

TECHNICAL NOTE 2  
**GEOTECHNICAL RISK**

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GOOD PRACTICE NOTE ON  
**DAM SAFETY**



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# Technical Note 2: Geotechnical Risk

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## Introduction

This Technical Note is prepared to provide guidance to the World Bank task teams and clients regarding geological and geotechnical issues and recommended risk mitigation and management measures. The investigation, design, and construction of dams should identify and consider all potential hazards and threats to dam safety while being cognizant of the associated consequences of dam failure.

## Geotechnical Hazards

Geotechnical hazards<sup>1</sup> and threats for a dam must be considered for the overall dam system including dam body, appurtenant structures, foundations, abutments, and the reservoir rim. Critical hazards and threats that could lead to dam failure include:

- Internal erosion and piping of embankment or foundation material
- Hydraulic fracturing within the dam
- Surface erosion
- Slope instability
- Static and dynamic liquefaction of foundation soils or the embankment fill
- Excessive seepage

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<sup>1</sup> Hazard is here defined as a threat or condition that may result from external cause (for example, earthquake or flood) or internal vulnerability. Risk is defined by combining an assessment of the probability of the hazard occurring with an assessment of the impact that the hazard would cause if it occurs. More details are provided in the Geotechnical Risk Register section.

- Excessive uplift pressure
- Deformation of the dam
- Sliding on weak foundation planes
- Unsuitable construction materials

## Geological Hazards

Geotechnical hazards are derived from and linked with broader geological hazards surrounding dam sites and reservoir areas. Geologically, no two sites will be the same; many different geological processes and interactions can create complex sites and the materials available for dam construction. Geology will have a profound influence on the location of the dam site and layout of dam features. Geological hazards are those geological features that have the potential to negatively affect the successful construction of a dam at the chosen site. Geological hazards may affect the selection of dam sites and surrounding reservoir areas. The successful project will identify geological hazards and, where necessary, mitigate the effects that hazards could bring on the construction and operation of dams and reservoirs.

Geological hazards may include:

- Defects in rock foundations including joints, bedding planes, faults, infill seams, solution features, buried alluvial channels, and weathered or altered seams, which could become leakage paths or form unstable wedges in the dam foundation
- Defects in soil foundations including fissures, tension cracks, ancient landslides, and infilled features
- Potentially liquefiable foundation soils that would not support the dam body after an earthquake
- Soluble foundation rock that leads to leakage and erosion problems over time
- Varying stiffness of foundation material that could result in differential settlement within the dam
- Potentially unstable abutment slopes
- Potentially unstable slopes surrounding the reservoir shoreline that could cause an impulse wave that could overtop the dam
- Foundation material that is prone to erosion and scouring by energy dissipation of discharge from the dam spillway
- High-pressure groundwater systems that prevent foundation excavation and construction

- Chemically reactive aggregates that affect construction materials (for example, aggregates that would cause expansion cracks in concrete by alkali aggregate reaction or an earth dam filter material that cements)
- Active regional faults that could cause earthquakes resulting in severe shaking and displacements at or near the dam site
- Active faults that cross the reservoir or dam site with the potential to cause seiche waves in the reservoir that could overtop the dam

Geological hazards must be assessed using data obtained during geotechnical investigations, supplemented by geologists and geotechnical engineers' judgments and analysis. Mitigation measures need to be considered to reduce the effects of the hazard or reduce the likelihood of occurrence. If the risk would remain unacceptably high even after mitigation measures are taken, then the dam site may have to be abandoned.

### **Foundation Conditions**

Foundation defects can affect the integrity and stability of any dam type, and untreated foundation defects have contributed to some dam failures around the world. The foundation of any dam must fulfill the following five functions:

- It must provide stability.
- It must provide adequate stiffness to ensure that deformations are within acceptable limits.
- It must control and limit seepage flows and uplift/piezometric pressures beneath the dam.
- It must be resistant to internal erosion.
- It must not degrade over time.

Appropriate foundation engineering should address any concerns that arise in relation to these functions.

At some dam sites, geological conditions are reasonably straightforward, and all of the functions are readily satisfied. At other dam sites, geological conditions are complex, and critical defects may not become apparent until foundation excavation is underway. The challenge is to keep the uncertainties within acceptable limits; however, there are some geological environments that require more care during investigation, design, and construction.

Annex 1 of Environmental and Social Standard (ESS) 4 specifies that a dam featuring “foundations that are complex and difficult to prepare” should apply certain dam safety requirements regardless of the dam’s size. These foundation complexities and issues can include:

- Clean coarse sands, gravels, and cobbles that could provide a pathway for foundation piping or the piping of embankment materials into the foundation
- Loose silt or sand deposits that are potentially liquefiable
- Open or infilled joints in foundation rock that could be eroded and provide the potential for high leakage flows or the piping of embankment materials
- Interbedded soil deposits (fine against coarse) that could provide the potential for foundation piping
- Weak strata, interbeds, and seams with low strengths, which could result in potential sliding failure surfaces within the foundation
- Persistent subhorizontal joint sets that would limit the shear strength at the dam/foundation interface or within the dam foundation
- Faults and other major discontinuities that can incorporate low-strength materials and, if unfavourably orientated, affect dam stability
- Highly compressible or dispersive soils that could result in collapse, differential settlements, and cracking or foundation piping
- Karst features (caves and sinkholes) in limestone or soluble foundations (for example, gypsum), which can result in significant leakage and additional sinkholes following reservoir impoundment by dissolution or washing out of infilling or overlying materials
- Active faults that can cause earthquakes, resulting in displacements beneath a dam and the initiation of internal erosion, increased uplift pressures, and reductions in dam stability (see the Technical Note on Seismic Risk)
- Landslides or unstable abutments

## **Reservoir Rim Stability and Watertightness**

In addition to the dam foundation and abutment, geotechnical issues of the reservoir rim should also be assessed.

### **Reservoir Rim Stability**

The potential of landslides on the reservoir rim should be checked as part of the dam’s safety evaluation. The reservoir landslides could cause an impulse wave generated by rapid landslide movement (or rockfall) to overtop the dam or flood the communities surrounding the reservoir rim.



Alternatively, a landslide around the reservoir rim or in the upstream river, could create a “landslide dam”, blocking the river flow/reservoir water and eventually breaching with the resulting flood wave overtopping the dam.

ICOLD (2002) provides guidelines for the investigation and management of reservoir landslides, comments on possible risk mitigation measures, and discusses requirements and methods for the ongoing monitoring of reservoir landslide performance.

Considerations for landslides around the reservoir rim include:

- Whether there is any part of the reservoir perimeter (for example, a narrow ridge) that may be more likely to fail than the closure dam
- Whether there is any potential for landslide-generated waves to affect communities adjacent to the reservoir
- Whether any existing landslides may reactivate or new landslides may develop under any of the possible reservoir conditions, to the extent that the dam could be overtopped or the reservoir or upstream tributaries blocked
- Whether reservoir operation could result in toe erosion adjacent to dormant or potential landslide areas
- Whether any of the slopes near the spillway or low-level outlet facilities may fail and block the facilities or impair their functions
- What management regimen should be implemented to prevent sediment or debris from affecting the performance of the spillway or low-level outlet facilities
- What operational requirements should be implemented to ensure that the stability of dormant and potential landslide areas is not adversely affected by reservoir drawdown
- What management regimen should be implemented to monitor the performance of known landslides and any completed remedial works during dam commissioning and operation

### Reservoir Water Tightness

The water tightness of a reservoir depends on the permeability of foundation and surrounding material, existing groundwater around the reservoir, and gradients and lengths of potential seepage paths. Although minor reservoir water leakage will not cause dam safety and operation issues, a large amount of leakage can have several negative impacts. Excessive leakage could prevent the reservoir from being filled up and cause increased groundwater tables, leading to development of swamps downstream or landslides. Leakage water could exit to a downstream location in an uncontrolled manner, eroding the surrounding ground or dam structure.

The leakage rate will depend on the geological formation and material type surrounding the reservoir. Nonsoluble, soluble, and soil materials will have different levels of watertightness. Keys to understanding the watertightness of nonsoluble and soluble rocks include understanding the groundwater conditions around the reservoir and the site's history, regional topography, geology, and properties of materials surrounding the reservoir.

There are several treatment measures to prevent and reduce leakage, such as lining the reservoir, grouting, construction of cutoff walls, and so on. Because these treatment works could be quite expensive, it is important to undertake proper geological and geotechnical investigation and assess the costs of the treatment works to reduce the leakage amount to an acceptable level. The dam site may need to be re-evaluated depending on such assessments.

## **Dam Type Selection and Key Factors**

Dams are primarily constructed of “earthfill” (soil and rock) materials or concrete. The appropriate dam type and construction materials will depend on several factors, including the purpose and geological considerations. Table 1 shows the significant factors that should be considered for specific dam types to minimize dam safety hazards, along with possible design and mitigation measures that address the potential failure modes.

Some good reference books and guidelines on the design and remediation of dams include:

- Weaver and Bruce (2007) for foundation grouting
- Fell et al. (2005) for geotechnical engineering of dams.
- ICOLD (2005) for dam foundations including geologic considerations, investigation methods, treatment and monitoring
- ICOLD (2009) for the specification and quality control of concrete dams
- FEMA (2011) for embankment dam filters
- USBR (1987) for design of small dams

## **Investigation Program**

Comprehensive geotechnical investigations should be undertaken to understand the dam's foundation stratigraphy, design, and construction materials. All investigations and data assembly for the design must be on an appropriate level to the complexity of the dam site. Site investigations can be long, so it is important to start as soon as possible. Investigation needs to be in proportion to the hazard of the structure and the magnitude of the risk. There can be a temptation to delay investigation activities until the implementation phase, but by then the construction contract will have been signed and unexpected ground conditions are more likely to become the source of contractual dispute. Investigations should be preferably staged so that lessons learned guide the scope for subsequent stages of investigation.

**TABLE 1. Dam Type Selection and Key Factors**

Dam type and key features	Typical potential failure modes	Key factors and considerations	Key design and mitigation measures
<p><b>Homogeneous embankment dams</b></p> <ul style="list-style-type: none"> <li>Constructed of a single low permeability material; may have a pervious zone on the downstream toe</li> <li>Relies on erosion resistance of impervious material</li> <li>More common for small dams</li> <li>Better suited than a concrete dam to soil/gravel foundations and foundations likely to settle/deform (that is, of variable stiffness)</li> <li>Homogeneous earthfill dams can incorporate additional features to reduce and control seepage, such as upstream geomembrane liner, concrete core wall, and toe drains.</li> </ul>	<ul style="list-style-type: none"> <li>Leakage along crack or defect through core leading to erosion of core and dam failure</li> <li>Internal erosion and formation of pipe through core connecting to reservoir</li> <li>Internal erosion of core material into abutment defects leading to collapse of the core</li> </ul>	<ul style="list-style-type: none"> <li>Whether there is sufficient suitable impervious fill material naturally resistant to piping and internal erosion</li> <li>The vulnerability of selected materials to erosion or piping</li> <li>The durability, compressibility, and permeability of the fill material to limit settlement and control seepage</li> <li>Care in the use of dispersive soils</li> <li>Foundation material strength and potential defects</li> <li>Foundation shape—avoid steps and sharp changes in grade that could initiate cracks in the dam core</li> <li>Need for foundation treatments at the embankment contact</li> <li>Appropriate design of filter and drainage materials to prevent piping and control drainage of seepage</li> </ul>	<ul style="list-style-type: none"> <li>Adequate drainage within the dam and at the toe of the dam to prevent the downstream shoulder from becoming saturated</li> <li>Grout curtain or cutoff to control seepage through the foundation</li> <li>Foundation soil strengthening through grouting or deep soil mixing process (machine mixing of soil with grout)</li> <li>Stability buttress against downstream face if slope is potentially unstable</li> <li>Filter buttress against downstream face if piping risk through dam is too high</li> </ul>
<p><b>Zoned embankment dams</b></p> <ul style="list-style-type: none"> <li>Constructed with a low permeability zone (core) and earthfill or rockfill shoulder zones of higher permeability</li> <li>Core zone of low-permeability earth, silty gravel, asphalt, concrete, or geomembrane</li> <li>Typically include filter zones to prevent internal erosion of the core</li> <li>Drainage zones to control seepage</li> <li>Alternative form utilizes upstream impervious face of asphalt, concrete, or geomembrane</li> </ul>		<ul style="list-style-type: none"> <li>Select construction materials that will not naturally cement</li> <li>Risk of contamination or segregation of filters and drains through poor production or placement techniques</li> <li>Construction practices that prevent defects in the dam, such as near-horizontal preferential seepage paths that allow high seepage flows and velocities or high internal pressures</li> <li>Prevention of preferential paths for seepage and erosion at the abutments</li> </ul>	<ul style="list-style-type: none"> <li>Compatibility among zones and against foundation to prevent internal erosion and piping</li> <li>Adequate drainage within the dam and at the toe of the dam to prevent the downstream shoulder from becoming saturated</li> <li>Grout curtain or cutoff to control seepage through the foundation</li> <li>Foundation soil strengthening through grouting or deep soil mixing process (machine mixing of soil with grout)</li> <li>Stability buttress against downstream face if slope is potentially unstable</li> <li>Filter buttress against downstream face if piping risk through dam is too high</li> </ul>

*table continues on the next page*

TABLE 1. continued

Dam type and key features	Typical potential failure modes	Key factors and considerations	Key design and mitigation measures
<p><b>Concrete gravity dams</b></p> <p>Rely on the weight of concrete to retain the reservoir. Typically built on moderately strong to strong rock. Construction techniques include:</p> <ul style="list-style-type: none"> <li>• Conventional concrete gravity dams constructed with mass concrete</li> <li>• Roller compacted concrete dams (RCCs) constructed with road-building equipment</li> <li>• Hardfill dams constructed from cemented sand and gravel with a watertight concrete face</li> </ul>	<ul style="list-style-type: none"> <li>• Sliding on foundation/rock interface of subhorizontal defect plane in the foundation</li> <li>• Overturning caused by weak foundation strength</li> <li>• Sliding on defect in dam concrete</li> <li>• Expansion of concrete aggregates leading to degradation of dam body</li> <li>• Abutment failure</li> <li>• Piping of joint infill in foundation rock leading to uncontrolled leak from reservoir</li> <li>• Structural failure of upstream slab of buttress dam</li> </ul>	<ul style="list-style-type: none"> <li>• Potential deformation of foundation</li> <li>• Whether erodible foundation discontinuities are present in the foundation rock and present a leakage or stability risk</li> <li>• Whether subhorizontal planes of weakness are present in the foundation rock and whether they can be treated</li> <li>• Permeability of foundation rock and treatment plan</li> <li>• Effective internal drainage systems to reduce uplift pressures</li> <li>• Longevity of concrete material over lifetime of the structure—in particular, durability and reactivity of aggregates (avoid alkali-silica reactivity)</li> <li>• Joint treatments and watertightness of the upstream face</li> <li>• Temperature effects from uncontrolled heat of hydration; consider low heat cements and pozzolanic materials</li> </ul>	<ul style="list-style-type: none"> <li>• Grout curtain or cutoff to control seepage through the foundation.</li> <li>• Adequate drainage behind the grout curtain at the heel of the dam to prevent the high uplift pressures</li> <li>• Treatment of leakage paths in the foundation with cutoff shafts, mass concrete, and grouting</li> <li>• Removal of unstable blocks of rock in the foundation and replacement with mass concrete</li> <li>• Internal drainage of the concrete to prevent high pressures in the dam concrete</li> <li>• Water stops to prevent leaks through dam block joints</li> <li>• Mass concrete stability buttress against downstream face if dam is vulnerable to sliding on the foundation interface</li> <li>• Drainage systems to remove water from within the dam gallery system</li> <li>• Drainage and buttress of abutment if found to be unstable</li> </ul>
<p><b>Concrete buttress dams</b></p> <ul style="list-style-type: none"> <li>• Constructed of an upstream concrete face supported at intervals by a series of concrete buttresses</li> <li>• Typically built on moderately strong to strong rock</li> </ul>	<ul style="list-style-type: none"> <li>• Failure of wedge of rock in abutment removing support for arch</li> <li>• Excessive deformation of abutment leading to failure of arch concrete</li> <li>• Failure of arch dam at a defect in dam concrete</li> <li>• Expansion of concrete aggregates leading to degradation of dam body</li> <li>• Piping of joint infill in foundation rock leading to uncontrolled leak from reservoir</li> </ul>	<ul style="list-style-type: none"> <li>• Whether rock discontinuities are present that could form failure wedges or leakage paths and whether they can be treated</li> <li>• Whether the stiffness of the abutment rock is sufficient to control abutment deformation under dam loads to support arch dam and prevent failure</li> <li>• Whether the abutments and foundation can withstand high hydraulic gradients around the dam base; consider treatment options, for example, grouting</li> <li>• Whether erodible foundation discontinuities are present in the foundation rock and present a leakage or stability risk</li> <li>• Longevity of concrete material over the lifetime of the structure; in particular, durability and reactivity of aggregates</li> <li>• Joint treatments and watertightness of the upstream face</li> <li>• Temperature effects from uncontrolled head of hydration; consider low heat cements and pozzolanic materials</li> </ul>	<ul style="list-style-type: none"> <li>• Grout curtain or cutoff to control seepage through the foundation</li> <li>• Adequate drainage behind the grout curtain at the heel of the dam to prevent high uplift pressures, although less critical than for concrete gravity dams</li> <li>• Treatment of leakage paths in the foundation with cutoff shafts, mass concrete, and grouting</li> <li>• Removal of unstable blocks of rock in the foundation and abutment and replacement with mass concrete</li> <li>• Water stops to prevent leaks through dam block joints</li> <li>• Stiffening of abutments with grout or shafts and tunnels to reduce abutment deformation under load</li> <li>• Shear keys in abutments to prevent movement of rock blocks</li> <li>• Drainage and buttress of abutment if found to be unstable</li> </ul>
<p><b>Arch dams</b></p> <ul style="list-style-type: none"> <li>• Thin shell of concrete that uses arch shape to hold reservoir by transferring loads to the abutment through the dam shell</li> <li>• Typically requires hard rock and narrow valley shape</li> <li>• Arch dam design is complex and requires a high level of specialization</li> </ul>	<ul style="list-style-type: none"> <li>• Failure of wedge of rock in abutment removing support for arch</li> <li>• Excessive deformation of abutment leading to failure of arch concrete</li> <li>• Failure of arch dam at a defect in dam concrete</li> <li>• Expansion of concrete aggregates leading to degradation of dam body</li> <li>• Piping of joint infill in foundation rock leading to uncontrolled leak from reservoir</li> </ul>	<ul style="list-style-type: none"> <li>• Whether rock discontinuities are present that could form failure wedges or leakage paths and whether they can be treated</li> <li>• Whether the stiffness of the abutment rock is sufficient to control abutment deformation under dam loads to support arch dam and prevent failure</li> <li>• Whether the abutments and foundation can withstand high hydraulic gradients around the dam base; consider treatment options, for example, grouting</li> <li>• Whether erodible foundation discontinuities are present in the foundation rock and present a leakage or stability risk</li> <li>• Longevity of concrete material over the lifetime of the structure; in particular, durability and reactivity of aggregates</li> <li>• Joint treatments and watertightness of the upstream face</li> <li>• Temperature effects from uncontrolled head of hydration; consider low heat cements and pozzolanic materials</li> </ul>	<ul style="list-style-type: none"> <li>• Grout curtain or cutoff to control seepage through the foundation</li> <li>• Adequate drainage behind the grout curtain at the heel of the dam to prevent high uplift pressures, although less critical than for concrete gravity dams</li> <li>• Treatment of leakage paths in the foundation with cutoff shafts, mass concrete, and grouting</li> <li>• Removal of unstable blocks of rock in the foundation and abutment and replacement with mass concrete</li> <li>• Water stops to prevent leaks through dam block joints</li> <li>• Stiffening of abutments with grout or shafts and tunnels to reduce abutment deformation under load</li> <li>• Shear keys in abutments to prevent movement of rock blocks</li> <li>• Drainage and buttress of abutment if found to be unstable</li> </ul>

Investigations can be costly, but it is highly important to invest time and money in a phased manner to avoid surprises, even though it may be difficult to convince the client to spend money at the early project preparation stage. Investigation costs will depend on the complexity of the site and the nature of materials available. The risk rating of the structure should also be a factor in prudent investment in investigation to protect downstream communities. The greater the investment in well-planned investigation, the more likely geotechnical risks can be identified and mitigated, rather than being the reason for cost overruns later in the project. Major changes to design have occurred following the discovery of unforeseen ground conditions at some projects.<sup>2</sup>

It is also worth noting that investigation costs are often dominated by the cost to access the site and mobilize the equipment. The incremental costs of additional investigations once the initial investment has been made may be low relative to the access costs.

Most investigation programs are completed in a series of separate stages with the following objectives:

- *A prefeasibility investigation* to gain sufficient information for the planning of a feasibility investigation. At this stage the project would likely identify possible dam sites, dam types, or possible remedial measures. The dam's setting would be established in the regional geological and geomorphological context. Site reconnaissance, Google Earth, satellite images, regional geological mapping, and data searches would be used, but there may not be significant physical site investigations until a preferred site has been selected and a preferred dam type determined. It is important at the early stage to have technical experts visit the proposed site to assess its suitability.
- *A feasibility investigation* to identify the preferred solution, confirm the technical feasibility of the preferred solution, and estimate the cost of project development. At this stage the site conditions would be established and local hazards identified. With a site identified, Lidar imagery provides baseline topographic detail that an experienced geologist can use to identify potential faults and landslides. Geological mapping and an initial subsurface investigation (boreholes, permeability test, geophysical investigation, and laboratory testing of samples) would be expected. These investigations would focus on identifying geological hazards in the dam foundations and surrounding vicinity, the presence of suitable construction materials in volumes necessary for construction, and whether dam and reservoir hazards are present.
- *A design investigation* to determine specific details of the site and the materials for construction, and to address any outstanding issues raised by earlier investigations. Targeted physical investigations using boreholes, geophysical investigation, and laboratory testing of samples would be expected to carefully assess features, defects, and anomalies for the dam foundation and spillway location, the geotechnical properties (strength, gradation, compressibility, compatibility, and permeability) of the foundation and the construction materials, and the threat posed by any active faults and reservoir slope hazards.

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<sup>2</sup> Research of 40 dams in Australia built between 1888 and 2012 showed consequential project cost overruns of 49 percent (median) and 120 percent (mean) of the dam cost (estimated immediately prior to construction), with ground conditions being significant contributors to the overruns (Petheram and McMahon 2019).

The geotechnical investigation technique and purpose at different stages are summarized in table 2. ICOLD (2005) also provides an overview of investigation techniques to address geological situations.

All investigation programs should be progressively implemented to ensure that all unknowns are properly identified and addressed. An appropriate process for the completion of an investigation program involves:

1. Clearly defining the investigation objectives
2. Reviewing existing information and the identification of information gaps
3. Planning an investigation program

**TABLE 2. Phased Geotechnical Investigation Technique and Purpose**

	<b>Investigation technique</b>	<b>Purpose</b>
<b>Prefeasibility investigation</b>	<ul style="list-style-type: none"> <li>• Site reconnaissance</li> <li>• Google Earth</li> <li>• Satellite images</li> <li>• Regional geological mapping</li> <li>• Data searches</li> </ul>	<ul style="list-style-type: none"> <li>• Nature of ground conditions, typography, and so forth</li> <li>• Site access, land use</li> <li>• History of area, previous investigations</li> <li>• Geological lineaments, potential faults, potential landslide features</li> <li>• Rock types at dam site</li> <li>• Available construction materials</li> </ul>
<b>Feasibility investigation</b>	<ul style="list-style-type: none"> <li>• Site reconnaissance</li> <li>• Topographic survey/mapping</li> <li>• Geological mapping</li> <li>• Borehole drilling</li> <li>• Down-hole water tests</li> <li>• Trenching</li> <li>• Test pits</li> <li>• Geophysical investigation (seismic refraction, electric resistivity, radar, and so on)</li> <li>• Laboratory/in situ tests (such as UCS (unconfined compressive strength), triaxial shear test, and direct shear test)</li> <li>• Rock mass classification</li> </ul>	<ul style="list-style-type: none"> <li>• Nature of ground conditions</li> <li>• Typography, landforms</li> <li>• Identification of shears and faults crossing site</li> <li>• Subsurface exploration of dam site</li> <li>• Permeability of foundation</li> <li>• Geological features such as faults</li> <li>• Foundation conditions and materials for construction</li> <li>• Subsurface conditions (boundaries of materials and weathering profiles)</li> <li>• Engineering properties of materials (foundation and construction materials)</li> <li>• Engineering properties of rock</li> </ul>
<b>Design investigation</b> Carefully assess features, defects, and anomalies for the dam foundation and spillway location and the threat posed by any active faults and reservoir slope instability	<ul style="list-style-type: none"> <li>• Boreholes drilling with core recovery or downhole acoustic logging</li> <li>• Permeability (Lugeon) tests</li> <li>• Geophysical investigation (for example, seismic lines)</li> <li>• Laboratory testing of samples</li> <li>• Aerial photo reconnaissance, Lidar imagery, and satellite imagery</li> </ul>	<ul style="list-style-type: none"> <li>• Identification of depths of weathering, change of materials, and defects in foundation</li> <li>• Permeability of foundation for grouting or cutoff design</li> <li>• Foundation material zones</li> <li>• The geotechnical engineering properties (strength, gradation, compressibility, compatibility, and permeability) of the foundation and the construction materials</li> <li>• Identification of potential landslides and active faults</li> </ul>

4. Implementing the investigation program
5. Reviewing the investigation results and following up findings with further investigations if necessary
6. Interpreting and documenting the investigation findings

Determining responsibility for geological risks is notably important when preparing the contract for construction. It is likely to vary depending on the type of contract. The International Federation of Consulting Engineers (FIDIC) Red Book contract is normally used when the designer is engaged by the client. It assigns geological and geotechnical risks differently from the FIDIC Silver Book contract for Engineer, Procure, Construct (EPC). FIDIC Emerald Book (2019) also provides the risk allocation mechanism related to unforeseen ground conditions, particularly for tunnelling projects.<sup>3</sup>

Investigations should be undertaken by appropriate and competent geologists and engineers who are skilled in the type of structure and the type of geological conditions expected at the site. Geologists will carry out the field activities, map the site, and identify hazards. They should be skilled in dam investigations rather than other fields such as mining or road works. Engineers need to be experienced in dam design and dam engineering, rather than other fields of engineering, to use the geotechnical properties for dam design. It is important that the engineers develop a clear understanding of the geological model delivered by the geologists.

### **Geotechnical Reports and Baselines**

Documenting geotechnical information is vital to ensure that developing knowledge of the project geology, hydrogeology, natural hazards, and engineering materials is being retained for the record and passed on to other parties participating in the project. This approach will reduce the risk of errors and omissions as the project advances. Furthermore, documented geotechnical details become the baseline evidence during contractual disputes between the constructor and the dam owner.

A geological summary report may be sufficient for low-risk dams that are on relatively straightforward foundations and constructed of reliable materials. The report should describe the site in the context of regional geology, the specifics of site geology, and any known geological hazards that could affect the site (for example, faults or landslides). This information should be available from regional maps, satellite imagery, site inspection, and preliminary site investigations such as test pits.

The following are logical allocations of documentation for high-risk dams, those on complex foundations, or those constructed of challenging materials. The purpose and recommended content of

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<sup>3</sup> FIDIC (2017a) is known as the Red Book, FIDIC (2017b) is known as the Yellow Book, and FIDIC (2017c) is known as the Silver Book. The Emerald Book provides a standard-form contract that caters to the specificities of the tunnelling industry providing provision for the risk allocation mechanism of unforeseen ground conditions between contractual parties and disclosure of geological and geotechnical information with the use of the Geotechnical Baseline Report (GBR). This key document sets out the allocation of risk between contractor and employer for subsurface physical conditions in providing the contractual definition of foreseeable conditions. The Emerald Book also provides a more flexible mechanism for completion time delay and price adjustment related to ground conditions as well as multistage dispute resolution mechanism.

geotechnical reports is described in ASCE (2007). This document structure originated in the tunnelling industry to reduce the instances of expensive contract disputes over ground conditions. Dam projects have many geotechnical risks that, in the contract environment, have the potential for expensive contract disputes as well. Hence, the similar approach of report presentation is recommended for dam projects and fits well with FIDIC-type contract documents (FIDIC 2017 a, b, and c).

The following are more-specific geotechnical reports that would be required and useful for large construction contracts and / or high-risk dams.

- *Geotechnical Data Reports (GDRs)*, prepared by geologists, are factual reports containing raw data such as borehole logs and laboratory results. If geotechnical hazards are known, they should also be included. GDRs are intended to provide enough information to reduce the risk for projects and transfer information to the contractor.
- *Geotechnical Baseline Reports (GBRs)*, based on GDRs prepared by geologists, are instrumental in defining anticipated ground conditions during contract pricing. When the GBR is part of the construction contract, it sets the range of adverse physical ground conditions that ought to be provided for and included in the contract price. The GBR should provide a summary of anticipated ground and groundwater conditions of a potential work site for the purpose of understanding the risk for preparing proposals and bids for projects. The GBR may save construction costs and minimize disputes in unforeseen ground conditions.
- *Geotechnical Interpretative Reports (GIRs)* are prepared by a team of qualified engineers and geologists to apply the factual report to geotechnical analysis. Expert judgment is necessary in developing conclusions in these reports.

The geologist should focus on geological information (description and foundation parameters) and identification of geological hazards and conditions to be expected. The design of the dam is carried out by the engineer, who should pay close attention to the engineering properties of the materials being investigated. Once the dam foundation has been stripped and exposed, the excavation findings should be compiled into a report and compared with the GBR.

Preparation of these reports is a good opportunity to build capacity in local engineering and geological institutions and their staff.

The detail and availability of these reports should consider the construction contract model. Contract documents should clearly express the risk allocated to the dam owner and to the contractor. In a unit rate contract, the usual risk-sharing principle is that ground condition risk is carried by the owner and production rates are within the risk sphere of the contractor. Therefore, any unexpected ground condition requiring greater excavation, ground treatment, structural support, or replacement not identified in the design will be the dam owner's cost to pay. An adequate amount of contingency should be allocated to provide the financial means to address unexpected conditions. The geotechnical reports should



identify what is known and therefore informs the contractor of the conditions to expect. If the dam owner has strong internal capacity and a capable designer, then the GBR information is desirable as a baseline for contractual claims of unforeseen ground conditions. Challenging ground conditions would make the GBR far more important than a site with a consistent good-quality dam foundation. Strong capability within the owner and their designer is more important when more complex site conditions are present.

If the dam owner cannot manage the contract, they should engage an experienced owner's engineer for assistance. A panel of experts including a geologist/geotechnical specialist and potentially including experts with construction supervision and contract management expertise may be considered for high-risk dams with complex geotechnical conditions. The dam owner may wish to transfer the ground condition risk by using a lump sum contract, design/build contract, engineer, procure, construct (EPC), or turnkey contract, but the dam owner needs to understand and accept that in these cases the contractor will either include a large amount of contingency in the lump sum price or insist on investigating the site themselves before providing a fixed price. For these contracts, it is especially important to hand over all geotechnical investigation information (that is, GDR, GBR, and any GIRs) compiled by the owner before negotiating the contract. It is then up to the contractor to satisfy themselves of the geotechnical risks on the site.

## Geotechnical Risk Register

A Geotechnical Risk Register (GRR) is recommended for every project. The GRR shows the degree of risk attached to various ground-related aspects of the project. The purpose of the GRR is to provide an assessment of the risk to the project posed by ground- or construction material-related problems and identify suitable mitigation measures that would control the risk to an acceptable level. The risk register should be developed and refined as the geotechnical design and assessment progresses. Guidance on development of GRRs is presented in several references, including ICE (2001).

The degree of risk (R) is determined by combining an assessment of the probability (P) of the hazard occurring with an assessment of the impact (I) that the hazard<sup>4</sup> will cause if it occurs ( $R = P \times I$ ). Table 3 shows the scale against which the probability and impact are measured and the resulting degree of risk determined.

Table 4 provides an example risk register for a concrete dam with an embankment saddle dam.

A probability of “very unlikely” indicates a condition that the available data suggests should not be present. The inclusion of a risk in the register does not constitute confirmation that the problem exists at the site, but it identifies the risk that the mitigation will be required to enable the project to progress.

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<sup>4</sup> Whilst hazard is used as a measure of consequences in case of dam failure as per dams engineering practice in other sections of this Technical Note, hazard is here defined as a threat or condition that may result from external cause (for example, an earthquake or flood) or internal vulnerability.

**TABLE 3. Geotechnical Risk Classification**

		Impact				
		Very low	Low	Medium	High	Very high
Probability	Very likely	Minor	Moderate	Major	Severe	Severe
	Likely	None/negligible	Minor	Moderate	Major	Severe
	Possible	None/negligible	Minor	Minor	Moderate	Major
	Unlikely	None/negligible	None/negligible	Minor	Minor	Moderate
	Very unlikely	None/negligible	None/negligible	None/negligible	None/negligible	Minor

**TABLE 4. An Example Risk Register of a Concrete Dam with an Embankment Saddle Dam**

Feature	Condition	Hazard	Before control			Comments and proposed mitigation	Residual risk once mitigated
			Probability	Impact	Risk		
<b>Foundation of concrete dam</b>	Horizontal defect	Sliding	Likely	Very high	Severe	Extensive bedding plane. Excavate shear key and backfill with concrete to prevent sliding.	Minor
<b>Saddle dam body</b>	Incompatible zones	Piping of fill material	Likely	Very high	Severe	Difficult to detect. Install granular filters to stop erosion.	Minor
<b>Saddle dam Foundation</b>	Steps in foundation	Differential settlement	Likely	Very high	Severe	Reflective cracking in dam body providing route for leak and piping of embankment. Avoid steps. Install granular filters to fill cracks and stop erosion.	Minor
<b>Concrete dam Foundation</b>	High permeability zones	High uplift pressure	Likely	High	Major	Uplift decreases stability. Install grout curtain and drainage curtain.	Minor
<b>Concrete dam abutment</b>	Low modulus of deformation	Excessive deformation	Unlikely	Very high	Major	Deformation leads to cracking or instability. Stiffen abutment or change dam type.	Minor
<b>Reservoir</b>	Landslide	Impulse wave	Unlikely	High	Minor	Ancient landslide feature unlikely to reactivate.	Minor

Investigation should lead to design of mitigation measures to reduce significant geotechnical risks. Should the employer realise that objective difficulties and schedule constraints have not allowed to do that satisfactorily, it can include provision for a condition delay event (CDE) in the contract. CDE process is as follows:

- During the mobilization period, the contractor carries out additional investigations and conveys their results to the employer with proposed design modifications.
- The employer reviews the submission and instructs the contractor on what to implement or not.
- Conclusions are summarized in a report and the contract’s bill of quantities (BoQ) is revised accordingly.

Construction may still uncover previously unidentified geotechnical issues. It is important that issues are addressed whenever identified. Such geotechnical issues should be addressed by design changes or application of contingency measures planned in advance of construction. Contracts should allow for changes in response to geotechnical risks identified during construction. Associated contractor's claims would be managed according to contractual provisions.

If conditions are shown to be unacceptable through these means, then further mitigation measures may be necessary to address remaining safety issues. These measures might include:

- Improved drainage to relieve pressure and filters to control seepage gradients
- Remedial grouting to reduce pressure or leakage
- Lowering the reservoir level to reduce load on the dam or reduce the potential consequence downstream of the dam
- Constructing buttresses to prevent further deformation

The acceptable residual risk after the identified risk has been mitigated would depend on the potential economic impacts on the project and downstream consequence considering the dam's risk category. The residual risks may be addressed by:

- Surveillance, instrumentation, and monitoring during construction, commissioning, and operation of dams
- Operation and maintenance (O&M) procedures suited to the dam and documented in an O&M plan
- Readily available Emergency Preparedness Plans (EPPs)

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