Geology 101 – Dam Good Foundations

Introduction

The behavior and performance of manmade structures (buildings, dams, roads, tunnels, etc.) depend on the foundation that supports them. A foundation is formed by existing geology at the site. Being familiar with geology and being able to identify the foundation's rock or soil type assists in developing an understanding of what types of issues should be considered when designing, constructing, modifying, or repairing a structure.

Understanding how to deal with issues related to geology can prevent costly mistakes. (What makes the situation better, what makes it worse?) What are the limitations of different soil and rock types?

Figure 1 - Leaning Tower of Pisa

Recognizing basic geologic conditions can help evaluate how dams will behave with respect to seepage, settlement, slope stability, piping, and other problems that affect dams.

Civil engineers like Terzaghi, Peck, and Leggett, recognized that major engineered structures were constrained by the foundations they were placed upon or the materials available for their construction. It could be argued that these men coined the term "Engineering Geologist", which is a way to differentiate the study of geology as it is applied to the use of earth's natural materials to house (tunnels, pipelines, underground structures), found (structures with shallow to deep foundations), and build (dams, dikes, levees, concrete) engineered structures.

This article is intended as a geologic primer for the basics of geology and geologic principles, different rock and soil types and simple ways to distinguish between them, and potential issues affecting dams as related to different types of geology.

Rock

The three classes of rock are igneous, sedimentary, and metamorphic. Igneous rocks are formed by cooling and crystallization of liquid rock materials and as a result have distinctive texture and composition. Sedimentary rocks form at the earth's surface through the activity of the hydrologic system. Two main types of sedimentary rocks are clastic rocks, consisting of rock and mineral fragments, and chemical or organic rocks consisting of chemical precipitates or organic material. The conglomerate shown in Figure 2 is an example of a clastic sedimentary rock.

Figure 2 - Outcrop of Conglomerate

Metamorphic rocks result from changes in temperature and pressure and the chemistry of pore fluids. Igneous and sedimentary rock can each be subjected to these forces to become metamorphosed.

Minerals are formed by compounds of elements. The most common compounds are silicates, carbonates, oxides, and sulfates. These compounds form hundreds of minerals, but there are a few common rock-forming minerals that can be easily identified in the field to help classify rocks. Silica and feldspar are the most abundant minerals in the upper part of the earth's crust. Using a quartz, alkali, plagioclase (QAP) diagram, the percent of quartz, plagioclase feldspar, and alkali feldspar is estimated and gives the rock type. Figure 3 shows a QAP diagram for intrusive igneous rocks and Figure 4 shows a QAP diagram for extrusive rock.

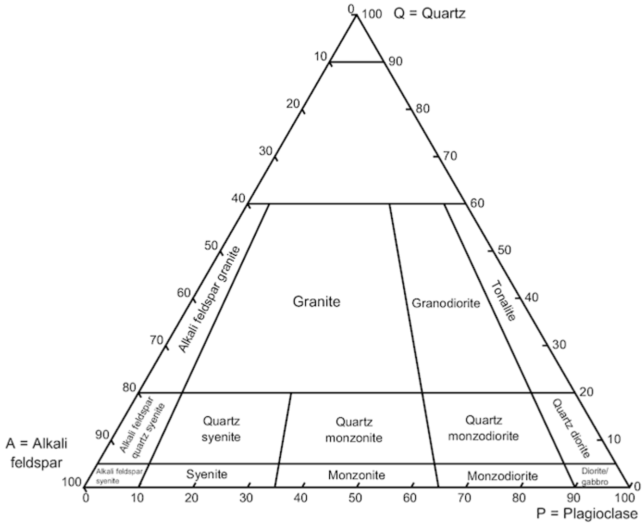

Figure 3 - QAP Diagram for Intrusive Rock

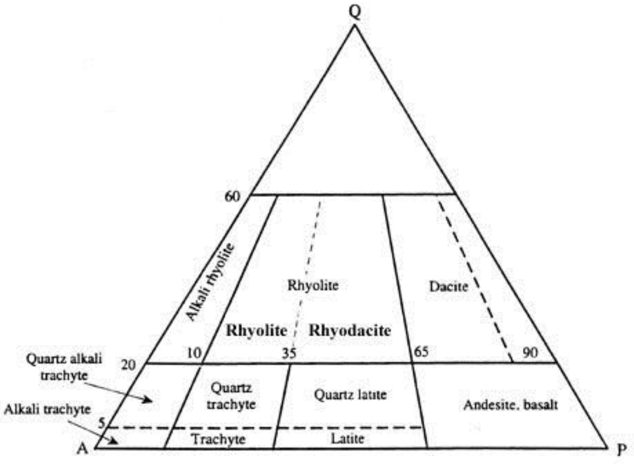

Figure 4 - QAP Diagram for Extrusive Rock

Igneous rocks are an assemblage of crystalline minerals. Igneous rocks started as molten masses of minerals and elements. As these masses moved away from their sources and cooled, the minerals in the mix cooled and solidified into rock. Igneous rocks are classified by whether they cooled below or above the earth's surface and by the texture and type of minerals. Igneous intrusive rocks form below the earth's surface. Igneous extrusive rocks formed as the molten magma cooled at or above the ground surface. Texture of igneous rocks can be fine-grained (aphanitic) or coarse-grained (phaneritic) depending on how quickly the magma cooled. Intrusive rocks, such as granite, diorite, and gabbro, cooled slowly at depth, are medium- to coarse-grained and usually dark colored. Figure 5 shows an example of a coarse-grained granite and a fine-grained basalt.

Sample of Granite

Sample of Basalt

Figure 5 - Examples of Igneous Rocks

A pegmatite is a granitic rock that cooled slowly and allowed feldspar, quartz, and mica crystals to grow large. Although these rocks are beautiful, from an engineering standpoint, they present more problems than rocks with smaller and tighter crystal structures. Figure 6 shows an example of granitic igneous intrusive rock at Half Dome in Yosemite Valley.

Figure 6 - Igneous Rock at Half Dome in Yosemite

Extrusive rocks such as basalt and andesite lava flows cooled fast at the surface, are fine-grained, and are usually dark colored like the basalt flow shown on Figure 7.

Figure 7 - Basalt Flow in Hawaii

Clastic sedimentary rocks, such as conglomerate, sandstone, and shale are formed from the fragments of other rocks. Limestone is an example of an organic sedimentary rock.

Most people who drive on I-70 near Denver will be familiar with the road cut shown on Figure 8. This cut slope exposes an example of a sequence of sedimentary rock that has been tilted from uplift of the Rocky Mountains.

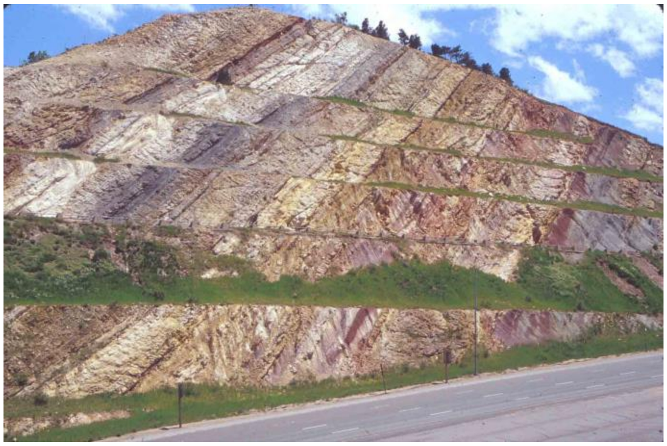

Figure 8 - I-70 Road Cut in Sedimentary Rock just West of Denver

Not all sedimentary rocks are created equal and there are categories of strong rock and weak rock. Throughout the west, many sedimentary rocks were deposited during a time when an inland seaway dominated the area. The rocks deposited in this environment are fine-grained sandstones, limestones, shale, and mudstones. A few examples of these rock types are shown on Figure 9 and Figure 10, respectively.

Sample of Sandstone Outcrop of Limestone

Figure 9 - Examples of Sandstone and Limestone

Thin layers of Shale Blocky Mudstone

Figure 10 - Examples of Shale and Mudstone

Sedimentary rocks are layered or stratified. The layers, or stratigraphy, are called beds and represent changes in the energy in the depositional environment, sediment particle size, sediment composition, or time between deposition of individual beds. Bedding is the most dominant structural feature in sedimentary rock and often has the most significant impact on the engineering properties of the rock. Bedding planes are often the weakest part of sedimentary rocks since they are breaks in the overall rock mass. The degree of consolidation and cementing of particles impact the nature of sedimentary rocks. Older rocks, buried deeply and subjected to great pressures, will be stronger and more resistant than younger rocks not subjected to those forces.

Metamorphic rocks are an assemblage of crystalline minerals, formed when an existing rock, which can be sedimentary, igneous, or even metamorphic, is changed due to heat and pressure. Metamorphic rocks that partially melt often retain minerals and characteristics of the parent rock. During metamorphism, new crystals grow in the orientation of least stress, producing a planar element in the rock called foliation. The three main types of foliation are (a) slately cleavage, (b) schistosity, and (c) gneissic layering or banding as shown on Figure 11. Rocks with only one mineral such as limestone or sandstone do not develop strong foliation but instead develop a granular texture with larger crystals.

Figure 11 - Outcrop of Metamorphic Gneiss (Pronounced "Nice")

Gneiss is identified by its alternating light and dark layers and usually wavy appearance. Quartzite usually resembles sandstone but the sand grains are fused together. Figure 12 shows an example of gneiss and quartzite.

Sample of Gneiss
Sample of Quartzite

Figure 12 - Examples of Metamorphic Rocks

Weathering

Weathering is a process that decomposes all geologic materials into a soil over time. Weathering can be a physical process or a chemical process. Physical weathering occurs when wind, water, waves, ice, and other environmental conditions break down a rock and transform it into soil. This break-down process can occur in-place or it can result in erosion of the rock into particles that are transported and deposited as a soil at some other location. Generally, the properties of soils formed by in-place physical weathering retain some of the characteristics of the parent material.

Chemical weathering occurs when chemical reactions between minerals and other compounds cause disintegration of rock. Exothermic chemical reactions result in an increase in volume that tends to break rocks apart. The most common chemical reactions are hydration, hydrolysis, solutioning and oxidation.

The type of material resulting from chemical weathering is based on the chemical composition of the parent rock and the type of reaction. For example, hydrolysis is the reaction of a mineral with water to produce a new mineral. An example of this is when feldspar reacts with water to form kaolinite – rich clay soil.

The weathering process is very complex and entire books have been devoted to characterizing the properties of weathered rocks and how they behave. Weathered rocks have a wide range of properties and are probably the most difficult material to characterize. As a result, they have been the focus of many financial claims during construction projects. The effects of weathering degrade all rocks that are exposed to these physical and chemical weathering processes, so it is highly likely that most excavations will encounter weathered rock. When dealing with weathered rock, it is important to recognize that engineering properties may change over very short distances and depths. Table 1 presents descriptions for weathered rock and some basic field recognition tests.

Table 1 - Weathering Descriptions and Field Identification

Weathering Description	Field Recognition
Fresh	No discoloration; hammer rings when rock is hit
Slightly Weathered	Surface discoloration only; rock strength unaltered
Moderately Weathered	Discoloration penetrates rock slightly; iron minerals have rusty appearance; rock is slightly weakened
Highly Weathered	Discoloration penetrates throughout rock; iron minerals altered to clay; rock is weak and can be broken by hand or with light hammer blows
Decomposed	Completely discolored, feldspar and iron altered to clay; quartz may be unaltered;, partial rock structure may remain, but mostly resembles soil

Soil

Most soils form from physical processes as material is eroded from one location, transported by wind, water or gravity, and then deposited in a new location. These soil deposits are named based on their depositional environment. Some examples of these materials include alluvium, colluvium, eolian, and glacial drift. There are other depositional environments that have unique types of deposits such as material deposited by landslides or other mass wasting events. Soils formed by deposition will consist of unconsolidated particles of clay, silt, sand, gravel, or boulders depending on the parent material and the depositional environment (i.e., high energy river deposits that have gravels and boulders or low energy marine deposits that have clays and silts).

Alluvium describes materials deposited by moving water. These deposits are stratified layers of clay, silt, sand, gravel, cobble and boulders depending on the energy of the flow. If the flow of water is very fast, the material that is deposited is coarse-grained (gravel, cobble and boulder). If the flow of water is very slow the material deposited is fine-grained (clay and silt).

Figure 13 - Typical Alluvial Fan Deposit. Rock is Eroded from Above and Deposited Below as Soil.

Figure 13 shows an example of an alluviual fan deposit at the mouth of a canyon. In this example, coarse-grained material is deposited near the mouth, where the flow of water is fast and fine-grained material is deposited near the perimeter of the fan, where the flow of water slows and loses energy. Alluvial deposits are heterogeneous and can have interbedded layers of clay and silt within thick beds of gravel and cobble. Due to the action of water and movement of the particles, alluvial deposits are characterized by an assemblage of sub-rounded to rounded particles. Some typical engineering properties of alluvium are listed below:

Coarse-grained alluvium

- Highly permeable
- Good source of aggregate
- Good bearing capacity in gravel and cobble
- Low shrink and swell potential
- Sand deposits can be liquefiable

Fine-grained alluvium

- Low permeability
- Low bearing capacity
- High shrink and swell potential
- Low shear strength

Colluvium describes material deposited by gravity. Weathered rock and soil can creep slowly downslope by gravity or material can be deposited relatively quickly as blocks of rock and other lithic fragments fall to the bases of slopes and are incorporated into a matrix of material. The matrix of material at the base of a slope can be coarse-grained or fine-grained. Coarse-grained deposits are sometimes called tallus. Colluvium is a heterogeneous deposit that usually consists of a random mixture of large fragments of rock in a fine-grained matrix that can be composed of material ranging from sand to clay. Since colluvial deposits have been transported relatively short distances, the larger particles, or clasts, are characteristically angular to sub-angular. A few typical engineering properties of colluvium are listed below.

- Extremely heterogeneous
- Usually contains large rock fragments
- Usually at natural angle of repose; cut slopes can be unstable
- Can have tendency to move
- Coarse deposits are usually difficult to excavate

Eolian soils are deposited by wind. These soils are usually composed of sand and silt sized particles. The coarser sand sized particles can form dunes such as the dunes found in the Mojave Desert in California. The fine-grained silt (loess) stays suspended in the air longer than the sand, and as a result, loess deposits usually accumulate down-wind of dunes and other arid desert environments. Some engineering properties of eolian soils are listed below:

- Prone to hydro-collapse
- Can be liquefiable
- Poor resistance to erosion
- Sand deposits can be a source for fine aggregate
- Low expansive
- Easy to excavate

Glacial drift is a general term that describes material deposited by glaciers. There are many terms used to describe the particular deposits from glaciers, but the two main modes of deposition are either directly from the glacial ice (these deposits are called till), or from streams of melt water (these deposits are called outwash).

Generally, glacial till is deposited when the glacier retreats and dumps sediment as ice melts. This sediment, sometime called moraine, is defined by where it was deposited. For example, terminal moraine is deposited at the furthest downstream front of the glacier as it begins to retreat; lateral moraine describes the material deposited on the sides of the glacier as it retreats. Glacial till is extremely heterogeneous, non-stratified, poorly sorted, and contains particles of all sizes that are angular to sub-rounded.

Glacial outwash deposits are similar to alluvial deposits and consist of stratified gravel and sand layers. Due to transport by flowing water, these deposits have well-sorted and rounded to sub-rounded particles.

Some engineering properties of glacial drift are listed below.

Glacial Till

- Permeable to highly permeable
- Extremely heterogeneous mix
- Good source of aggregate
- Difficult to excavate
- Good bearing capacity

Glacial outwash

- Highly permeable
- Can be liquefiable
- Good source of fine aggregate
- Good bearing capacity
- Low shrink and swell potential

Dam Issues Related to Geology

Rock Foundations

In most cases, foundations composed of igneous or metamorphic rocks are well-suited for construction of embankment dams. Igneous and metamorphic rocks are generally much stronger than the soil materials used to construct embankment dams. The stability of foundations and abutments for igneous or metamorphic foundations are mostly a function of the degree of jointing and weathering. Geologic investigations for rock dam sites focus the potential effects of those features on the structures.

Perhaps the most significant problem associated with embankment dams with foundations composed of igneous or metamorphic rocks is related to seepage. Seepage could simply be a water loss problem and not necessarily a dam safety issue when the reservoir basin and abutments cannot hold water. Additionally, when an earthen embankment is constructed on top of a fractured bedrock foundation, care must be taken to prevent internal erosion and piping. When fractures and joints in the foundation are wide enough and continuous, seepage passing through the embankment becomes concentrated into these rock defects. This concentrated seepage induces high seepage velocities/forces that can lead to mobilization (internal erosion) of the overlying embankment material into the foundation. This condition was not well recognized by early dam engineers and has become a prominent failure mode during risk assessments of older dams.

Problematic types of sedimentary rock for dam foundations include shales, mudstones, and other fine-grained rocks. One of the reasons fine-grained sedimentary rocks are problematic is the relatively low strength material that composes them. Geologically young, clay-rich fine-grained sedimentary rock found in much of the west has the tendency to slake. Slaking occurs in fine-grained sedimentary rocks when they are exposed to air. Slaking essentially causes a rock to deteriorate and breakdown. Some types of shale and mudstones begin to slake immediately after they are exposed to air. With shale, the process of slaking usually results in cracking along thin shale layers causing the layers to open like pages in a book. With mudstones, slaking usually results in cracks forming throughout the mass of rock eventually causing the rock to break up into small cubes.

Not all shale deposits and mudstones behave this way. Investigations must be performed on these materials to test how they will behave and perform as a dam foundation. Depending on the chemical composition and minerals that form the rock, the effects of slaking can be severe or hardly noticeable. The Bureau of Reclamation has a procedure that can be used to test if a material is prone to slaking. (Bureau of Reclamation, Engineering Geology Manual, page 80). Rocks whose samples show signs of slaking behavior during testing will need to have special treatments during construction to prevent slaking. Figure 14 shows a sign of a significantly slaked mudstone.

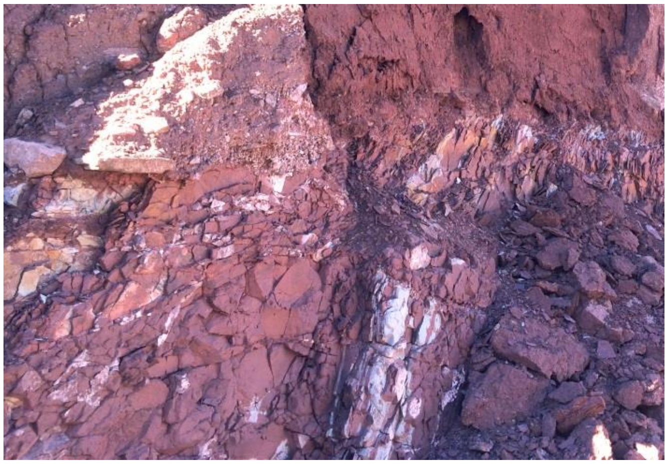

Figure 14 - Effects of Slaking on Mudstone

Soil Foundations

The fundamental characteristics of soil deposits that form dam foundations include plasticity, density, and gradation, which in turn influence the foundation's strength, permeability, compressibility (including settlement and collapse), and dispersiveness/erosiveness. (See our previous article, "Soil Characterization – Here's the Dirt (Part 1)" for more information.) Problems associated with dams founded on deposits of alluvial, colluvial, eolian and glacial soils are related to the soils' permeability and initial degree of consolidation or density. Low density, soft, or loose soils of all types can settle when extra weight is added on top of them. Differential settlement across a valley with irregular steps in the foundation, or between materials with different densities, can result in cracks in the embankment, and cracks in rigid structures such as outlet works, spillways, valve structures, and vaults. Settlement can also gradually lower the crest elevation, which would reduce the available freeboard. Removal of soft soils or densification of soft soils may be needed at sites where excessive settlement is expected to occur.

Stability is also a concern when constructing a dam on soil. The shear strength of very soft to soft soil is less than that of the compacted material used to build the embankment. This condition results in shear surfaces that will pass through the foundation causing slides, slumps, and cracks in the embankment. To mitigate for this situation, soft foundation soils should be removed. The slopes of the embankment can also be flattened, increasing the footprint of the dam, which moves greater shear strength into the foundation, thereby improving stability.

Deposits of sand, gravel, and cobble are often adequate foundation materials with respect to support of the embankment; however, the major problems associated with these materials include their higher permeability and potentially open matrix. High permeability foundations can lead to excessive seepage, high gradients, and uplift pressures. Open matrix deposits are similar to open fractures in rock and must be isolated from or made filter compatible with the embankment materials they support to prevent internal erosion and/or piping from damaging the embankment or leading to failure.

Seepage and water loss through the foundation can also be an economic problem. Dams that store water intended for irrigation, drinking water, industrial, or commercial uses may not be able to tolerate high water losses. In these cases, porous foundation materials should be removed or treated with low permeable synthetic or clay liners or cutoffs.

Loose, low density, saturated sand, and silt deposits subjected to earthquake loading have the potential to liquefy and lose strength. Liquefaction of foundation soils can lead to slope stability and settlement issues that are similar to the issues related to soft, low density soil foundations. These issues include settlement and loss of crest height that could result in a breach of the dam. Near surface liquefiable material should be removed from the dam foundation. These types of materials should be evaluated by a professional dam engineer.

The above discussion describes only a small selection of foundation problems to be considered in the evaluation and repair of existing dams and the design and construction of new dams. Projects located in varied geologic settings can benefit from the participation of professional geologists, engineering geologists, and/or geological engineers.

Case Histories

QUAIL CREEK DAM AND RESERVOIR

Quail Creek Reservoir is located in the southwestern part of Utah near Saint George. The reservoir is formed by a main dam and dike. On January 1, 1989, the 78-foot-tall dike failed and released 25,000 acre-feet of water causing approximately 12 million dollars in damage (Carlson, D.D. and Meyer, D.F. 1989).

The foundation of the dike was formed by sedimentary rocks deposited in a marine tidal flat environment and consisted of alternating, thin beds of gypsiferous siltstone, sandstone, gypsum, and dolomite (Robert James, J. et al. 1989). The geology was complex, and the rock was described as very weathered, highly fractured, faulted, and folded. **Figure 15** is an aerial photograph after the failure of the dike that scoured soils away exposing the underlying bedrock.

Figure 15 - Quail Creek Dike

Upon first filling of the reservoir, seepage began to flow immediately through the foundation. The response to the seepage was a grouting program and installation of an unfiltered rock toe drain. Three different phases of grouting were done between 1986 and 1988. On December 31, 1988, brown, discolored seepage was observed flowing at about 200 to 300 gallons per minute. A filter was constructed over the seepage area, but ultimately the flow was too great and a backwards piping erosion failure mode caused portions of the embankment to collapse, causing a catastrophic failure.

After the failure occurred, an investigation revealed that although the complexity of the foundation geology was known ahead of time, proper treatment of foundation defects, such as openings and voids along bedding planes, was not used during construction. Figure 16 shows an example of some of the openings along bedding at Quail Creek Dike. In addition to the nature of the foundation defects, the orientation of bedding played important role in the failure. As shown above in **Figure 15**, the orientation of bedding is perpendicular to the axis of the dike which allowed continuous, downstream pathways for foundation seepage.

Figure 16 - Openings along Bedding Planes

Perhaps the most significant deficiency that led to breach of the dike was the failure to provide adequate filters to protect the core of the dam from internal erosion and piping into and along the foundation. The investigation of the failure concluded that several adverse conditions existed that contributed to breach of the dike. The conditions included:

- Open joints along bedding planes were not treated during construction and allowed an unfiltered seepage path with a direct connection with the reservoir.

- Unprotected, erodible core material was placed directly on a poorly treated, weathered, jointed, and (in places) soluble foundation.
- The initial response of foundation grouting to address seepage observed during first filling sealed deeper foundation seepage pathways and forced the seepage closer to the embankment/foundation contact. Seepage along this contact introduced an unfiltered exit through the rock toe drain.

Study of the Quail Creek Dike failure shows the importance of applying the correct design features commensurate with foundation geology and the importance of recognizing how geologic conditions can affect seepage, internal erosion, and piping failure modes.

TARRYALL DAM

Tarryall Dam is located in Central Colorado downstream of the town of Jefferson. It was designed in 1929 as a thin arch dam to be founded on rock.

Figure 17 – Downstream Face of Tarryall Dam from the Right Abutment

The dam has a structural height of 70 feet and a hydraulic height of 38 feet, meaning that the dam itself extends 32 feet below the ground surface as shown on Figure 17. Figure 17 also shows that while the left abutment is a thin arch against jointed rock, the right abutment arch section is supported by a large gravity buttress.

As previously stated, the dam was intended to be a thin arch structure supported by competent abutment rock. Granitic igneous rocks outcrop on both abutments and although moderately jointed, were thought to be suitable for support of this type of dam. However, during the excavation of the cutoff trench to bedrock, the field engineers encountered unsuitable, highly weathered and fractured rock in the right abutment. Realizing this rock would not support an arch, the design was modified to include a large concrete gravity section to provide both increased anchorage for the arch, and a gravity section to prevent overturning or sliding of the dam on this abutment. This configuration worked relatively well for nearly 70 years, until cracking was observed in the arch section monolith joint closest to the gravity buttress section. In 2001, the reservoir was ordered lowered to 5 feet below the spillway to reduce the load on the dam while additional studies were performed. In 2002 the additional studies showed that in fact the dam was unstable at high loading conditions and a zero-storage restriction order was imposed, forcing the reservoir to be fully drained until repairs could be made.

Repair designs focused on providing additional anchorage of the right abutment arch and gravity sections to better support that end of the dam against movement and also to provide additional reaction force for the remaining arch section. A series of eight, multi-strand rock anchors were designed and installed through both the arch section and gravity section to depths up to 111 feet. The anchors secured the dam on the abutment, providing the necessary resistance to overtopping and sliding, and also provided additional reaction for the remaining unanchored arch.

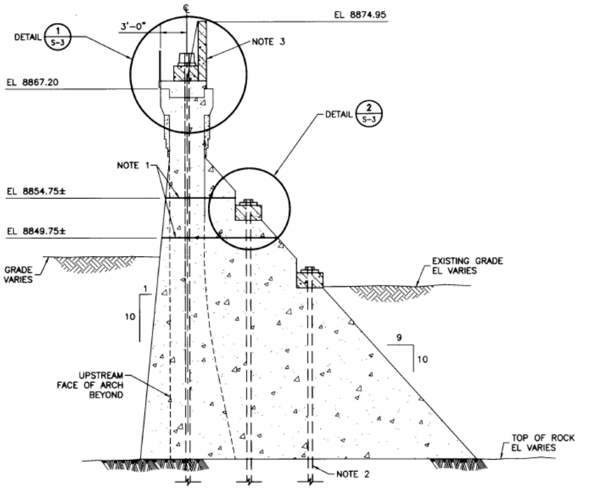

Figure 18 – Detail of Plan for Anchors through Right Abutment Arch and Gravity Sections

Figure 19 – Photo of Anchors Installed through Right Abutment Arch Section.

Conclusion

The benefits of geologic observations made during investigations for new dams or for repairs to existing dams are sometimes overlooked but are essential in preventing costly oversights. After soil and rock types have been identified and geologic constraints defined, the potential issues that may affect dam construction and performance can be evaluated and mitigation strategies developed. In some cases, the potential issues may be minor; in other cases, where geology is complex, problematic, or difficult to characterize, the potential issues may be serious and create inherent uncertainties in how the structure is performing or will perform. This article introduced some basic geologic terminology and principles and provided just a few examples of how geologic conditions might impact a given project. Future articles will be used to delve deeper into these important concepts.

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