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# Hydropower Geotechnical Foundations:

## *Executive Summary* on Current Practice and Innovation Opportunities for Low-Head Applications

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Photograph at bottom 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.

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# FOREWORD

The following content provides a companion executive summary of *Hydropower Geotechnical Foundations: Current Practice and Innovation Opportunities for Low-Head Applications* (DeNeale et al. 2020), a technical report developed by Oak Ridge National Laboratory (ORNL) and Knight Piésold Consulting, with funding from the US Department of Energy (DOE) Water Power Technologies Office (WPTO). This executive summary provides a brief synopsis of the broader information contained in the technical report. This study (and the associated technical report)

(1) covers background information on hydropower;

(2) describes various characteristics relevant to hydropower foundations for undeveloped US streams;

(3) presents the current state of practice in foundation development;

(4) provides a representative assessment of conventional hydropower foundation costs and timelines;

(5) addresses key challenges facing conventional hydropower foundations; and

(6) presents opportunity areas and examples for innovative hydropower foundation technologies while highlighting some advances in non-hydropower industries.

Although geotechnical foundations are required for constructing a variety of hydropower system structures across all types of hydropower development, this study focuses primarily on geotechnical foundations applicable to **conventional hydropower** for **low-head** dam applications (up to 30 ft of hydraulic head, or roughly 50 ft of structural height). Foundations for less-conventional modular superstructures are also considered for their potential cost and timeline reductions; however, geotechnical foundations related to conventional hydropower are the main focus. This study is further focused primarily on 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), which represents the largest source of currently undeveloped hydropower resource potential in the US.

Through this study,[1] 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, risk, and environmental impact reductions**.

**Study Scope and Focus**

- Geotechnical foundations for low-head hydropower application (30 ft or less 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.

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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 document and its associated technical report are intended to provide concise information, rather than guidance.

# 1. OVERVIEW OF HYDROPOWER GEOTECHNICAL FOUNDATIONS

Hydropower uses flowing water under pressure to produce renewable electricity and has been the leading source of renewable energy generation for over a century. Hydroelectricity benefits from low fuel costs and provides unique value to US power system operation, offering high reliability, flexibility, and predictability. In addition to the renewable power produced, hydropower offers numerous ancillary grid services—including generation flexibility, frequency response and regulation, spinning and non-spinning reserves, and black start capabilities—which enable safe, reliable, and economical power system operation (DOE 2016).

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. An example schematic of a typical conventional hydropower facility (a concrete dam is shown) is provided in Figure 1.

Hydropower developers must consider the interplay of a project's **cost**, **timeline**, and **risk**. Among the challenges facing hydropower growth, 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. While foundations are central to dam safety and must be developed to minimize environmental disturbance, their design and construction can lead to major project delays and cost overruns, potentially jeopardizing a project's success.

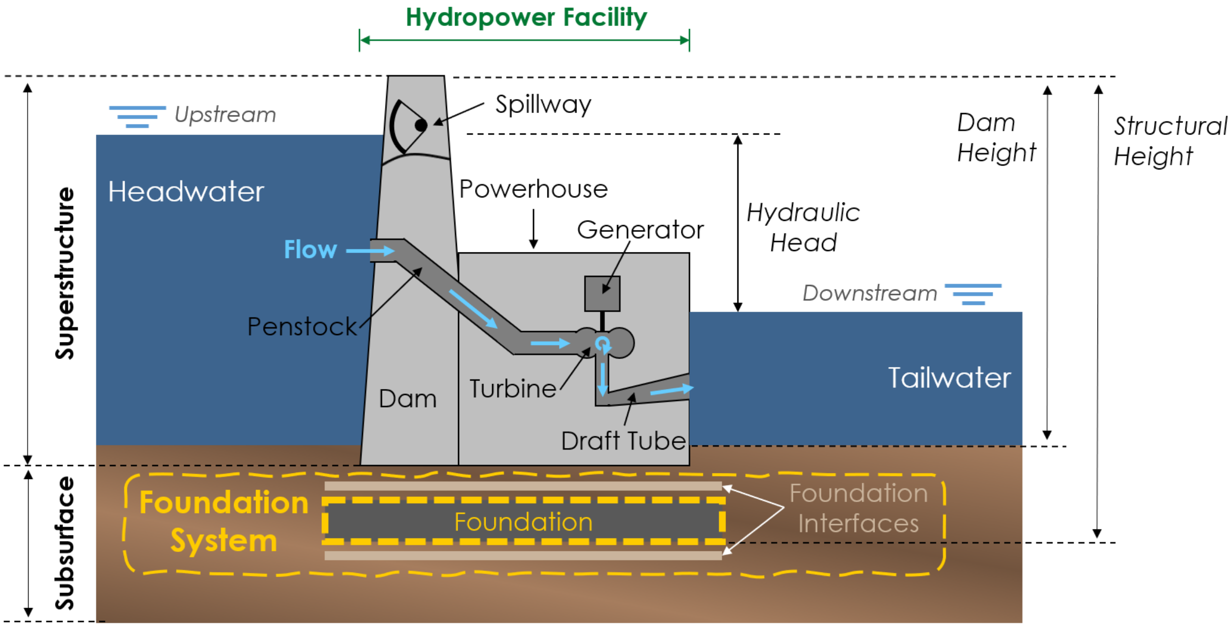

**Figure 1. Typical conventional concrete-dam hydropower facility with important components indicated.**
Source: ORNL. Some facility components (e.g., abutments) are not illustrated. Not to scale.

## 2. FOUNDATION SYSTEM HIERARCHY AND CONTEXT

The uncertain and often site-specific nature of hydropower foundation development introduces additional challenges that most other civil infrastructure foundations do not face. In particular, hydrodynamic and seepage conditions associated with water impoundment impart additional complexities for hydropower foundation design compared with other civil works infrastructure applications (see Figure 2 for an example load diagram for a concrete gravity dam and foundation).

With footprints spanning a stream or river, the construction of hydropower foundations requires care of water, which involves constructing temporary diversion structures upstream and often downstream (called cofferdams) and water diversion systems that route water around the construction site. These pre-excavation activities can prove costly and may introduce risk should the design prove inadequate, or a beyond-design flood occur. Moreover, dewatering and coffer damming can induce environmental disruptions and uncertainty, which carry risk for a project.

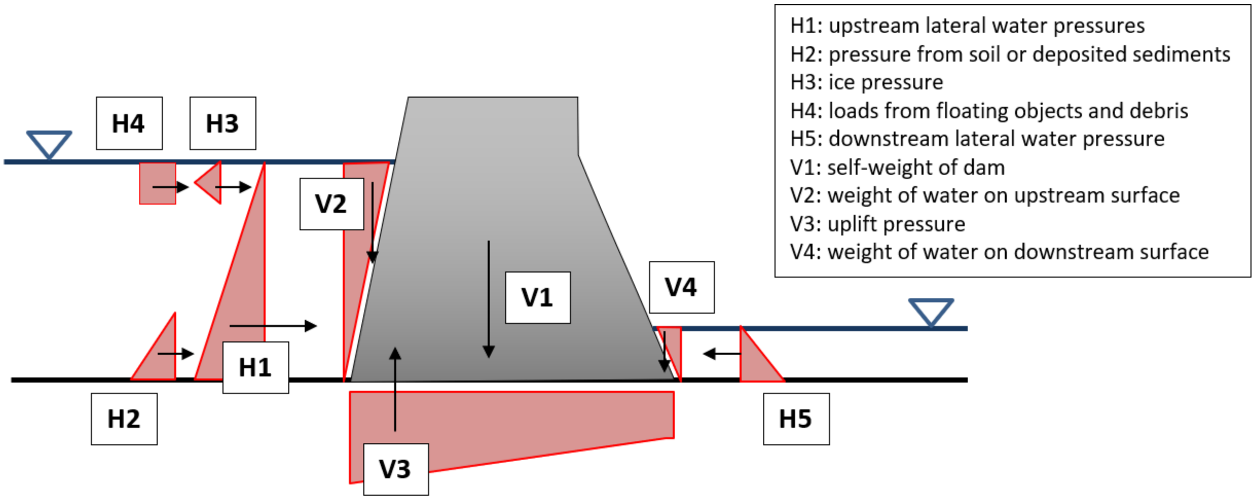

**Figure 2. Common vertical and horizontal loads on a concrete gravity dam and foundation.** Red triangles (not to scale) represent vertical and horizontal load distributions impacting the dam. Source: Smith et al. 2017; adapted from European Small Hydropower Association (ESHA) 2004.

Given the complex interactions of physical and environmental factors affecting a hydropower facility and its associated foundation, a structured framework for assessing foundations systems is warranted. To meet this objective, this study models an in-stream hydropower facility as a system of three interconnected components: subsurface, foundation system, and superstructure.

- 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.
- 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. 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. Various types of 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).

- The ***superstructure*** 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. Dam subcomponents considered part of the superstructure include the dam core, filters and drains, and geotextile membranes/blankets.

Figure 3 presents a hydropower foundation system hierarchy for defining the physical bounds of these three components while demonstrating their interdependencies within hydropower engineering practice. As shown in Figure 3, information about the stream environment and subsurface is used to perform ***geotechnical site assessment*** and inform ***foundation design*** and ***foundation construction*** through an iterative process. The foundation interface is designed and constructed depending 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 as well as technoeconomic considerations influencing the development process.

As the foundation system hierarchy (Figure 3) demonstrates, foundation system development involves complex interactions across the hydropower facility (i.e., between the foundation system and the superstructure), between the foundation system and subsurface, and within the stream environment. Gravitational, hydrologic, and geologic forces (Figure 2) induce loads on the subsurface and superstructure which must be withstood through engineered foundation design and construction. These geotechnical interconnections are not unique to hydropower, though design for hydrodynamic and seepage conditions associated with water impoundment imparts additional complexities to those for other civil works infrastructure applications. Risk and uncertainty also stem from the site geology and riverbed composition, long regulatory process, desktop-level data availability, and site access.

Thus, a hydropower facility's geotechnical foundation is often highly specific to the site, with proper site selection and assessment being important to project success.

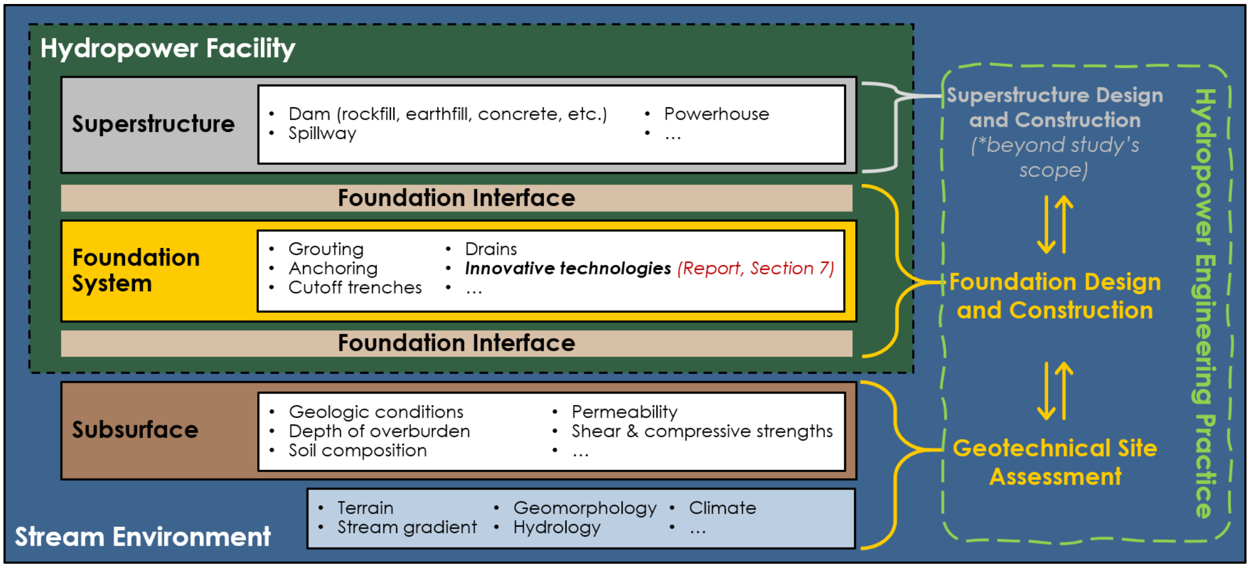

**Figure 3. Hierarchy of hydropower foundation system within the context of a stream environment and engineering practice.** Note that ellipses represent additional information beyond what is shown in the diagram.

# 3. FOUNDATION-RELATED CHARACTERISTICS

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 it supports. This study summarizes key foundation-related characteristics among two main categories:

- **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. Among the many important watershed and stream characteristics driving foundation development, the site's location within a watershed implies other key information, including (generally) the relative stream gradient, occurrence of rock, and stream bed content. For the purposes of this study, three terrain classes are identified to idealize stream representations: ***mountainous*** (i.e., Zone 1), ***hilly*** (i.e., Zone 2), and ***valley*** (i.e., Zone 3), as shown in Figure 4.
- **Subsurface and geologic characteristics**: The local subsurface at a proposed site can be immediately distinguished by its composition of rock and soil. **Rocks** (defined as any naturally occurring solid mass or aggregate of minerals or mineraloid matter) can be classified into three major classes based on their formation: ***igneous***, ***sedimentary***, and ***metamorphic***. Rock type presence and characteristics are tied to a site's geologic formation and progression. **Soils** (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) can be classified into four major classes based on depositional process: ***alluvial***, ***colluvial***, ***residual***, and ***glacial***. Soil presence and characteristics are highly dependent on a site's geology, climatology, and hydrogeological depositional environment.

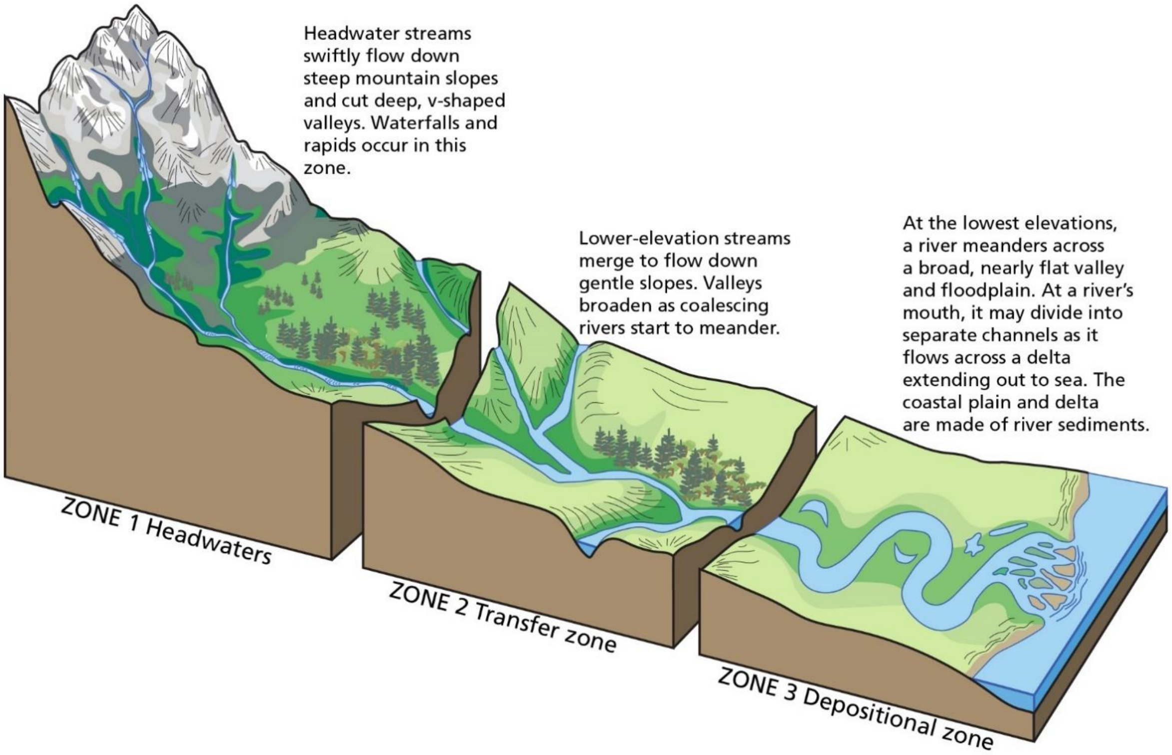

**Figure 4. Coarse representation of a watershed's terrain classes in terms of sediment transport processes.** Source: Trista L. Thornberry-Ehrlich, Colorado State University; redrafted from Miller, G. T. 1990. *Living in the Environment: An Introduction to Environmental Science*. Wadsworth Publishing.

Dam designers must understand the underlying rock and soil characteristics at a proposed site to inform foundation and superstructure designs that will minimize construction time and cost while mitigating the risk of failure. As project development progresses, developers gain increasingly refined information about the subsurface and geologic conditions at a site. Subsurface conditions should be classified to inform foundation design.

Rock, when suitable and accessible in the local subsurface, can provide direct support for a dam's foundation. In general, structurally sound or competent rock foundations are suitable for many types of dams following proper foundation treatment (e.g., grouting, anchoring, trenching). Rock foundations can be classified based on the predominant rock type; however, the site-specific properties of the rock mass are very important. Rock properties can vary over short distances and can be non-uniform within the same rock formation; they can be subdivided more broadly between those relating to the rock itself (intrinsic rock properties) and rock mass properties, including discontinuities.

- ***Intrinsic rock properties*** include rock type, hardness, strength, color, grain size, and texture.
- ***Rock mass properties*** include porosity, consolidation, shear resistance, attitude, and structure.
- Other physical properties related to both rock material and mass include seismic velocity and weathering.

Important rock mass properties include the compressive strength, the shear resistance. The permeability, and the general structure, which describes the discontinuities (e.g., joints, faults, fractures) within the rock mass. Discontinuities in the rock are often treated with grout to ensure watertightness and limit consolidation during construction; however, excessive grout take can be expensive.

Soil presence and characteristics can vary along the streamwise, vertical, and lateral directions based on the geologic, climatologic, and hydrogeologic depositional environment. Each formation will also contain specific compositions of each soil type. Therefore, in-person site assessments are crucial for identifying the rock and soil conditions. However, a general understanding of soil material classes will help inform superstructure selection and other engineering considerations for hydropower foundations. At a high level, soils with similar engineering properties can be classified by the depositional environments.

A preliminary estimate of soil properties of concern to dam designers can often be obtained by using published soil type correlations in literature. The engineering properties of soil formations vary widely, and they can preclude certain dam types and treatment methods. More detailed and precise information is gathered through field and laboratory measurements. Soil properties of interest include *intrinsic particle properties*, *bulk properties*, and *soil mechanical properties*.

- ***Intrinsic particle properties*** include particle size, gradation, angularity, and shape.
- ***Bulk properties*** include moisture content, degree of saturation, unit weight, bulk unit weight, porosity, hydraulic gradient, permeability, hydraulic conductivity, flow rate, seepage velocity, and cohesion.
- ***Soil mechanical properties*** include plasticity, Atterberg limits, pore water pressure, stresses, strain, stiffness, strength, compaction, compressibility, consolidation, and settlement.

The important soil engineering properties, such as permeability, shear strength, and plasticity indices, are primarily controlled by the distribution of particle sizes. For soils with large particle sizes (i.e. coarse-grained soils), gradation, or the distribution of all particle sizes, is particularly important.

## 4. FOUNDATION-RELATED FEATURES OF UNDEVELOPED US STREAMS

In addition to describing the various foundation-related stream and subsurface characteristics relevant to hydropower, this study presents a high-level analysis of available low-head hydropower (NSD) sites based on available national data, providing an approximation intended to help characterize likely subsurface presence across nearly 9,000 low-head NSD sites (Kao et al. 2014). The study results are uncertain given the lack of site-specific assessments available for national-scale assessment and the assumptions made.

Based on the available data and generalized sediment transport theory, the following conditions were selected to indicate where streams are more likely to have a layer of overburden indicative of a likely soil foundation site. A site was classified as soil if it met any one of the following conditions:

- 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 resulting analysis indicates **most (approximately 81%) of the undeveloped, low-head hydropower in the United States is likely to be sited on soil foundations**, rather than rock foundations (Figure 5). This result agrees closely with the National Inventory of Dams database that reports 80% of existing low-head dam sites are built on soil foundations. In addition, of all the NSD sites, 36% are expected to have alluvial soil foundations and 26% to have residual soil foundations. Based on this distribution of subsurface classes, 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.

It is important to note that no subsurface profile is perfectly uniform and no two subsurfaces are exactly the same. Therefore, geotechnical experts are needed to properly characterize a hydropower site. Every stream has an underlying geologic (rock) formation, so the primary difference is the depth and types of soil above this formation. Since there are very limited data regarding instream subsurface composition, the high-level relationships and processes that determine soil type and depth are presented.

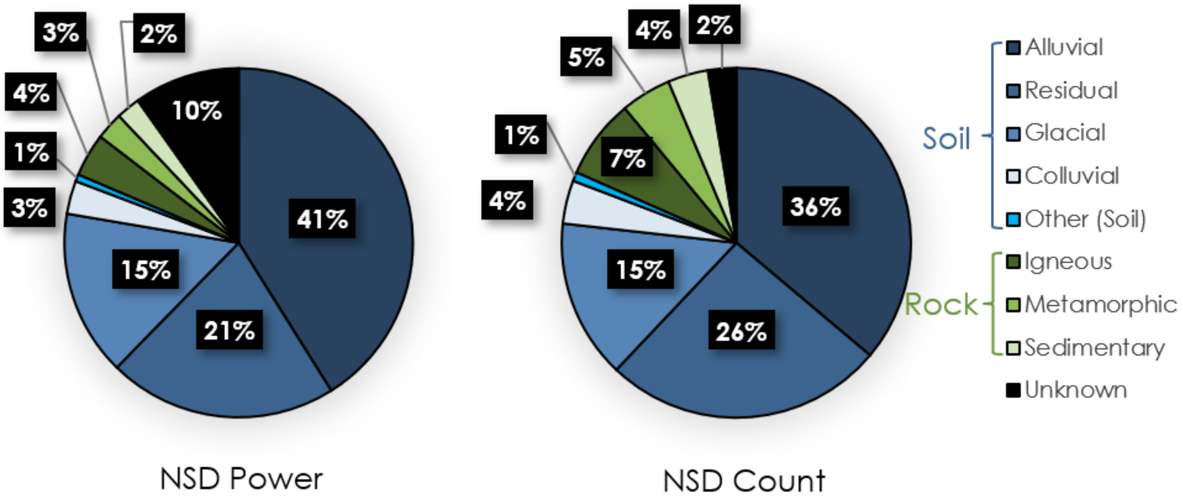

**Figure 5. Distribution of low-head NSD site subsurface classes.**

# 5. REVIEW OF CURRENT STATE OF PRACTICE IN HYDROPOWER FOUNDATIONS

Hydropower foundation engineering typically occurs in three main development phases: (1) geotechnical site assessment, (2) foundation design, and (3) foundation construction. Since subsurface characterization is difficult and expensive, designers never have perfect information about the site and must be flexible in their decision-making. Therefore, the development phases are often concurrent activities, comprising an iterative process which must integrate with overall project planning activities (Figure 6).

**Geotechnical Site Assessment**: *Activities performed to obtain information needed to design and construct a foundation system.* Key objectives of a geotechnical site assessment are to establish baseline information, model the subsurface geologic and hydrologic conditions, and evaluate engineering characteristics .

**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.* Foundations are designed to be compatible with the structures they support, and each site has unique characteristics that the designer must consider in developing a design solution (hence the iterative process described above). Major design criteria include providing for structural stability and support, and controlling seepage.

**Foundation Construction**: *Activities performed by the contractor, from mobilization through project commissioning, to fully develop the foundation system.* Foundation construction encompasses various pre-excavation activities, excavation activities, and foundation treatments. Pre-excavation activities include mobilization, site preparation, dewatering and coffer damming, and other best management practices to minimize ecological impacts during construction. Foundation treatments can include material excavation, surface (dental) concrete placement, anchoring, cutoff trenching, grout curtain/blanket placement, structural/relief wall construction, and combinations of multiple methods.

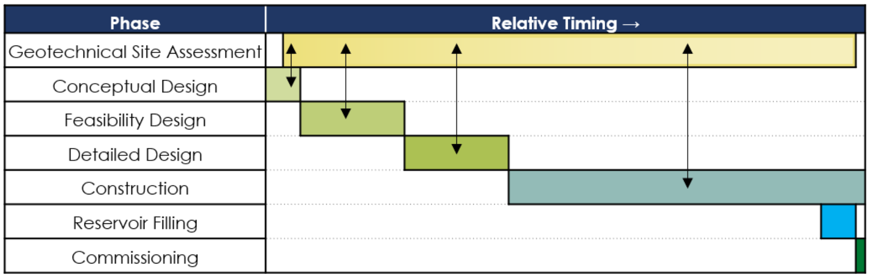

**Figure 6. Representative sequence of principal phases for design, construction, and commissioning of small hydropower development.**

A hydropower foundation design must align with the site's geologic and subsurface conditions, which can also dictate superstructure (i.e., dam) selection and design. As the foundation development progresses, additional geotechnical site assessments may be needed as additional information or conditions arise throughout the design and construction phases. New site information can reveal the potential for significant cost overruns or even fatal flaws (site conditions that would be too expensive to remedy or present too high a risk to dam safety) that make the project cost-prohibitive. For low-head NSD hydropower applications, cost-effective dam design and construction alternatives are typically limited to earthfill, rockfill, and concrete gravity dams. Modular superstructures represent a less conventional design approach that, while largely unproven, could offer potential cost and schedule reductions.

Desirable goals to reduce project performance metrics (cost, time, risk) include (1) reduce construction costs (e.g., through standardization or modularity); (2) reduce overall construction times (e.g., through standardization or modularity); (3) reduce uncertainty related to foundation treatment costs, structural stability, and risk of failure; (4) minimize ground excavation or create systems that require less excavation to avoid seepage; and (5) minimize disturbances in river connectivity during installation, operation, and maintenance.

# 6. CHALLENGES AND OPPORTUNITIES FOR HYDROPOWER FOUNDATIONS

To provide additional insight into the major cost and time drivers, this study presents information on representative costs and timelines for conventional, low-head projects (less than 30 ft of hydraulic head or less than 50 ft of structural height) based on combinations of generalized site terrain, foundation type, and dam type as a framework. The typical project types considered include (1) rock foundations in mountainous terrain, (2) rock and permeable soil foundations in hilly terrain, and (3) permeable soil foundations in valley terrain.

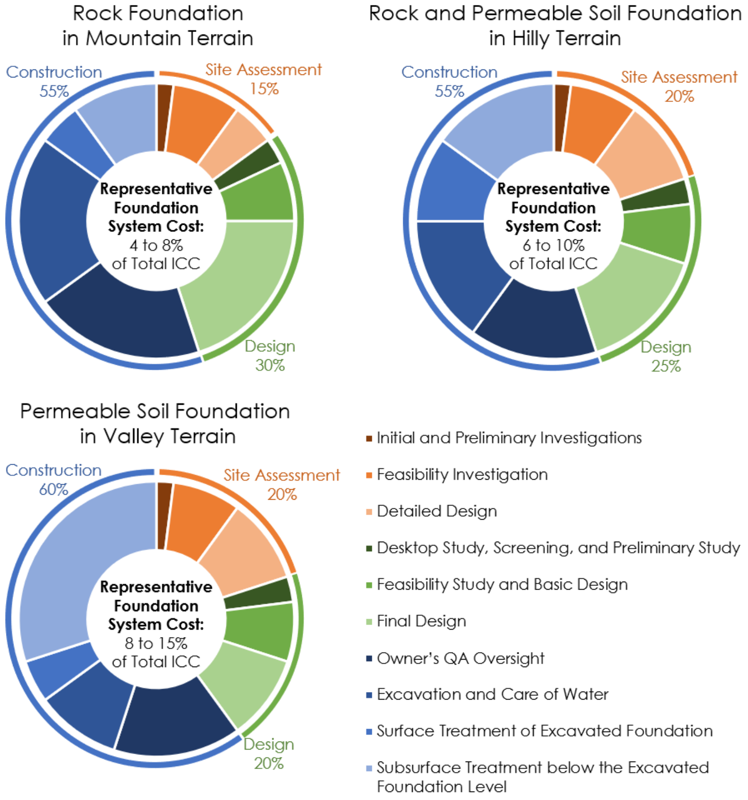

**Figure 7. Representative foundation system cost breakdown by project type.** Based on actual industry project experience (unpublished).

Representative cost breakdowns are provided for various foundation development activities and system components, as shown in Figure 7; representative foundation system costs (to achieve reasonable foundation economic feasibility) are also presented, as a percentage of total project initial capital cost. The main cost drivers identified include the foundation footprint size, excavation depth, and foundation treatment extent. Construction activities and materials are found to represent the largest category of costs; however, any knowledge gaps, uncertainties, or other complexities involving geotechnical site assessments and foundation design could carry weight throughout the foundation development phases.

In addition to costs, representative timelines among the three typical project types are assessed. Overall foundation investigations and design work timelines typically vary from 12 to 18 months, with valley terrain (i.e., predominantly soil foundation sites) requiring a relatively longer process than mountainous terrain (i.e., predominantly rock foundation sites). River diversion and care of water (including cofferdams, bypasses, and canals), although temporary, can represent cost drivers. Careful planning and fine balancing of cost, risk, and time are essential for efficient construction of a hydropower foundation.

Based on the representative costs and timelines presented and additional information, hydropower foundation challenges and opportunities for innovative technology solutions are identified in the following areas. These **opportunity areas are not necessarily mutually exclusive** (i.e., solutions could span one, two, or all three areas). Table 1 provides some **example** opportunities within these three opportunity areas.

- **Geotechnical site assessment** (offsite and on-site): Challenges can involve site access difficulties; regulatory approval timelines; high-resolution satellite and/or aerial imagery; geophysical exploration limitations; soil and rock sampling reliability; rock joint strength; site material erosion; and modeling limitations, among others.

- **Foundation design and materials**: Challenges can include unexpected site conditions, as well as structural stability, strength, and seepage calculations for conventional and innovative designs.
- **Foundation construction and technology**: Challenges can include risk quantification and communication; unexpected geologic and subsurface conditions; construction scheduling delays; water diversion system installation costs and mitigation; and performance monitoring availability.

**Table 1. Example opportunities for hydropower geotechnical foundations.**

| | |
|---|---|
| **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 artificial intelligence, or AI) to improve the 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) |
| **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 |
| **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 best management practices 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 |

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