies among sources. This document's terminology follows FERC definitions and guidelines. However, the terms listed in this appendix are for use in the context of this report and may differ somewhat from their use in other available literature. Several terms are original and are used to describe concepts developed for this report. Where terms are taken from existing literature, proper citation is provided.

- **Foundation system**: A collection of engineered structural features constructed at or below the preconstruction ground surface that interfaces with the superstructure and subsurface of a dam. The primary purpose of the foundation system is to provide structural stability and support and to control seepage. The foundation system also includes the subsurface resulting from engineered treatment methods such as grouting, anchoring, and trenching, and could include modular foundation technologies. Various construction activities (such as dewatering and excavation) are often required to enable engineered treatment. Design components that may be considered for a dam foundation include anchors (typically for concrete gravity dams), cutoff trenches, trenches, and walls.
- **Subsurface**: The site conditions existing at a site before development. The subsurface is highly site-specific and comprises the soil and geologic formations below the dam site and other facilities associated with the project.
- **Soil:** Surface material composed of varying degrees of organic and mineral constituents, primarily resulting from the decay of plants and/or weathering of rock.
- **Rock**: Any naturally occurring solid mass or aggregate of minerals or mineraloid matter.
- **Superstructure**: The facility features above the foundation that provide the functions necessary for a hydropower facility, such as blocking and passing water, generating electricity, and providing maintenance access. Superstructures include dams, spillways, and powerhouses. Dam subcomponents considered part of the superstructure include the dam core, filters and drains, and geotextile membranes/blankets.
  - **Dam**: "An artificial barrier that has the ability to impound water, wastewater, or any liquid-borne material, for the purpose of storage or control of water" (FEMA, 2004).
    - **Embankment dam**: Dams that uses excavated natural materials (soil or rock) or man-made materials to provide water retention.
    - **Concrete dam**: Dams that uses reinforced or unreinforced concrete to create a barrier.
  - **Powerhouse**: The structure where the powertrain (turbine-generator) and other equipment are housed.
  - **Spillway**: A structure that passes water over, around, or through the impoundment structure for non-hydropower purposes.
    - **Service spillways**: Structures regularly used to provide continuous or frequent water releases. Accordingly, they are made from extremely damage-resistant materials (DeNeale et al., 2019).
    - **Auxiliary spillways**: Spillways that are used in a secondary capacity to provide infrequent releases (e.g., to increase spilling capacity in flood events) and thus may be made of materials that are less damage-resistant than those for service spillways (DeNeale et al., 2019).
    - **Emergency spillways**: Spillways used in extreme circumstances to provide additional spilling capacity (e.g., when the service or auxiliary spillways are inoperable, or in major flood events) (DeNeale et al., 2019).

- **Geotechnical foundation engineering**: Discipline involving the study of soil and rock behavior and its application in engineering, specifically for foundation systems.
    - **Geotechnical site assessment**: Activities performed to obtain information needed to design and construct a foundation system .
    - **Foundation design**: The process of using information from the site assessment to perform analyses and develop a cost-effective foundation system that meets the project design criteria.
    - **Foundation construction**: Activities performed by the contractor, from mobilization through project commissioning, to fully develop the foundation system.
- **Hydropower**: A renewable energy resource that produces electricity from flowing water under pressure.
    - **Low-head hydropower**: A hydropower project with 30 ft or less of head.
- **New stream-reach development**: New hydropower development along stream-reaches that do not currently have hydroelectric facilities or other forms of infrastructure, such as dams.
- **Dam height**: "The vertical distance between the lowest point on the crest of the dam and the lowest point in the original streambed." (USACE NID Data Dictionary30)
- **Structural height**: "The vertical distance from the lowest point of the excavated foundation to the top of the dam. The top of the dam refers to the parapet wall and not the crest." (USACE NID Data Dictionary30)
- **Hydraulic head**: The difference in elevation between upstream and downstream water levels.
- **Standardizatio**n: A framework of universal details, guidelines, and specifications to maximize module replication and compatibility across multiple sites. For hydropower specifically, standardization includes design, review, regulation, manufacturing, operation, maintenance, and other features intended to reduce site specificity and project costs.
- **Modularity**: The virtual or physical division of system components into distinct, readily transferable functional units known as "modules."
- **Standard Modular Hydropower**: A research project led by Oak Ridge National Laboratory, with funding from the Department of Energy Water Power Technologies Office, that aims to foster the development of environmentally compatible, cost-effective hydropower through modularization and standardization.
- **Module:** A discrete functional unit that either independently or in combination with other modules achieves a dedicated purpose at a selected site.
    - **Generation modules**: Dedicated structures that transform incoming water flow into an energy output and outgoing water flow.
    - **Passage modules**: Dedicated structures that transfer water, fish, sediment, or boats safely through a facility.

Foundation modules: Dedicated structures that provide a stable platform and enable the foundation and other modules to maintain location, orientation, and stability.

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[30] Available at https://nid.sec.usace.army.mil/ords/NID_R.downloadFile?InFileName=NID_DataDictionary.pdf (accessed August 10, 2020).

APPENDIX B. WATERSHED AND STREAM CHARACTERISTICS

This appendix provides additional information to supplement that provided in Section 3.1, Watershed and Stream Characteristics. The information presented includes additional information and associated terminology related to watershed and stream classifications and characteristics.

B.1 WATERSHED CHARACTERISTICS

A *watershed* (also called a drainage basin or catchment) is defined as an area that collects water from surface water (including precipitation, snowmelt, and stream flow) and groundwater and conveys it to a common outlet (e.g., a river, mouth of a bay, ocean) via a set of channels. For a hydropower site, a watershed represents the upstream area contributing runoff and flow to the site. The main components of a watershed are

- *Hillslope*: undissected elevated areas between valleys
- *Hollows*: valleys without channels
- *Channels*: concentrated transport of water and sediments between defined banks
- *Floodplain*: relatively flat region formed by the rivers during the current climate period and inundated during high flows

The three main phases of water transport in the surface hydrologic cycle are precipitation, runoff, and evapotranspiration. Precipitation encompasses any form of water falling from the sky to the ground (e.g., rain, hail, snow, or sleet), of which a portion infiltrates into the ground (i.e., groundwater). The remainder either (1) is temporarily stored in snow, ice, or an aquifer; or (2) flows above the surface and is referred to as “runoff,” representing the percentage of precipitation that directly reaches the stream (also referred to as “overland flow”). This percentage is a function of the watershed’s physical characteristics—such as soil type, land cover, land use, and vegetation—and the antecedent soil moisture content. Evapotranspiration constitutes all water returning to the atmosphere from rivers, reservoirs, oceans, and other water bodies as vapor. Evaporated water condenses in the atmosphere and eventually leads to precipitation, completing the hydrologic cycle.

Hydrographs (i.e., graphs showing flow rate over time), particularly their magnitude and duration data, are used to aid understanding of how a watershed responds to precipitation by describing the rate of water discharge (i.e., runoff) over a specific time period. Engineers use flood hydrographs to design various civil infrastructures that interact with water. Infrastructure such as bridges, highways, or culverts is designed using specific-frequency hydrographs, in which a particular frequency of occurrence (i.e., the probability that a representative flood with a specific magnitude will occur or be exceeded) is statistically assigned to a discharge within a specific period (e.g., 50-year or 100-year floods). More properly, such events are estimated based on the annual exceedance probability (AEP) that a flow rate (or water level) will be equaled or exceeded. For example, a 50-year event is associated with a 0.02 AEP, whereas, a 100-year flood is associated with a 0.01 AEP. Dams, on the other hand, could cause public safety issues and extensive property damage should they fail. Therefore, dams or dam components (e.g., spillways) are often designed based on the probable maximum flood hydrograph, representing “the maximum runoff condition resulting from the most severe combination of hydrologic and meteorological conditions considered reasonably possible for the drainage basin under study” (USBR, 2006a), or based on a probabilistic analysis (e.g., 100-year inflow design). In particular, extreme events (e.g., flooding, earthquakes) can create deleterious conditions for a dam by inducing overtopping or overstressing of the dam crest (DeNeale et al., 2019) and leading to erosion of the dam toe. Dam design considerations associated with protecting against these extreme events can involve improvements to the foundation system. Furthermore, variations in river flow throughout the year often dictate the construction schedule of the foundation system, dam, and other superstructures, with typical practice targeting the beginning of excavation and substrate treatment work during the river's dry season (Section 4.3.1.3).

According to the American Society of Civil Engineers (ASCE, 2008), the erosion process can be geologic (i.e., occurring by natural processes) or accelerated (i.e., influenced by human-induced activities such as agricultural, commercial, and industrial development). These natural geologic processes include tectonic activity (e.g., earthquakes), physical weathering (e.g., landslides, glacial scouring, freeze-thaw cycles), chemical decomposition, and long-term atmospheric actions. Erosion can be separated into two key types, surface and channel:

- *Surface erosion* primarily comprises actions that denude and lower the surrounding land surface via weathering.
- *Channel erosion* refers to the actions that incise or widen a stream channel.

By volume, surface erosion typically produces most of the sediment carried by streams. Upland surface erosion (i.e., erosion occurring in the headwaters) is most frequently caused by combinations of physical weathering, rainfall, and runoff. Beyond gravity-driven mass-wasting events, the two basic forms of surface erosion are sheet (or interrill) and rill:

- *Sheet erosion* refers to the direct impact of raindrops on soil.
- *Rill erosion*, which occurs via small channels in the soil, carries runoff and mobilizes sediment from the interrill areas and any sediment eroded as a result of runoff within the rill itself. Rill erosion increases as the channel slope and length increases, and as the amount of runoff increases, to form a concentrated flow.

The main factors influencing upland erosion are soil types and characteristics, vegetation, topography, land use, climate, and time. In particular, the soil type and its physical properties significantly impact its resistance to erosion and its mobilization and transport, including water infiltration and runoff. Vegetation, on the other hand, increases the soil's resistance to erosion by serving as a shield or barrier to rainfall, and topography affects the severity of runoff and thus rill erosion. The Universal Soil Loss Equation, originally developed by Wischmeier and Smith (1965; 1978) combines all these factors to estimate the annual soil erosion rates for upland slopes over a wide range of rainfall, soil, slope, cover, and management conditions:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \,,$$

where A is the spatial and temporal average soil loss per unit of area (expressed in the same units chosen for K and period selected for R), R is the rainfall-runoff erosivity factor, K is the soil erodibility, L is the slope length factor, S is the slope steepness factor, C is the cover-management factor, and P is the support practice factor. More information on the equation and the specific parameters can be found in Wischmeier and Smith (1965; 1978); a revised version of the equation was reported by Renard et al. (1997).

B.2 STREAM CHARACTERISTICS

Across the watershed system, upland surface erosion is the main source of sediment transport into a stream system. The resulting sediment distribution along the reach is primarily governed by the flow transport capacity, morphology, and sediment yield of the river. Additional erosion can occur on the channel bed and banks within the stream if the flow is extremely high and sediment yield is low (i.e., channel degradation); that process is contrary to channel aggradation, where the flow is low and sediment yield is high, allowing deposition to occur.

In channels with a moderate gradient, sediment transport can be divided into two main categories, *bedload* and *suspended load*, which together make up the *total sediment load*.

- *Bedload* consists of coarse particles intermittently transported (e.g., rolled, hopped, slid) along the channel bottom. The primary mechanism driving this process is shear stress imposed by the water flow, which occurs when the shear stress exceeds the critical threshold of motion, which is a specific characteristic of the sediments. This granular movement at the bottom of the river is illustrated by the migration and evolution of bedforms such as ripples, dunes, antidunes, or bars.

- *Suspended load* refers to finer particles suspended in the channel (by turbulence) that move at the same velocity as the water flow.

Although these classifications are useful to illustrate sediment transport, the exact movement of particles in a river greatly depends on the local velocity, flow rate, and turbulence level (i.e., coarser particles could be a suspended load, depending on flow conditions). Sediment transport is a function of grain size and material density; fluid density and viscosity; and flow and turbulence intensity. A variety of formulas have been developed to predict sediment transport (ASCE, 2008). Despite some theoretical background, most sediment transport formulas are empirical, relying on studies and laboratory data.

Geologic setting and stream sediment transport characteristics are ultimately responsible for channel morphology and evolution (i.e., shape and location). In general, over time, these changes are primarily determined by the water flow, geologic conditions, quantity and type of sediment load, characteristics of bed and bank material (including vegetation), and topography. Although rivers are dynamic features that evolve over time, several classification schemes for channel forms have been proposed. Morphological characteristics of a stream are strongly interconnected to fluvial processes; therefore, a channel's present form may offer some insight to its geomorphological evolution. The first level of distinction among streams is between *alluvial* and *non-alluvial channels*.

- *Alluvial channels* are formed in and by sediment transported in the river (alluvium) under its current hydrologic and climatologic regime; these channels are self-formed and can change their form and location depending on the variation in water flow and sediment load.

- *Non-alluvial channels* are not formed via alluvium and therefore may not change dynamically; these rivers are usually bounded by bedrock, concrete, or very coarse glacial deposits.

Many stream classification schemes for channel forms are based on the pioneering study by Leopold and Wolman (1957), which used three main categories: *straight* (rare), *multi-thread* (braided and anastomosed), and *single-thread* (meandering). The main parameter that controls the transition between these types is the channel aspect ratio, also known as the width-to-depth ratio (ratio between the channel width and the average water depth).

- *Straight rivers* (Figure B.1a) are rare and inherently unstable at width-to-depth ratios greater than 10 and are often the result of man-made channelization.

- *Multi-thread* rivers are classified into braided and anastomosed rivers:
    - *Braided rivers* (Figure B.1b) are multi-threaded, with water flowing through several sand bars (islands) that are constantly forming, eroding and reforming, and are comparable in size to the thread width. This type is typically formed by large and shallow channels, with a width-to-depth

ratio greater than 50:100. They are characterized by high concentrations of bedload and suspended load.

  - *Anastomosed rivers* are similar to braided, but their islands are typically very stable and large compared with the thread width.

- *Meandering rivers* (Figure B.1c) are also characterized by high suspended load and bedload but have a single dynamic thread, usually confined by vegetation. The channel sinuosity, defined as the ratio of the distance measured along the channel (channel length) to the distance measured along the valley axis (valley length), is a distinctive parameter for this type of river that is used to describe the degree of meandering.

More recent classifications extend upon the Leopold and Wolman (1957) form classification to include geologic characteristics of the watershed, vegetation surrounding the channel, bed and bank material, hydrology, sediment concentration, and channel pattern and stability. Among these, one of the most widely used among river engineers is the classification by Rosgen (1994). Other practical references include the US Bureau of Reclamation Erosion and Sedimentation Manual (USBR, 2006b).

Figure B.1. Different types of rivers: (a) straight (River Rother, East Sussex, Great Britain), (b) braiding (Waimakariri River, South Island, New Zealand), and (c) meandering (Nowitna River, Alaska). Source: Images are copyrighted by unknown authors and made available under Creative Commons Attribution 3.0 unported licenses.

APPENDIX C. SUPPLEMENTAL INFORMATION ON SUBSURFACE CLASSIFICATION AND CHARACTERISTICS

This appendix provides additional information to supplement that provided in Section 3.2, Subsurface and Geologic Characteristics. The information presented includes additional information and associated terminology related to subsurface classifications and characteristics.

The authors acknowledge that terminology use varies depending on practice, and alternate and varying terminology may exist in the literature. Some subsurface characteristics presented apply to both rock and soil, and the reader is encouraged to consult additional resources for more detailed descriptions of key characteristics.

C.1 SUBSURFACE CLASSIFICATIONS AND GENERAL CHARACTERISTICS

Section 3.2 presents a hierarchy of subsurface classes (Figure 4) used to inform other parts of the report; the hierarchy is an example, and other classification schemes exist in literature. In particular, the USGS classification systems are widely used within geology and other fields. Figure C.1 and Figure C.2 illustrate the US Geological Survey (USGS) lithologic classification of geologic map units, available on the USGS website:[31] This classification provides an additional level of detail beyond the subsurface classification used in the main body of this report (as presented in Figure 4 in Section 3.2) and is presented as an additional resource.

For the purposes of this report, *rock* is defined as **any naturally occurring solid mass or aggregate of minerals or mineraloid matter**. Rocks are broadly classified by their formation process as follows

- Igneous rocks are formed the solidification of molten siliceous material, in which the associated silica content and conditions of formation (e.g., bulk chemistry, temperature, pressure, and rate of cooling) directly determines their particular properties.

- Sedimentary rocks are formed at or near the Earth's surface via the accumulation, consolidation, and lithification of sediment.

- Metamorphic rocks arise from existing igneous and/or sedimentary rocks subjected to high temperatures and pressures (e.g., when continental plates collide),often producing very hard materials (e.g., limestone and sandstone can metamorphose into marble and quartzite, respectively).

For the purposes of this report, soil is defined as **surface material composed of varying degrees of organic and mineral constituents, primarily resulting from the decay of plants and/or weathering of rock**. Common classes of soil depositional environments encountered at dam sites are:

- *Alluvial soils* are particles deposited in the streambed or floodplain by flowing water and can include a variety of particles from silts and clays to sands and gravels. These soils are transported downstream through the processes described in Section 3.1.

- *Colluvial soils* are those deposited at the bottom of hillslopes from runoff and gravity action. Colluvial soils further consist of scree or talus (larger rock fragment deposits resulting from steep hillslopes), slope debris (admixtures of smaller particles; deposited by water erosion and slope creep caused by gravity), and landslide debris (highly variable soil mixtures resulting from ash flows or avalanches).

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[31] Available from https://www2.usgs.gov/science/about/thesaurus-full.php?thcode=5 (accessed August 10, 2020).

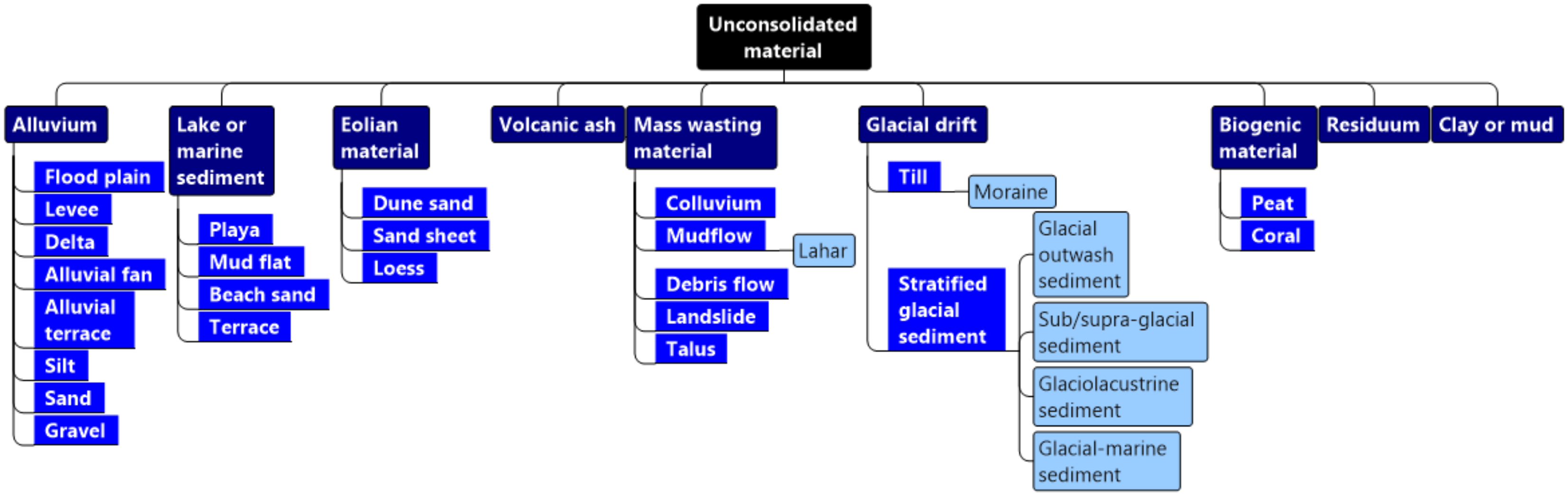

Figure C.1. USGS unconsolidated material (soil) classification diagram. Source: Based on USGS Lithologic Classification of Geologic Map Units.[31]

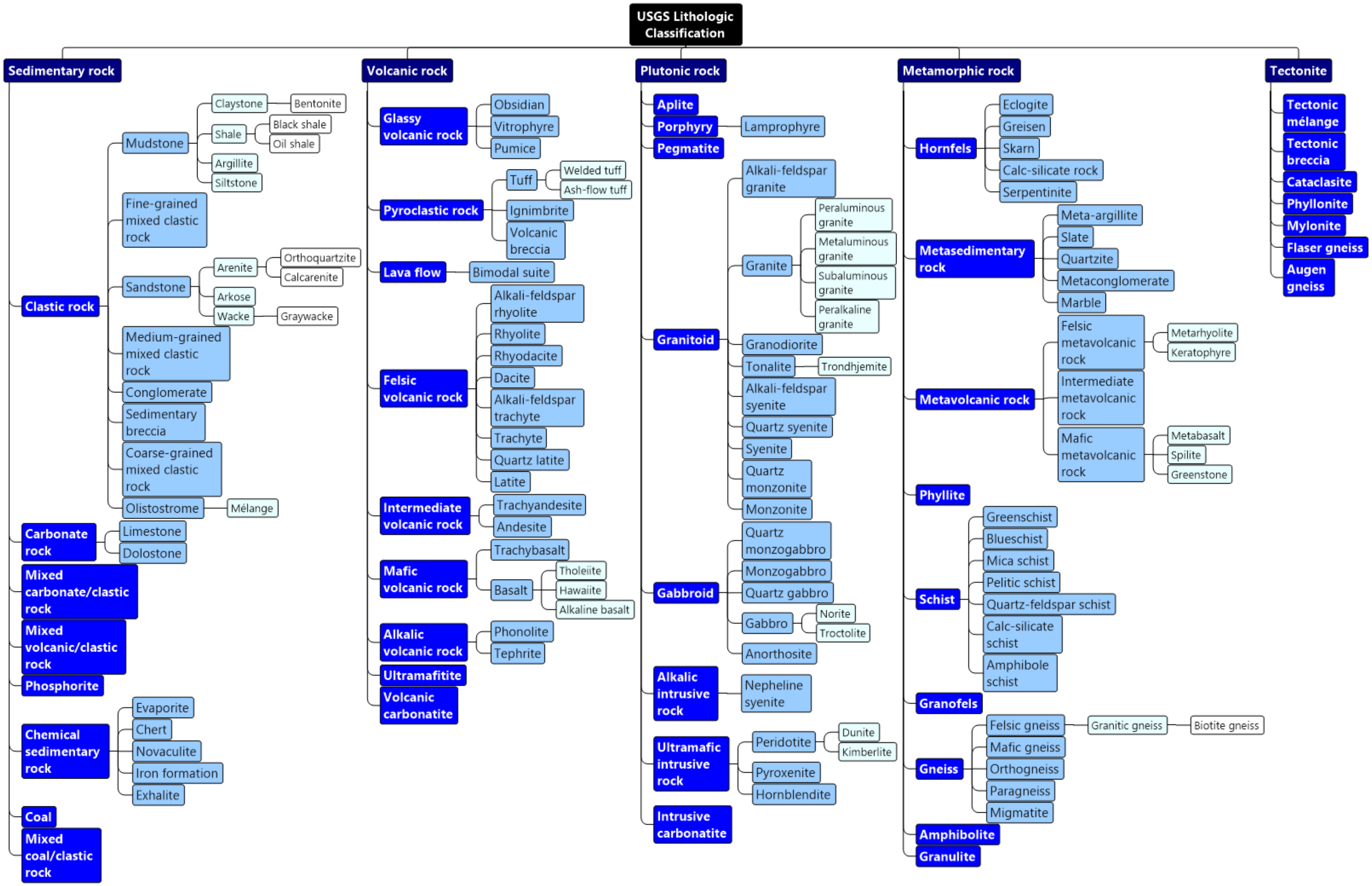

Figure C.2. USGS rock classification diagram. Source: Based on USGS Lithologic Classification of Geologic Map Units.[31]

- *Residual soils* are those formed from in situ chemical or physical weathering of soils and rocks over time. Lateritic soils, a common residual soil type, are created in tropical climates containing high concentrations of iron oxide and aluminum oxide, which provide a red coloration. The hardness, thickness, and composition of these soils vary based on the parent material, duration of weathering, and other environmental conditions.
- *Glacial soils* are those deposited by ice action during the Pleistocene and can contain a variety of soil types and sizes. Fell et al. (2014) provides more information about these depositional classes and their properties. These depositional environments contribute to the lateral and vertical heterogeneity of soils and the types of soil present.

Rock characteristics can be subdivided between those relating to the rock itself (*intrinsic rock properties*) and *rock mass properties*, including discontinuities. For soil, properties of interest include *intrinsic particle properties*, *bulk properties*, and *soil mechanical properties*. The information below describes these various characteristics. Some terminology is common to both rock material and soil mass, and includes:

- *Color* is the visual attribute of the material that can indicate the state of weathering and changes between material types.
- *Porosity* is the ratio of void volume to total volume of rock or soil
- *Total unit weight* is the weight of soil or rock solids and water divided by the total sample volume.
- *Dry unit weight* is the weight of soil or rock solids divided by total volume.
- *Submerged unit weight* is total unit weight less the unit weight of water.
- *Seismic velocity* is the velocity of propagation of seismic waves in a rock mass. Seismic velocity is a function of many rock material properties such as temperature, density, porosity, mineral composition, and the degree of cementation and consolidation; it is also a function of various rock mass properties, including degree of fracturing and degree of weathering.
- *Weathering* is the physical or chemical deterioration of the material resulting in an alteration of most of the properties listed herein. The effects of weathering can be assessed in the field and they tend to diminish with increasing depth, depending on the tectonic history of the site.
- *Soil stress* is the gravitational, hydraulic, and geologic forces that act on a unit area of soil.
- *Strain* describes deformation in terms of relative displacement in the soil or rock mass
- *Pore water pressure* is the water pressure within soil and rock pore spaces (e.g. between grains), typically measured in the field using a piezometer and in the laboratory using a pressure transducer mounted behind a porous stone.
- *Effective stress* is the stress carried by the soil particle structure. Equal to the total stress minus the pore water pressure.
- *Hydraulic conductivity* is measure of the ability of a fluid to flow through a porous material when subjected to a hydraulic gradient and has dimension of length per time. It depends on the porosity of the material, the degree of saturation, and the density and viscosity of the fluid. In rock, permeability also depends on factors including porosity, the shape and interconnectivity of the pore spaces with a

rock mass and spacing and aperture of fractures and joints. In soil, grain size distribution is an important determinant.

- *Hydraulic gradient* is the change in hydraulic head (pressure) between two or points along a flow path.
- *Flow rate (*or more formally, the specific discharge*)* is calculated as the flow velocity (length per unit time) multiplied by the total area (soil plus voids) of flow (length^2). It is traditionally estimated based on Darcy's law and is useful for calculating flow quantities
- *Seepage velocity (*length per time*)* is the velocity of water flow in open pore space. It is always higher than the flow rate, and is useful for calculating arrival time of solutes within water

C.2 ROCK CHARACTERISTICS

Intrinsic rock properties include the following:

- *Rock type* is a simplified geologic classification based on the rock's formation process (refer to the broad classification scheme introduced in Figure 4).
- *Hardness* as defined by (ASTM 2011) is a qualitative description of the material's resistance to physical weathering (e.g., impact or abrasion), being largely a function of rock type subject to modification by either chemical weathering or tectonic history. It is not the same as mineral hardness(Mohs scale), which refers solely to scratch resistance; however, the Mohs scale and field tools (e.g., Schmidt Hammer, pocket knife, geologist hammer) can be used to help assess a material's hardness.
- *Intact Rock Strength* is the intrinsic resistance of a rock to an external force, commonly assessed in terms of *unconfined compressive strength*, which is the amount of applied stress a material can withstand before failure. Additionally, intact rock strength is function of the formation process and other rock material properties (e.g., mineralogical composition, texture, grain shape and size, crystallinity), as well as secondary processes such as weathering and cementation. The US Natural Resource Conservation Service (NRCS) offers a guide to correlate intact rock strength to hardness[12]. However, due to the influence of discontinuities and defects, the intact rock strength rarely governs the behavior of rock foundations for dams.
- *Grain size and texture* encompasses the size of individual mineral or detrital particles that compose a sedimentary rock, and the crystallinity and granularity of igneous and crystalline metamorphic rocks, respectively. These sizes should be consistent with those used for soil.

Rock mass properties of interest for a dam scale foundation relate to geologic characteristics, including discontinuities, joints, fractures, and abrupt changes in lithology. The properties include the following:

- *Consolidation* is the process of reduction of void volume over time. In geology, consolidation refers to the process by which an unconsolidated deposit becomes sedimentary rock as a result of increasing vertical stress due to progressive burial.
- *Shear resistance* is the resistance to shear forces. Highly weathered rocks, poorly cemented shales, and siltstone may have very low shear resistance. Rock mass discontinuities are important determinants of shearing resistance. Adverse dip downstream in the foundation or in an excavation may cause instability.

- *Attitude* is the orientation of (planar) faults, strata, and fractures relative to the horizontal plane. Attitude is expressed as strike and dip. *Strike* is the azimuthal direction of the line of intersection of the feature with the horizontal plane. *Dip* is the vertical inclination angle (down from horizontal) of the feature, perpendicular to the strike direction.

- *Structure* includes any discontinuity in the rock, meaning any distinct interruption in the continuity and integrity of the rock mass (e.g., holes, cavities, joints, bedding planes, fractures, cleavage, schistosity, lenses, faults, folds). These features can be classified as stratigraphic and structural. Stratigraphic discontinuities (called unconformities, of which several types) exist are an interruption of a normal stratigraphic sequence caused by an interval of erosion or nondeposition. Structural discontinuities are the result of an external or internal (e.g., cooling) stress that acted on the rock mass after its initial formation; they can include planes of weakness, faults, joints, shear zones, and other features. Structural discontinuities can contribute to water seepage, as well as sliding and slipping along the superstructure-foundation interface. More information about discontinuities in rock masses can be found in Part 631 of the National Engineering Handbook[12].

C.3 SOIL CHARACTERISTICS

Intrinsic soil particle properties include the following:

- *Particle size* refers to the dimensions of individual particles. ASTM Test Method D422 defines the standard geotechnical test procedures used to measure particle size. Sieving is used for sand sizes and larger. A hydrometer test is used to measure silt and clay sizes Note that the maximum particle size determined through testing will depend on, and may be limited by, the sampling method. Using Test Method D-2487-17 (ASTM International, 2017) soil particles are classified into the following categories:
  - *Boulders* have particle sizes greater than 256 mm
  - *Cobbles* have particle sizes between 64 and 256 mm
  - *Gravel* have particle sizes between 4.76 and 64 mm
  - *Sand* have particle sizes between 0.074 and 4.76 mm
  - *Silt* have particle sizes between 0.002 and 0.074 mm
  - *Clay* has particle sizes smaller than 0.002 mm

- *Gradation* is the distribution of particles sizes within the bulk material, as measured by a sieve analysis or using a hydrometer analysis (used for smaller particle sizes). Well graded soils have an even representation of all sizes, whereas poorly graded soils are either uniform (a large majority of the particles are all one size) or gap graded (one or more intermittent size fractions are excluded).

- *Shape* refers to the geometric shape of the particle surfaces. For soils, grain shape is visually classified as rounded, sub-rounded, sub-angular, and angular. The shape is often determined using visual observation, experience, and judgement

Bulk soil properties[32] include the following:

- *Moisture (water) content* is the ratio of the weight of water to the weight of solids for an in situ soil sample. Soil moisture content classes include dry, moist, and wet.
- *Degree of saturation* is the ratio of the volume of water to the volume of voids a soil sample.

Soil mechanical properties[33] related to geotechnical engineering that can be estimated through field or laboratory testing include the following:

- *Plasticity* is the property of a soil to deform without cracking and is measured by an Atterberg limits test. Clay typically has some degree of plasticity, while clean sand and gravel are non-plastic. Silts range from non-plastic to high-plastic depending on factors such as mineralogy, grain size distribution and shape. Engineering properties are often correlated with Atterberg limits and other index values to estimate engineering parameters used in foundation design.
- *Atterberg limits* are the values of water content at which a soil changes between states (solid, semi-solid, plastic, and liquid), determined through Atterberg limit tests performed using a standard test method defined by ASTM.
  - Liquid limit is the water content value that represents the boundary between liquid and plastic states.
  - Plastic limit is the water content value that represents the boundary between plastic and semi-solid states.
  - *Plasticity index* is a relative measure of the range of water contents over which a soil behaves in a plastic state. Plasticity index is equal to the liquid limit minus the plastic limit.
- *Soil stiffness* is a measure of a soil's susceptibility to deformation, as governed by its stress-strain relationship.
- *Soil strength* is the maximum force (stress) that a soil can withstand without failure, as governed by effective stress. The strength of a soil is a very complex topic, and depends on bulk properties and mineralogy of the soil, the history of past stresses applied to the soil, the degree of saturation, the ability of water in the soil pores to drain in response to stress changes, and relative magnitude and direction of the applied forces, to list only some of the many factors that influence a soil's strength.
- *Maximum shear stress* is equivalent to the maximum resistive force (strength) a soil can withstand without deforming (failing). Because they typically exhibit high compressive strength and low tensile strength, soils generally fail in shear while under compressive loading.
- *Compressibility* is the ease with which a soil decreases in volume when acted on by a mechanical load. Compressibility is a critical property of soils for foundation design. Compression of larger soil

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[32] The US Environmental Protection Agency provides multiple online tools for site assessment calculation related to soil bulk characteristics, including hydraulic gradient, moisture content, flow rate, and seepage velocity. The tools are available at: https://www3.epa.gov/ceampubl/learn2model/part-two/onsite/b0_onsite.html (Accessed August 10, 2020).

[33] Soil mechanics are highly important to foundation system design and construction to ensure consolidation, settlement, seepage, and strength properties, among others, are met. The theoretical and practical information presented in (Terzaghi and Peck 1948) and its updated editions is still widely applied in current geotechnical engineering practice.

particles occurs relatively quickly; whereas, compression of finer particles (i.e., silts and clays) occurs more slowly and is referred to as consolidation.

Other terms often used in geotechnical engineering and related fields include the following:

- *Consolidation*[34] refers to the process by which silts or clays gradually reduce pore space volume (and therefore increase unit weight) in response to a change in pressure. In saturated or nearly saturated samples, water must flow to a drainage point before soil pore volume can change. This distance in combination with the soil permeability can substantially impact the consolidation rate.

- *Compaction* is the process of increasing a soil's bulk density by reducing void space occupied by air. Compaction can occur due to natural processes, such as burial of a sand or partially saturated silt or clay. Soils are also compacted using construction equipment in the field and drop hammers in the laboratory. The maximum density that can be achieved depends on the applied energy and the soil moisture content. ASTM defines a Standard Proctor or Modified Proctor test method to determine the relationship between soil moisture content and maximum dry density. The difference between the two tests is the Modified Proctor method applies more energy than the Standard Proctor test.

- *Settlement* is the vertical movement of subsurface material, including soils, due to stress and strain behavior over time. Settlement in the foundation (or elsewhere in the subsurface) can create differential movement of the superstructure that may cause cracking in soil and concrete that leads to adverse behavior.

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[34] Note that *consolidation* refers to similar properties of rock and soil, though addressing consolidation properties can help an engineer infer different treatment options for rock (e.g., grouting) vs soil (e.g., compaction).

APPENDIX D. SUPPLEMENTAL INFORMATION ON HYDROPOWER FOUNDATION ENGINEERING PRACTICE

Figures and tables are provided in this appendix as supplemental information to that in Section 4, Current State of Practice in Hydropower Foundations:

- Figure D.1. Illustration of common earthfill dam types.
- Figure D.2. Illustration of common rockfill dam types.
- Figure D.3. Illustration of common concrete dam types.
- Table D.1. Summary of potential design issues for relatively common geologic environments for rock foundations.
- Table D.2. Summary of potential design issues for relatively common geologic environments for soil foundations.
- Table D.3. Common geotechnical laboratory tests for soils.
- Table D.4. Characterization of structures, compatible foundations, and watertightness for common dam types.
- Table D.5. Applicability and procedures for common dam foundation treatments.

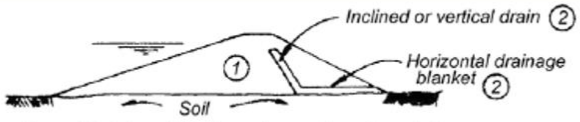
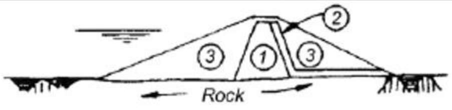
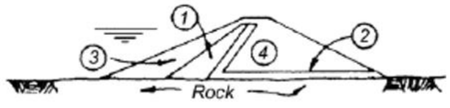
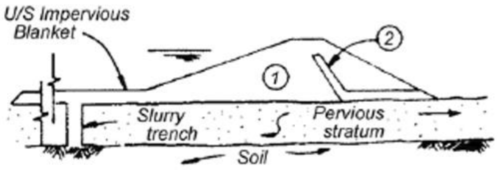
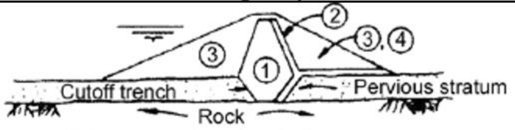
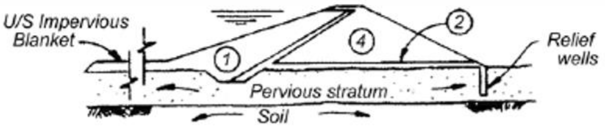
ID	Dam Type	Foundation Material	Illustration
E1	Homogeneous earthfill with internal drain	Impervious soil	 a. Homogenous dam with internal drain on impervious foundation
E2	Central or inclined core, zoned earthfill	Impervious rock	 b. Central core, zoned dam on impervious foundation  c. Inclined core, zoned dam on impervious foundation
E3	Homogeneous earthfill with internal drain	Pervious soil (or highly weathered rock or regolith)	 d. Homogenous dam with internal drainage on pervious foundation
E4	Central core, zoned earthfill	Pervious soil (or highly weathered rock or regolith)	 e. Central core, zoned dam on pervious foundation
E5	Zoned earthfill with upstream impervious zone	Pervious soil (or highly weathered rock or regolith)	 f. Zoned dam with upstream impervious zone on pervious foundation

Figure D.1. Illustration of common earthfill dam types. Source: Modified from (USBR (2006a).

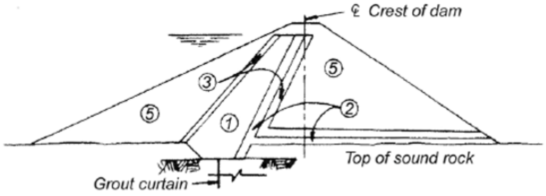
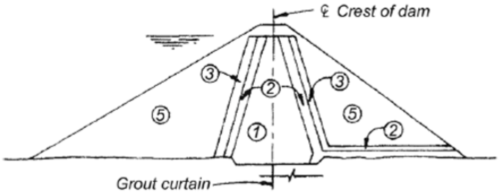
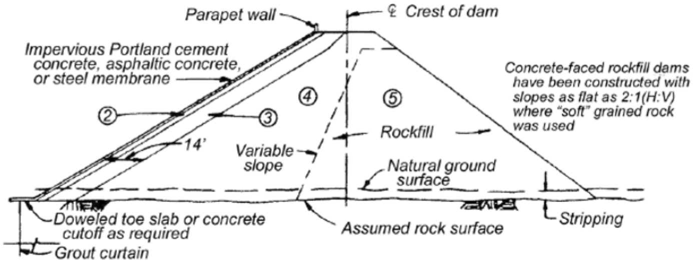
ID	Dam Type	Foundation Material	Illustration
R1	Rockfill with central or inclined core	Competent rock, treated as necessary for low permeability below core	 a. Dam with inclined impervious zone  b. Dam with central core
R2	Rockfill with upstream membrane (assumed CFRD)	Competent, impervious rock	 c. Dam with upstream membrane

Figure D.2. Illustration of common rockfill dam types. Source: Modified from (USBR (2006a).

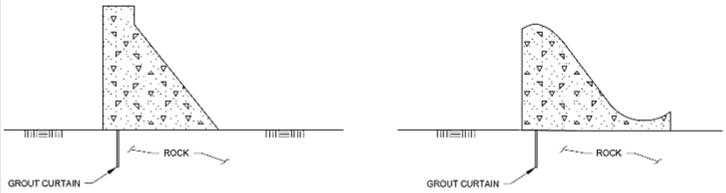
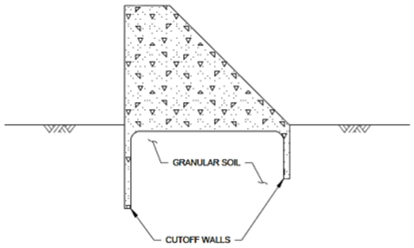
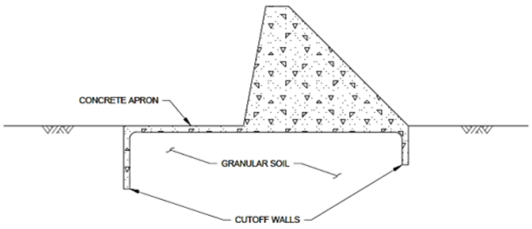
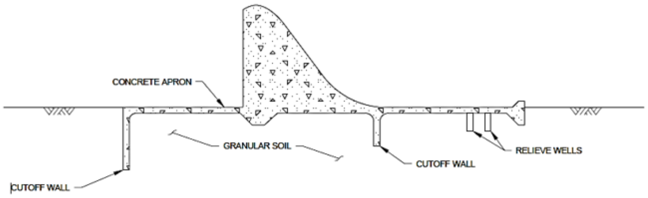
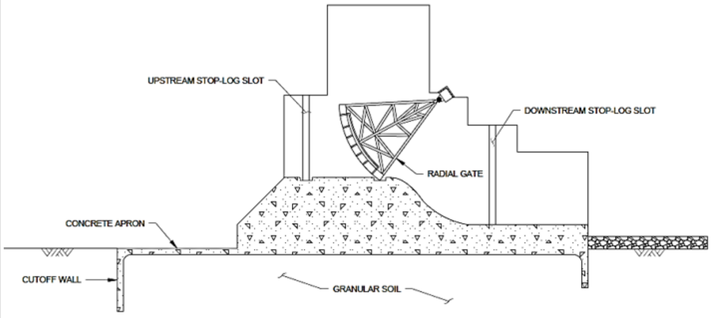
ID	Dam Type	Foundation Material	Illustration
C1	Concrete hydraulic structure (non-overflow section, overflow section, power intake, etc.)	Competent, impervious rock	a) Non-Overflow and Ungated Overflow Sections of Concrete Gravity Dam on Impervious Foundation 
C2	Concrete hydraulic structure (non-overflow section, overflow section, power intake, etc.)	Pervious competent soil (or highly weathered rock or regolith)	b) Non-Overflow Section of Concrete Gravity Dam on Pervious Foundation  c) Non-Overflow Section of Concrete Gravity Dam on Pervious Foundation with Upstream Concrete Apron  d) Ungated Concrete Overflow Section on Pervious Foundation with Upstream Concrete Apron  e) Gated Concrete Overflow Section on Pervious Foundation with Upstream Concrete Apron 

Figure D.3. Illustration of common concrete dam types.

Table D.1. Summary of potential design issues for relatively common geologic environments for rock foundations. Source: Modified from Fell et al. (2014).

Foundation subcategory	Typical strength classification	Transmissivity and seepage	Potential design issues
Igneous rock foundations			
Granite	Sound	Occasionally requires treatment	• Concealed sheet joints • Fresh rock outcrop • Chemically altered zones • Extremely weathered materials
Volcanic rocks (intrusive and flow)	Sound	Often requires treatment	• Vesicular zones • Clinker or breccia zones • Lava tunnels • Old weathered profiles • High mass permeability • Interbedded pyroclastic or sedimentary materials • Columnar joint patterns • Toppling failure • Difficulties in blast hole drilling • Poor fragmentation during blasting • Irregular joint patterns and pillow structure • Alteration effects—secondary materials • Very high-plasticity soils, expansive, fissured • Unstable slopes • Alkali-aggregate reaction
Metamorphic rock foundations			
Schistose	Usually sound	Sometimes requires treatment	• Degree of anisotropy • Low durability in exposed faces • Particle shapes and strengths inadequate for filter, concrete, or pavement materials • Suitability for use as rockfill • Foliation shears • Kink bands • Mica-rich layers • Unstable slopes
Sedimentary rock foundations			
Pyroclastics and airfall volcanics	Variable	Usually requires treatment	• Extreme variability • Very low in situ densities, collapse type behavior • Clays with adverse mineralogy (e.g., smectite) • High in situ permeability • Brittle in situ and when compacted • Highly erodible in situ and when compacted • Highly to extremely sensitive zones • Complex groundwater distribution • Welded rocks: gaping joints • Columnar jointed welded rocks: poorly graded rockfill, quarrying problems • Interbedded lavas? • Intrusive dikes, sills, or plugs • Alkali-aggregate reaction
Mudrocks	Variable	Occasionally requires treatment	• Slaking or disintegration on exposure • Swelling on exposure • Valley bulging • Soluble minerals in beds or veins • Presence of sulfide minerals • Slickenside fissures • Progressive shear failures

Foundation subcategory	Typical strength classification	Transmissivity and seepage	Potential design issues
			• Bedding plane surface false or shears • Unstable slopes, either shallow or deep seated • Possibility of high pore pressures, in layered sequences • Suitability for rockfill, random field, earthfill, and haul roads
Sandstone and related	Often sound	Often requires treatment	• Relatively high porosity, permeable • Gypsum or anhydrite present as cement • Quartzites: high quarry and handling costs, difficult to compact • Rocks of medium or lower strength may not produce freely draining rockfill • Interbeds of shale or clay stone • Betting surface faults at bed boundaries • Horizontal beds: open joints and bedding surface crushed seams near surface due to stress relief • Horizontal beds with shale interbeds: cambering and collapse due to removal of support by weathering shale • Land sliding in colluvium developed on weathering sandstone or shale slopes
Carbonate	Depends on solution activity	Often requires treatment	• Geologic age • Cavities, air-filled, water-filled, or soil-filled • Collapse of cavities • Extremely irregular, often pinnacled surface of fresh rock • Sharp boundary between residual soils and fresh rock • Strong rock around solution tubes and cavities in weak porous rocks • Solution cavities in altered carbonate rocks or metamorphosed impure carbonate rocks • Very weak, low-density, irritable weathered materials • Extremely high permeability • Extreme variations in permeability • Possibly deep, major leakage paths out of reservoir • Presence of sinkholes, exposed or concealed • Composition and pH of the groundwater and reservoir water • Presence, amount, and distribution of any sulfide minerals • Potential for dangerous ongoing solution in the dam foundation • Suitability for use as embankment materials • Suitability for use in concrete and pavements • Alkali carbonate reaction • Chert present: alkali silica reaction • Shaley (argillaceous) rocks: durability • Unstable slopes, where interbeds of mudrocks are present
Evaporites	Requires investigation	Depends on solution activity	• Cavities, air-filled, water-filled, or soil-filled • Collapse of cavities—subsidence • Ground weakening due to ongoing solution • Increasing permeability due to ongoing solution • Heaving due to growth of gypsum crystals • Large-scale heave due to hydration of anhydrite • Chemical composition of groundwater and reservoir water • Presence of halite—chemical tests • Possibility of cementation of filter materials by gypsum

Table D.2. Summary of potential design issues for relatively common geologic environments for soil foundations. Source: Modified from Fell et al. (2014).

Foundation subcategory	Typical strength classification	Transmissivity and seepage	Potential design issues
Alluvial soil foundations			
All	Often sound	Usually requires treatment	• Vertical and lateral variability related to deposition conditions • Lenticular deposits of openwork gravels with extremely high permeability • Anisotropy due to layering • High anisotropy in permeability • Oxbow lake deposits, compressible organic soils • Cracks, fissures, holes after rotting vegetation or burrowing animals, all either open or backfilled • Cemented layers • Buried timber, rotten or preserved, large voids
Colluvial soil foundations			
Scree and talus	Often unsound	Usually requires treatment	• High permeability and compressibility • Timber debris rotted or preserved • Potential for instability or debris flow
Slope wash			• Tubular voids causing high mass permeability • Compressible • Erodible • Potential for slope instability
Landslide debris			• Variability in composition and properties: laterally and vertically • Boulders • Large voids • Gaping or infilled cracks • High compressibility
Residual soil foundations (Laterites and lateritic weathering profile)			
All	Often sound	Sometimes requires treatment	• Lateral and vertical variability • Deeply weathered • High in situ density at depth • If sinkholes present, their mechanism and effect • Fine soils suitable for earth core • Gravelly ferricrete or alcrete suitable for pavements • Cemented material in crust suitable for rockfill or riprap • Silcrete horizon or quartzite bed
Glacial soil foundations (Glacial deposits and landforms)			
All	Often sound	Sometimes requires treatment	• Buried valleys • Bedrock surface or boulder • Bedrock disrupted near upper surface • Wide variety of tilt types • Materials unsorted: clay to boulder sizes • Slickensides in clay-rich till • Variable compaction and cementation • High-permeability sands and gravels • Loess • Landslide deposits • Creeping landslides

Table D.3. Common geotechnical laboratory tests for soils. Source: Modified from NAVFAC (1986).

Test	Description/purpose	Parameters obtained	Procedure reference
Natural moisture content and natural density	Obtain moisture content and density of foundation soils for geotechnical design based on natural field conditions	Moisture content (w), natural density (ρ)	ASTM D2216 (moisture), ASTM D2166 (density)
Specific gravity	Obtain specific gravity of soils, which is used to infer weight-volume relationships of soil. Can be used to estimate drainage and strength characteristics	Specific gravity (Gs)	ASTM D854
Atterberg limits (liquid limit and plastic limit)	Liquid limit: water content at which soil begins behaving like a liquid. Plastic limit: water content at which soil begins behaving like a semi-solid (i.e., at which soil will stop deforming and will break). Atterberg limits are used to quantify the plasticity of a soil, which can be used to estimate liquefaction potential, shear strength, consolidation, soil classification, and so on	Plastic limit (PL), liquid limit (LL), plasticity index (PI)	ASTM D4318
Particle size distributions (sieve analysis and hydrometer analysis)	Used to classify soils per USCS. Sieve analysis used to determine % gravels, % sands, and % fines (clay and silt). Hydrometer analysis used to determine % clay and % silt. Soil classification is useful in predicting soil behavior	Soil classification per USCS	ASTM D6913 (All Sieves), ASTM D7928 (including. hydrometer)
Corrosivity (pH, sulphate and electro-conductivity [EC])	EC test results provide an indication of soil chloride content. High pH, sulphate, or chloride content may require Type V cement and other design measures to mitigate corrosive attack	pH, ppm sulfate, milliSiemens per meter (EC)	AASHTO T-290 (sulphate) ASTM E70 and D497 (pH) ASTM G57 (resistivity—inverse of EC)
Flexible-wall permeability test	Determine saturated hydraulic conductivity of soils at varying confining stresses. Used in seepage analysis, which is important for earth dam stability and operation	k_{20} (permeability at temperature normalized to 20°C)	ASTM D5084
Consolidation	Tests performed to determine relationship between effective stress and void ratio/strain. These data are used to estimate magnitude and rate of differential and total settlement for cohesive soils	Preconsolidation pressure (Pc), coefficient of consolidation (Cv), compression index (Cc), recompression index (Cr)	ASTM D2435
Swell/collapse potential	Used to determine collapse/heave potential of a soil at varying confining stresses and water contents	Collapse index, swelling index	ASTM D4546
Shear strength (triaxial compression undrained)	Soil specimens are prepared and sheared to estimate their effective stress strength parameters. Used for slope stability and foundation shear strength analysis. Typically applied to cohesionless or unsaturated soils	Effective friction angle (φ') and cohesion intercept (c')	ASTM D4767 (consolidated undrained) D2850 (unconsolidated undrained) D7181 (consolidated drained)
Shear strength (direct simple shear)	Soil specimens are prepared and sheared to estimate their undrained strength parameters. Used for slope stability and foundation shear strength analysis. Typically applied to cohesive and saturated soils	Undrained strength ratio (Su/Sig'v)	ASTM D6528
Compaction (standard or modified proctor)	Used to determine relationship between molding water content and dry unit weight of soils. Results are used to provide percent compaction and water molding content needed to achieve the required engineering properties	Maximum dry density (MDD) and optimum moisture content (OMC)	ASTM D698 (standard) ASTM D1557 (modified)

Table D.4. Characterization of structures, compatible foundations, and watertightness for common dam types. Note: ID refers to the dam types shown in Figures D.1, D.2, and D.3.

ID	Structure principal material	Assumed compatible foundation material	Watertightness considerations		
			Phreatic water surface through structure?	Conventional measures to reduce seepage through rock foundations	Conventional measures to elongate the seepage path through a soil (or highly weathered rock) foundation
E1 (a)	Homogeneous earth fill with internal drain	Impervious soil	Yes	N/A	N/A
E2 (b, c)	Central or inclined core, zoned earth fill	Impervious rock	Yes	Foundation grouting	
E3 (d)	Homogeneous earth fill with internal drain	Pervious soil (or highly weathered rock or regolith)	Yes		Slurry trench, upstream impervious blanket
E4 (e)	Central core, zoned earth fill	Pervious soil (or highly weathered rock or regolith)	Yes	Foundation grouting in bottom of core trench	
E5 (f)	Zoned earth fill with upstream impervious zone	Pervious soil (or highly weathered rock or regolith)	Yes		Upstream impervious blanket
R1 (a, b)	Rock fill with central or inclined core	Impervious rock for clay core and pervious soil (or highly weathered rock or regolith) for shoulders	Yes	Foundation grouting in bottom of core trench	
R2 (c)	Rockfill with upstream membrane (assumed concrete-faced rockfill dam)	Impervious rock	No	Foundation grouting along upstream toe slab (plinth)	
C1 (a, 2 sections)	Concrete hydraulic structure (e.g., non-overflow section, overflow section, power intake)	Impervious rock	No	Foundation grouting	
C2 (b, c, d, e)	Concrete hydraulic structure (e.g., non-overflow section, overflow section, power intake)	Pervious soil (or highly weathered rock or regolith)	No		Slurry trench, cutoff wall (sheet pile or concrete), or upstream impermeable concrete apron.

Table D.5. Applicability and procedures for common dam foundation treatments. Source: Modified from Fell et al. (2014).

Treatment	Foundation type	Applicability			Procedure reference
		Concrete dam	Rockfill dam	Earthfill dam	
General foundation excavation	Rock	☑	☑	☑	Excavation of compressible and low-strength soil and weathered rock as is necessary to form a surface sufficiently strong to support the dam and to limit settlement to acceptable values
	Soil	☑	☑	☑	
Foundation cutoff excavation	Rock	☑	☑	☑	Excavation below general foundation level to remove highly permeable or erodible soil and rock, or both
	Soil	☑	☑	☑	
Cutoff foundation wall	Rock	☑	☑	☑	Examples are sheet piles and slurry cutoff walls
	Soil	☑	☑	☑	
Curtain grouting	Rock	☑	☑	☑	Drilling of holes into the foundation and injecting grout (usually cement slurry) under pressure to reduce the permeability of the rock
	Soil	×	×	×	
Consolidation grouting, also called blanket or stitch grouting	Rock	☑	☑	☑	Grouting carried out in the upper part of the cut-off foundation to reduce permeability of the rock
	Soil	×	×	×	
Rock anchors[35]	Rock	☑	×	×	Post-tensioned tendons installed in drilled holes where the entire bond length is located in rock. The anchor force is transmitted to the rock by bonding between grout placed between the tendon and the rock wall of the drill hole
	Soil	×	×	×	
Ground improvement	Rock	×	×	×	Includes a wide range of technology, including stone columns, dynamic compaction, vibroflotation, and wick drains; see Schaefer et al. (2012) for a relatively recent and comprehensive overview
	Soil	☑	☑	☑	
Relief wells	Rock	×	×	×	Construction of wells that will overflow if excess groundwater pressure develops, relieving pore water pressures in the aquifer and improving stability
	Soil	☑	☑	☑	
Upstream impermeable blanket or concrete apron	Rock	×	×	×	Material with low hydraulic conductivity placed immediately upstream of dams to lengthen the flow path of seepage within the dam, thus reducing hydraulic gradients and the seepage quantity at the downstream portion of the dam
	Soil	☑	☑	☑	

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[35] Rock anchors are often used for spillways and stilling basins, regardless of dam type.

APPENDIX E. LITERATURE REVIEW OF NON-HYDROPOWER FOUNDATIONS

Although hydropower foundations experience unique conditions (e.g., resisting and supporting loads imposed by the surrounding hydrologic environment, especially during extreme weather events, and problems with induced subsurface flow), technologies found in other industries could potentially be relevant in advancing foundation R&D for hydropower. Foundations are a crucial part of most structures across the transportation, offshore wind energy, marine and hydrokinetic (MHK) energy, and residential/commercial building industries. Accordingly, many techniques used in these industries may share similarities to hydropower foundation site assessment, design, and construction and thereby could have crossover applicability. Even non-foundation technologies, such as instrumentation and autonomous equipment used in industries such as mining, could have relevance.

E.1 BRIDGE FOUNDATIONS

For the greater part of human history, bridges have been used to cross riverine and marine waterways that posed difficult barriers to transportation. To accomplish their purpose, bridges typically must rely on structures constructed throughout the waterway—piers connect the bridge to the foundation system placed in the waterway. These foundations must be able to withstand continuous partial-to-full submergence and extreme weather events while supporting the static and dynamic loads of the bridge in and out of operation; these demands draw a parallel to some of the conditions of a hydropower foundation, especially given that some dams are even used as bridges. Bridge foundations are typically divided into two main types (Figure E.1): shallow, structures with a wide base spread across the ground (usually the bedrock is within 10 ft of the surface and the loads are lighter), and deep structures that penetrate deep into the subsurface, such as piles, drilled shafts, and micropiles/augercast piles (WDOT, 2017).[36] For most aquatic applications, deep foundations are deployed, owing to their ability to securely support large loads for long periods of time. Of these, piles are typically used because they cost less (WDOT, 2017). Similar to conventional hydropower construction methods, construction of bridge foundations generally involves cofferdam dewatering unless the site is small, in terms of both bridge size and water depth. Battered piling also is used, which involves piling multiple beams that are twisted in different directions.[37]

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[36] Available from http://madridengineering.com/deep-foundations-and-bridge-construction/ (accessed August 10, 2020).

[37] Available from https://www.foundationstructures.com/foundation-construction-process-bridges/ (accessed August 10, 2020).

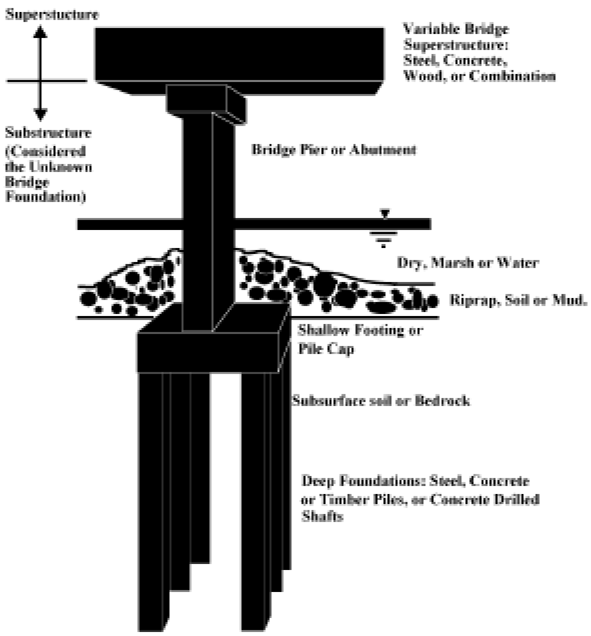

Figure E.1. Depiction of two types of foundations associated with bridge superstructures—shallow and deep. Source: FHWA (2013).

Because of the high importance of bridges in the transportation network, the technology driving bridge foundation design and construction is constantly advancing. Innovations in design-phase load testing by engineers working on the new Sakonnet River Bridge project—a major transportation corridor between Rhode Island and Massachusetts—allowed for final design adjustments, including testing of new technologies, before the start of construction. Such adjustments are typically not possible for the difficult subsurface conditions present at such sites (Locsin et al., 2015). One technology that proved successful and was included in the final design was the use of an internal, recessed plate to improve the resistance of steel-pipe piles (Locsin et al., 2015). Other innovations involved advancements in the materials employed in foundation construction, such as cement/concrete, shape-memory alloys, and alternate materials (Abhyankar and Subramanian, 2018). New types of concrete are being developed that have increased strength, ductility, and other structural properties, which increase their versatility across various environments. A key technology currently undergoing laboratory tests is self-healing concrete, which contains dormant bacteria and calcium lactate in “pods” that can be activated by water to fill up cracks, increasing the longevity of the structure, especially under extreme conditions (Abhyankar and Subramanian, 2018). Another advanced technology is shape-memory alloys that have increased elasticity (much greater than that of typical concretes and steels) and the ability to revert to their initial shape when certain temperature requirements are met (Abhyankar and Subramanian, 2018). Alternate materials, as opposed to typical concrete, are also being pursued that have more sustainable production processes, such as manufactured sand, iron-copper-steel aggregates, and industrial byproduct–cement mixtures (e.g., fly ash, slag cement, silica fume, rice hush ash, and natural pozzolans (Abhyankar and Subramanian, 2018). Whether improved design-phase methodologies or innovative materials with increased structural properties and performance, bridge-building technologies can potentially be relevant to hydropower foundation design and construction, and even other areas of development.

E.2 OFFSHORE WIND

Across the world, offshore wind energy is increasingly being pursued because of the existence of abundant resources along the coasts of many countries; for instance, the United States has theoretical resources totaling more than 2,000 GW of generation potential (Esteban et al., 2011).[38] This boom is spearheading extensive innovation across all aspects of development, from foundations to turbine blades and rotors, with support from organizations such as the DOE Wind Energy Technologies Office.[39] Wind developers are also capitalizing on the experiences of the oil and gas industry, which has been extensively involved in planning, designing, and constructing semi-permanent offshore structures for many decades.[37] For an offshore wind turbine, the foundation represents approximately 35% of the total cost and signifies a critical structure system, much like hydropower foundations (Esteban, López-Gutiérrez, and Negro, 2019). To date, nearly 80% of worldwide offshore wind turbine foundations are monopiles, or cylinders that are drilled into the seafloor upon which the base of the turbine is attached.[39] Because of the limited versatility of monopiles (i.e., they are mainly constrained to shallow waters with non-rocky soils and cannot support large turbines), in addition to the negative environmental impacts associated with their installation (e.g., loud noise and ground disturbances that negatively impact marine wildlife), other foundation technologies are being used and researched.[39] One such technology is four-legged jackets, which can support larger turbines, can be installed in deeper waters, and support more weight. A more modular version, the "twisted" three-legged jacket, is available as well.[39] The modularity of the latter results from a streamlined design that reduces the materials and times associated with construction, transportation, and installation compared with the traditional jacket.[39] Other foundation technologies being explored are suction buckets (ideal for soft, sandy soils)[39]; floating platforms anchored to the seafloor (ideal for deep water); and gravity-based structures, which are ideal for rocky or sandy soils and shallow or deep water, but only in soils with high bearing capacities (IRENA, 2016; Esteban, López-Gutiérrez, and Negro, 2019). Figure E.2 illustrates multiple types of offshore wind turbine foundations.

Figure E.2. Illustration of different types of wind turbine foundations (left to right: monopile, jacket, twisted jacket, spar-submersible, tension leg platform, spar buoy). Source: Josh Bauer, National Renewable Energy Laboratory.[40]

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[38] Available from https://www.energy.gov/eere/wind/offshore-wind-research-and-development (accessed August 10, 2020).

[39] Available from https://www.awea.org/policy-and-issues/u-s-offshore-wind (accessed August 10, 2020).

[40] Available from https://www.energy.gov/eere/articles/us-conditions-drive-innovation-offshore-wind-foundations (accessed August 10, 2020).

A major advantage of offshore wind turbine foundations is their modularity—nearly all foundation systems are manufactured offsite and then transported to the site and installed with a relatively simple procedure that requires no dewatering. For these offshore foundation systems, the riverine environments of hydropower development offer different challenges from the marine environments where such structures are usually deployed, in terms of corrosion, flow profiles and induced scouring, and depth ranges. For instance, the extreme depths and bidirectional tidal currents that offshore foundations face are rare occurrences in rivers; rivers, in turn, will have differing effects on scouring of obstructions placed in the waterway. Furthermore, offshore deployments typically do not experience induced subsurface flows (i.e., seepage) such as are common in riverine environments associated with dams.

E.3 MARINE HYDROKINETIC

Some "current energy converter" MHK devices resemble wind turbines in design and function (i.e., both convert the kinetic energy of a moving fluid into electricity), and their foundation technologies are similar (Chen and Lam, 2014). Although it is not specific to riverine applications, a useful report recently released by Sandia National Laboratories and the University of Exeter details the specific requirements for MHK foundation systems in ocean environments, including the necessary inputs and tools for the design and anchoring of arrays (Heath et al., 2014). Additionally, the report analyzes the key geotechnical properties having the greatest impact on foundation system design and the associated environmental impacts of deployment, primarily in terms of cyclical loading and sediment response. Even though these technologies may not be applicable to the design and construction of hydropower facilities (dams specifically), the methodologies and intuition used in accelerating offshore wind and MHK power development can prove insightful, especially as some hydropower R&D is exploring more modular technologies that can take advantage of foundations designed for smaller structures (refer to Section 3.4.1.2 for more information about this hydropower research area).

E.4 FOUNDATION SCOUR PROTECTION

A shared design consideration among the MHK, offshore wind, and transportation industries, in addition to the hydraulic structures (e.g., spillways), is the challenge of scouring due to the varying flow of water in and around underwater structures. Many technologies and techniques have been developed over the years to reduce the severity of these problems (e.g., riprap or vegetative covering around the base of the structure; alterations of the water channel upstream of the structure). Their effectiveness is increased with consistent monitoring and maintenance when appropriate (IHRB, 2006). However, because of the long lifespans of most of the structures in these industries, scouring protection technologies and techniques are constantly evolving. For instance, DHI and LIC Engineering developed an innovative scouring system that combines two steps in the installation process for armoring scour systems on offshore wind turbines to reduce construction timelines and costs.[41] They created a wide-grade material that encompasses both a filler layer of finer material and an armor layer of coarser material.[41] Another technology currently being researched is the SISProtect system (Self-Installing Scour Protection) for offshore wind farms. It revolutionizes the frond mat concept (used in the oil and gas industry) for offshore wind applications by creating a deployment system to allow installation of the mats directly alongside the foundation, thereby reducing timelines, costs, and environmental impacts.[42] Frond mats are beds of artificial seaweed that require no ongoing maintenance, use sustainable materials, can be deployed at depths of up to 100 m, and have a simple installation process compared with conventional riprap technologies.[42] Although these technologies may not be applicable to foundations because of their placement in the subsurface, distant

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[41] Available from https://www.dhigroup.com/global/news/2019/06/innovative-design-lowers-costs-of-offshore-wind-farm-scour-protection-systems (accessed August 10, 2020).

[42] Available from https://gtr.ukri.org/projects?ref=104364 (accessed August 10, 2020).

from hydraulic flows, they can potentially be useful in many other superstructure applications (e.g., spillways, tailraces).

E.5 BUILDING CONSTRUCTION

Although technologies used in other, non-hydropower aquatic industries can have the greatest impact on advancing hydropower-specific foundation R&D, inland industries such as residential and commercial building construction nonetheless offer good insights because of their widespread adoption (e.g., more houses are built per year than hydropower facilities). Foundations used in residential construction are typically divided into four categories, mainly based on the residential purpose of the foundation: slab (no purpose), basement (residential purposes), crawl space (maintenance purposes), and pier (for more challenging environments such as those prone to flooding, expansive or collapsible soils, or mountainous/hilly terrain).[43] Because of the high demand the residential housing industry has recently experienced, and its projected increase across the coming years, prefabrication technologies have been explored to reduce timelines and costs; but greater strides have been made in simplifying the design and construction of the superstructure compared with the foundation (Teodosio et al., 2018). However, advancements in precast concrete foundation walls and floors are being explored, as they eliminate weather constraints (poured concrete requires specific weather conditions for optimal forming to avoid imperfections), save time, and potentially save costs for labor and materials typical construction produces much waste material and has a greater environmental impact).[44,45,46] Over the past decade, states have been strengthening their housing codes in regard to fire and water resistance in light of recent natural disasters (e.g., tornadoes, hurricanes, wildfires); the revised codes play to the strengths of precast concrete compared with poured concrete.[45,46] Additionally, fluctuations in market conditions have unfavorable implications for housing quality and craftsmanship, which modular, precast technologies potentially can avoid. The advantages of these technologies and methodologies can also be argued for hydropower foundations, and greater hydropower facility construction in general, as any design and construction cost and time reductions greatly increase overall project feasibility, especially when they reduce environmental impacts (refer to ORNL's SMH project in Section 3.4.1.2).

Commercial buildings can also benefit from innovations in modular, precast foundation technologies, but such structures must be built to support much greater loads and adhere to stricter regulations than residential homes.[47] Therefore, technological innovations for commercial construction have larger hurdles to overcome, similar to advancements occurring in the hydropower, transportation, offshore wind, and MHK industries. However, such challenges provide opportunities for advancements in materials (i.e., alternatives to concrete or steel) and design/construction methodologies, especially given the many different types of commercial foundations. Similar to bridge systems, commercial building foundations can be divided into two main categories based on depth: shallow (the load is distributed across the upper subsurface layers; e.g., continuous or spot footings, monolithic slabs, certain types of mats) and deep (the load is transferred deeper into the subsurface through the use of piles or mats).[48] As these foundation types will largely depend on the type of superstructure envisioned, innovation specific to the foundation

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[43] Available from https://edensstructural.com/a-look-at-the-different-types-of-home-foundations/ (accessed August 10, 2020).

[44] Available from https://precast.org/2017/06/business-case-engineered-precast-concrete-walls/ (accessed August 10, 2020).

[45] Available from https://precast.org/2010/05/precast-in-residential-applications/ (accessed August 10, 2020).

[46] Available from https://www.builderonline.com/building/building-science/new-foundation-system-could-revolutionize-basement-construction_o (accessed April 26, 2020).

[47] Available from https://mwconstructionutah.com/commercial-vs-residential-construction/ (accessed August 10, 2020).

[48] Available from https://www.matthewswallanchor.com/commercial/commercial-foundation-types/ (accessed August 10, 2020).

system can also be included, at least partly, in the superstructure. For instance, Smith-Midland's Sierra Wall II is a precast concrete highway sound barrier that has the foundation system included in its design.[49] Although prefabricated foundation-superstructure systems may not be feasible for larger hydropower projects, they may be applicable in smaller, more modular systems that follow paradigms such as ORNL's SMH project (refer to Section 3.4.1.2), depending on a site's geologic and hydraulic conditions. Additionally, innovative materials and design/construction methodologies used in these industries can have a significant degree of applicability to hydropower foundations and superstructures.

E.6 MINING, TUNNELING, AND AUTONOMOUS EQUIPMENT

Beyond innovative foundation technologies across inland industries, the use of autonomous equipment and instrumentation has been advancing rapidly across many industries in recent years. One of these industries is mining, in which the increasing use of sensors and analytic software allows for more accurate planning of maintenance outages and reduces maintenance requirements, thereby lowing costs.[50,51] Additionally, robotics and autonomous equipment are reducing the need for human labor, making operations safer and more economical.[50] Across the mining industry as a whole—which has experienced declines in productivity for a significant part of the past two decades—these technical advancements show great promise, especially in times of increasingly stringent environmental constraints and other regulations that limit the ability of developers to obtain licenses.[50] The hydropower industry faces similar hurdles, as conventional developments have an extensive regulatory process that severely hampers project feasibility. However, advanced instrumentation and analytic technology could help ensure environmental and other types of regulatory compliance throughout the entire construction and operation phases of a project, in addition to the potential for autonomous equipment to increase worker safety and reduce project costs. For foundation-specific applications, advanced software and sensor technology could be useful to detect early signs of damage resulting from seismic activity, extreme weather events, or regular wear-and-tear, helping to prevent future dam/facility incidents or failures. Although such technologies might not have a significant impact on upfront project costs, they could potentially reduce operation and maintenance costs throughout the lifetime of the facility.

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[49] Available from https://smithmidland.com/images/pdfs/Smith_Midland_Case_Study_one.pdf (accessed August 10, 2020).

[50] Available from https://www.mckinsey.com/industries/metals-and-mining/our-insights/behind-the-mining-productivity-upswing-technology-enabled-transformation (accessed August 10, 2020).

[51] Available from https://www.mckinsey.com/industries/metals-and-mining/our-insights/how-digital-innovation-can-improve-mining-productivity (accessed August 10, 2020).