Foundation Preparation for RCC Dams Founded on Difficult Foundation Conditions
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1.0 Introduction

RCC Dams, normally designed as traditional gravity structures similar to conventional concrete dams, require treatment of the foundation rock in accordance with generally accepted practices developed and improved by the profession over the last 50 years or so. However, with RCC Dams there is at least one option to the designer that can be used when the rock is of exceptionally low quality, possibly precluding the use of a traditional gravity section.

This paper describes the foundation preparation work carried for two RCC Dams—one with a traditional gravity section and one with symmetrical section where the rock was judged to be of such quality that the traditional gravity section is deemed unsuitable.

The new Saluda Dam, near Columbia, SC, USA is a traditional gravity section with 1.3 million CY of RCC, making it the second largest modern RCC Dam in the USA. It is founded on folded and faulted gneiss and granite, with intense weathering in zones to depths as deep as 10 m below the dam/rock interface.

The new Dam that will form the Upper Reservoir at the Taum Sauk Pump Storage Project near Lesterville MO, USA, currently (2006 to 2009) under construction, is the largest RCC Dam (2.7 million CY) in the USA. The new Dam is replacing the original concrete face rockfill dike that failed catastrophically in December 2005. The new Dam is founded on highly fractured rhyolites with deep weathering features, intrusive granites and weathered diorite dikes. The rock foundation is deemed unsuitable for a traditional gravity section, and therefore a symmetrical RCC section is being constructed.

The engineering and construction work associated with the foundation preparation work is described in this paper with a series of photographs taken during construction.

2.0 Foundation Preparation at Saluda Dam

Saluda Dam is located on the Saluda River approximately 10 miles upstream (west) of Columbia, South Carolina. The Dam impounds Lake Murray, which is one of the largest lakes on the East Coast, and is owned and operated by South Carolina Electric and Gas Company. Saluda Dam is a semi-hydraulic fill (“puddle fill”) embankment Dam.
constructed in 1930 as part of a 203 MW hydroelectric facility. Remediation of this dam for seismic stability consisted of the construction of a combination Rockfill and Roller Compacted Concrete (RCC) Berm along the toe of the existing Saluda Dam. For about 5,800 feet of the 7,800-foot long Dam, the remedial design called for the construction of a Rockfill Berm. Where space constraints did not allow for the construction of a Rockfill Berm an approximate 2,000-foot long RCC Berm was constructed. The excavation for the Rockfill Berm was to competent residual soil. Center cells were excavated to competent bedrock. In this excavated area behind and extending north and south of the Saluda Powerhouse, 1.3 million cubic yards of Roller Compacted Concrete (RCC) were placed to create the new RCC Berm.

**Figure 1 – Completed Saluda Dam**
The RCC Berm at Saluda Dam is founded on competent rock as defined by the commencement of coring operation and verified during construction. Coring operations defined an approximate excavation depth prior to construction. Foundation rock was shaped to remove overhangs and steep surfaces. High rock surfaces were cut back to remain stable during construction and to maintain a smooth continuous profile to minimize differential settlement and stress concentrations within the embankment.
Geology played an integral role in determining depth of excavation. As stated above, over-excavation in limited areas was required due to presence of weathered, fractured, or faulted rock. The foundation bedrock at Saluda Dam is composed of metamorphosed mid to upper-level amphibolite grade facies rocks. The foundation lies along the Modoc Shear Zone, a 4-5 km wide fault zone characterized by a steep metamorphic gradient and multiple phases of ductile and brittle deformation. Generally, the Modoc Zone extends from the east of the Saluda Dam to Clark Hill Reservoir on the Savannah River. The Carolina Slate Belt borders the northeastern terminus of the Modoc zone outcrop to the east of Lake Murray. The complex nature of the geology such as three distinct lithologies, pervasive foliation (Figure 4), intrusive dikes, faults, and throughgoing fractures posed significant challenges to foundation preparation.
Geologists mapped the entire foundation once excavation was approved including all lithologies, discontinuities and their orientations, and overall competency of the foundation on which the RCC berm was to be built. The U.S. Bureau of Reclamation Engineering Geology Field Guide was used as the standard for mapping and foundation description by the geologist. Data collected was used to calculate rock mass rating (RMR) for the foundation and geologic and RMR maps were produced in order to verify and record foundation conditions. Geologists also tested the foundation with a geologic hammer, recording the number of blows required to break intact rock and the sound generated upon striking the rock and using these observations to determine and map the degree of weathering per the United States Department of Interior, Bureau of Reclamation Engineering Geology Field Guide. Slightly weathered to fresh rock was accepted foundation.

Treatment of the exposed rock surface after removal of unsuitable overlying materials depended on the type of rock and the irregularities present. As previously mentioned, the configuration of exposed hard rock surfaces was controlled largely by foliation, joints, faults, shear zones, and excavation methods. Depending on discontinuity orientations, these features sometimes resulted in vertical surfaces, benches, deep depressions, and overhangs. For example, a near-vertical bedrock surface (quartz plagioclase biotite schist) caused by differential weathering along the foliation was uncovered between penstocks 4 and 5, as seen on Fig5.

Features such as buried river channels, intrusive dikes, and faults/shear zones created additional irregularities. The foundation surface required shaping to provide a sufficiently regular surface on which dental concrete could be placed without excessive
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elevation differential. Over-excavation was required in zones of weathered rock.

Space constraints in the area of the Saluda Hydro Powerhouse required vertical or near-vertical cuts and temporary excavation support measures. Anchoring of an existing, non-reinforced concrete retaining wall behind the Powerhouse, as well as construction of new tieback walls north and south of this wall, provided support for the sides of the excavation. In addition, an excavation support retaining wall was required just upstream of the Meekin Station Steam Plant to permit excavation to rock for the RCC retaining wall while maintaining the existing storm water system in this area. While the intent of the Powerhouse area excavation was to expose a suitable rock foundation for the RCC Berm, tight working conditions immediately behind the Powerhouse due to the Penstocks for Saluda Units No. 1 to No. 4, an Arch Conduit for Saluda Unit No. 5, and the relocated Circulating Water Lines precluded the use of RCC material at the rock interface in all areas. In these areas, nonreinforced mass concrete was placed from the prepared rock foundation (approx. El. 165) up to El. 193 NAVD, an elevation above most of these structures. Thereafter, RCC was placed to complete the Berm. This area, being the highest section of the dam, required excavation to fresh rock. Excavation, cleaning, and repeat cleanings due to storm water flow and construction activity proved especially time consuming.

Excavation for the Bedrock Cells north and south of the area behind the Powerhouse proceeded in like fashion; however without the space restrictions and structure concerns, excavation occurred at a faster rate. Typical excavation and placement activities and equipment used can be seen on Figure 6.

Bedrock conditions proved unpredictable as excavation progressed to the north and south of Cell C-5. Several deep bedrock trenches caused by faults and lithologic contacts precluded excavation from progressing normally without using vertical or near-vertical slopes. Upstream retaining walls that were not originally included in the excavation design were required. Tied-back soldier-pile and lagging walls, similar to those on either side of the Powerhouse, were built along the upstream berm-axis alignment for portions of the excavation. Total length of these walls was approximately 950 ft with height as much as 30 ft.

**ROCK CLEANING AND DENTAL WORK**
The bedrock foundation for the RCC Berm was cleaned to provide acceptable conditions of contact between the dam and its foundation, and to provide for observation and documentation of foundation conditions at that interface. Exposure of potentially adverse conditions during cleanup provided the chance to undertake remedial activity.

During excavation, all loose and weathered material was removed by handwork, barring, picking, brooming, water jetting, and/or air jetting. Accumulated water from washing operations was typically removed by strategically placed sump pumps. Unsuitable material in cavities and along discontinuities was removed. Before RCC or concrete could be placed, the rock surface and all pockets or depressions were carefully cleaned of soil and rock fragments, which required compressed-air/water cleaning and handwork (Figure 7).

In some cases, excavation uncovered narrow faults and shears that exhibited zones of brecciated, altered, and severely weathered rock extending to depths that were impractical to remove. In such cases excavation extended to a minimum depth according to standards defined in the United States Department of Interior, Bureau of Reclamation Design Manual for Concrete Gravity Dams and dental concrete was used instead of RCC to fill these zones. Removing portions of the foundation capable of exhibiting less favorable deformation moduli and replacing with dental concrete provides some degree of beneficiation with respect to deformation modulus and is paramount in foundation preparation.

Dental concrete was also used to fill or shape holes, grooves, and extensive areas of deeper excavation created by discontinuities, buried river channels, lithologic contacts, and intrusive dikes. An example where dental concrete was placed in an overexcavation where a mafic intrusive body extended through the excavation cell is seen on Figure 8.

The mafic dike material was intensely fractured and weathered to a greater degree than the schist that it intruded. The composition of the dike has made it more susceptible to weathering over geologic time. In addition, the contact of the dike and schist and the intensely fractured dike acted as a groundwater flow path, thereby increasing the rate of weathering of the dike material. An area fifteen feet wide, ten feet deep, and five
hundred feet long was excavated in order to reach acceptable dike material.

Thin areas of dental concrete over rock projections on a jagged rock surface are likely places for concrete cracking and were avoided by using a sufficient thickness of dental concrete. The rock surface was thoroughly cleaned as described above and moistened prior to concrete placement to obtain a good bond between the concrete and the rock surface. When overhangs were filled with dental concrete, the concrete was well bonded to the upper surface of the overhang. Concrete was formed and placed so that the head of the concrete was higher than the upper surface of the overhang. Dental concrete was typically cured with water and operations were not permitted over the dental concrete until strength and temperature were tested and fell into the acceptable range as defined in the technical specifications. Figure 9 shows an area where unacceptable rock associated with an antiformal structure and intersecting fault have been excavated then leveled with several lifts of dental concrete. Faults posed specific challenges to the foundation excavation. For example, a large fault/breccia zone is near the contact of amphibolite and schist. Several other faults with large displacements occur near pegmatite-schist contacts.

A large fault zone, shown in Figure 10, dictated additional foundation preparation effort near the north end of the RCC berm foundation. This fault was oriented perpendicular to the axis of the RCC embankment with a breccia zone encountered to the south of the fault. As the broken, fractured rock of the breccia zone was excavated, a vertical rock wall along the fault was created with the south side of the fault about 23 ft. below the north side.

To account for the different foundation material properties and the resulting potential of differential movement across the fault, the closest construction joint to the fault (CJ-34) was moved to align with this feature. The upstream end of CJ-34 was moved 13 ft. to the south and the downstream end was moved 11.25 ft. to the south. In order to maintain reasonable spacing between construction joints, CJ-35 was also moved 16 ft. to the south.
To satisfy FERC concerns regarding fault activity, the presence of well developed epidote and quartz crystals as well as chlorite on the breccia surfaces was used as evidence that movement along this fault occurred when the fault was at pressure and temperature levels associated with greater than eight kilometers of burial. This higher pressure and temperature regime promoted solution and migration of minerals along the fault zone and crystallization of the aforementioned minerals.

Additional faults required special foundation treatment. *Figure 11* shows a fault zone excavated to remove moderately to intensely weathered rock prior to the placement of dental concrete.

*Figure 11* shows a fault zone requiring additional cleaning.

*Figure 12* shows a low angle thrust fault with a portion of the hanging wall in place. The hanging wall had to be evaluated regarding potential movement under the load of the RCC berm. Despite being made up of slightly weathered to fresh, slightly fractured rock, most of the hanging wall was removed.

*Figure 12* shows a low angle thrust fault offsetting pegmatite.

The northern portion of the RCC berm foundation
is composed primarily of two lithologies that presented varying excavation challenges: a quartz biotite plagioclase schist that is slightly to moderately weathered, intensely foliated (N50-70E, dipping 55-75 degrees to NW) and moderately fractured and; a slightly foliated, slightly weathered intrusive granitic unit. Within the schist are numerous alkali and plagioclase feldspar pegmatitic dikes striking roughly along foliation and two intermediate to felsic composition intrusive dikes that cross-cut foliation at approximately 90 degrees and steeply dip to the southwest. The largest felsic dike ranges from four to six feet in width. These felsic dikes were intensely fractured and required additional excavation and cleaning. Within the granite, exfoliation fractures, shown in

**Figure 13**, posed a unique excavation problem. These sub-horizontal fractures were the dominant feature of the granite and acted as flow paths for groundwater. Weathering along many of the fractures was intense and necessitated removal of sections of rock that appeared, at initial observation, acceptable. In addition, the flow along these fractures required additional de-watering of the excavation. These fractures dipped parallel (perpendicular to strike) to the axis of the dam and were very continuous only along the upstream third of the foundation. As a result, these joints did not pose a problem for sliding stability.

The most significant zone where foundation preparation required special attention was at the contact of the Lake Murray Gneiss and the biotite schist unit. While excavation depths typically ranged twenty to forty feet from ground surface for the rest of the foundation, this zone required excavation depths in excess of seventy feet. The inter-layered gneiss and schist units with massive pegmatite bodies along the contact were very intensely fractured and moderately to intensely weathered to depths as great as seventy feet. A slurry wall with tie-backs had to be installed to prevent flow of water from the Saluda River through the alluvium of the old river channel into the excavation. The bottom of the excavation was elevation 130 and the river elevation ranged from elevation 172 to 180. Dam design borings identified a lower elevation in competent rock, but twenty-two additional borings prior to excavation assisted in excavation design and in defining the depth and extent of this zone. As a result of these efforts all poor rock was successfully removed from this zone. **Figure 14** shows this zone of overexcavation.
3.0 Foundation Preparation at Taum Sauk Upper Reservoir

The Upper Reservoir at the Taum Sauk Pump Storage Plant was constructed in the early 1960's with an uncompacted rockfill dike with a concrete face, basically an early CFRD. On December 15, 2005, the CFRD catastrophically failed because of several reasons, including poor foundation preparation during the original foundation—the subject of this paper.

A new RCC Dam with a symmetrical cross-section has been designed and is now being constructed. The complex foundation rock, basically rhyolite with and an intrusive granite, is fractured with weathered zones that have degraded to clay-like materials. The Dam alignment is traversed with an intensely fractured zone and a diabase dike with a weathered clay zone overlying the dike. All of these features have resulted in a time consuming and intense foundation preparation effort as illustrated on the following figures.
The “OLD” Upper Reservoir

Figure 15 – Taum Sauk Upper Reservoir (before December 2005)

Upper Reservoir Post-Breach

Figure 16 – Taum Sauk Upper Reservoir (after December 15, 2005)
"Old" Rockfill Dike – Typical Section

Figure 17 – View of Foundation Conditions for the “Old” CFRD

View of North Side of Breach
Figure 18 – View of the “Old” CFRD Crossection and Foundation

New RCC Dam

Figure 19 Cross-section of new RCC Dam

Foundation Preparation – 6+00
Figure 20 – View of Typical Foundation Preparation

3+00 Excavation Looking Upstream

Figure 21 – View of Typical Foundation Preparation

RCC Placement at Rock Surface

Figure 22 – RCC Placement at Rock Surface
RCC Placement at Rock Surface

Figure 23 - RCC Placement at Rock Surface

Preparing Rock for 1st Lift Placement

Figure 24 – Rock Preparation for 1st RCC Lift
Figure 25 – Rendering of Completed Upper Reservoir Dam (Expected Spring 2009)