COMPLETION OF SALUDA DAM REMEDIATION – AN ENGINEERING CHALLENGE

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INTRODUCTION

The Saluda Dam located near Columbia, South Carolina is a semi-hydraulic fill embankment constructed in the late 1920. \textit{Figure 1} provides an aerial view of the Saluda Dam Project prior to remediation. The original Dam was constructed in the late 1920’s to generate hydroelectricity. It included a five-unit powerhouse located immediately downstream of the center Dam section. Following construction of the original Dam, a coal-fired steam plant was added along the downstream toe. The plant utilizes water from the existing penstocks as cooling water for operation. Economical operation of the steam plant required the operation of ash ponds and an ash landfill, both of which were also located along the downstream toe of the original Dam. Saluda Dam created Lake Murray, a largest man-made lake in North America, covering 78-square miles. The reservoir is rimmed with homes and businesses and is the primary source of water for three towns.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{saluda_dam_aerial_view_before_construction.png}
\caption{Figure No. 1 Aerial View Before Construction}
\end{figure}

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Due to construction methods, the original Dam is susceptible to liquefaction during the Design Seismic Event (DSE). The Dam owner (South Carolina Electric & Gas) retained Paul C. Rizzo Associates, Inc. (RIZZO) to investigate and complete detailed static, dynamic and post-seismic stability analyses, including finite element analyses for the critical sections of the existing Dam. Based on these analyses, the Dam may destabilize during the occurrence of the DSE, and calculations predicted wide-scale liquefaction of the existing embankment. The Dam is stable under static loading conditions; therefore, the remedial design focused on the seismic loading criteria.

The analysis of the original Saluda Dam and the design of the back-up Dam have been well-documented in previous publications. They are not the focus of this paper. This paper discusses how the remedial fix evolved from conceptual design through preparation of construction documents and during construction. Emphasis is given to the design and construction of the excavation necessary to construct the project as designed. One of the foremost challenges was that any remedial construction would have to be completed with minimal disruptions to the existing facilities both during and after construction. Draining the lake to allow for remediation would create incalculable environmental damage and economic hardship.

The selected remediation of the Saluda Dam consisted of construction of a combination Roller-Compacted Concrete (RCC) and Rock Fill Berm along the downstream toe of the existing dam. In essence, the remediation approach was to construct a back-up dam along the entire length of the 7,800-foot earthen embankment. This remedial construction was completed in 2005. Figure 2 provides an aerial view of the Saluda Dam Project after remediation.
Safety was the primary goal of the remediation; specifically, safety of the 120,000 people located in the downstream flood plain. While the overall stability improvement from the completed project is relatively easy to quantify, stability during construction was a key design concern. Further to the point, the threat of a large earthquake occurring in any given year is very remote, but the excavation for remedial construction created very real, current risks which had to be managed. Extensive measures were designed and employed during construction to constantly maintain acceptable safety, including an extensive instrumentation and monitoring program.

This paper presents interesting facets of the excavation concept and retaining wall construction, inspection, and monitoring; and discusses the evolution from the original excavation design to the as-built conditions. Topics of discussion include additional geotechnical testing and subsequent re-design, field and laboratory testing of wall materials, performance monitoring with instrumentation, and construction methods/procedures.

FROM CONCEPT TO CONSTRUCTION DOCUMENTS

The concept approach was the construction of a backup berm – which has about the same length, 7,800 feet and height, 211 feet, as Saluda Dam itself. It has two primary objectives: to prevent catastrophic flooding downstream and to ensure the safe shutdown of the facilities associated with the original Dam. Taking the design from a cross section to three dimensions was the first challenge. A number of criteria had to be better defined to both complete the design and to develop construction documents.

**Toe of Original Dam** – At RIZZO, we maintain a criterion that calls for no excavation into the original Dam. However, definition of the Dam toe was not straightforward. Since the original construction, riprap had been placed to strengthen the existing Dam. Also, roads were constructed along the downstream toe. As a result, the original toe was not visible and also expanded downstream. Riprap of varying thickness had been placed over the operating years for various reasons, including improved stability, seepage control, and plant access. Typically, the original Dam toe was covered by 10 to 30 feet of riprap. Following definition of the toe (both horizontally and vertically), excavation lines were drawn from this point upstream to the existing ground surface and downstream to the desired foundation elevation. Again, we developed our criteria to balance the safety of the existing Dam with the foundation requirements of the new RCC and Rock Fill sections. The original Dam toe is highlighted in Figure 3.

**Dewatering Design** – Extensive dewatering was required to ensure stability. The dewatering system consisted of deep and shallow wells, eductors and wellpoints. Dewatering was designed to achieve a 1.5 factor of safety during excavation; and extensive monitoring was planned. We used these criteria to develop the remedial berm in three dimensions and illustrate the extents on plan view drawings. Figure 3 shows a typical excavation section with the planned dewatering components.
Figure No. 3 Typical Rockfill Berm Section

Figure No. 4 Cell C-2 Looking North
Depth of Excavation – The overall depth of excavation had to be a balance between the foundation requirements of the new structure and the safety and stability of the original Dam. Over-design of the excavation could have had negative consequences on the stability of the existing Dam and under design of the excavation could have affected the long-term performance of the completed remediation and/or could have led to problems during construction. We began developing the excavation profile starting with the existing Dam toe. The excavation line was drawn from this point up to the existing ground surface at a 1.5H to 1V slope and down to the planned foundation excavation depth at the same slope with 15-foot-wide benches every 30 vertical feet. This methodology was utilized to develop the foundation excavation details for bid purposes. With this knowledge, the remedial design was completed with the assumed best-estimate of foundation elevation. An aerial plan view showing the relationship of planned excavations, original toe of the Dam and down stream site constraints are shown in Figure 4.

Although the above criterion was based on significant foundation exploration, changes during construction should always be anticipated. At Saluda, additional excavation to reach required foundation conditions was extremely difficult, given the presence of the existing Dam. For instance, the need for additional excavation to reach suitable foundation depths would typically not be known prior to excavation - only after excavating to planned depths (as much as 60 feet below existing grade) would the full extent of additional excavation be quantified. Also, shifting the upstream toe of the Dam downstream was not possible due to downstream constraints plus the fact that the Dam was constructed in discrete cells.

Figure No. 5 Completed Soil Nail Wall
Retaining Walls – While every effort was made during design to avoid vertical excavations, space constraints near to the hydroelectric powerhouse and at the Saluda River necessitated just that. Near the powerhouse, traditional soldier-pile and lagging walls were constructed flanking an existing concrete gravity wall, which was part of the original construction. These walls were over-designed somewhat given the risks involved. Also, every effort was made to place the footprint of the new dam in such a way as to minimize the lateral extent of these walls. Figure 5 shows typical tieback wall which varied in vertical height of 15 to 40-feet and from cantilever to three (3) anchored walls. The total length of the wall was about 2,800-feet.

The design concept of the required walls also incorporated the use of a cement bentonite (C-B) wall to act as a cutoff adjacent to Saluda River. Figure 6 shows typical C-B tieback wall which varied vertical in height up to 25-feet. The total length of the C-B wall was about 1,200-feet.

Tieback wall construction was called for in the original remediation design to support the excavation at the northwest corner of Saluda Powerhouse and a soil nail wall was required adjacent to the McMeekin section of the wall. Upon request of the contractor, the entire segment of this section was constructed with soil nail wall. Figure 7 shows typical cement soil nail wall which varied in vertical height from 5 to 7-feet over a length of about 2,500-feet.
SAFETY AND MONITORING DURING CONSTRUCTION

Several excavation safety measures were added to the Project’s design. These included excavation of the Dam in cells of about 250-feet in length thereby allowing for some improved stability due to three-dimensional effects. These cells required speedy construction. Specifically, the specifications called for continuous (24 hours per day/7 days per week) construction work whenever any excavation was opened. This required that the Contractor (Barnard Construction Company, Inc.) dedicate significant resources to the excavation and backfill operations — labor and equipment available to work three shifts each day to allow for continuous operation.

The opening of these cells and the rapidity with which they had to be filled demanded extensive monitoring during construction. RIZZO’s detailed monitoring plan included four specific threshold levels. The required action associated with each state — up to and including emergency backfill of the open excavation — was well-defined prior to any excavation.

CONSTRUCTION

Construction commenced in Cell N-5 on the north side of the embankment. N-5, planned as a rockfill section, was to be founded on dense residual soil. The planned foundation excavation was developed based on an extensive boring program and confirmed in the field with proof rolling once the planned subgrade elevation was reached. Extensive dewatering, including a significant reduction in the phreatic surface (20 to 40-feet total drawdown), was achieved prior to any excavation.

The first surprise encountered during excavation was pockets of water within the existing embankment. Numerous drainage features had been installed during the operating life of
the Dam. Many had been abandoned in-place after they were no longer effective. Evidence of these features was covered and some plant operators were unaware of their existence. As they were uncovered they produced seeps that would run clear after several hours and dry up after several days - all normal, explainable occurrences. But, during excavation to depths of 20 to 60-feet below existing grade, immediately downstream of a high-hazard dam impounding 750 billion gallons of water, these caused some initial alarms.

Because it is very difficult to determine whether a potential pipe has been uncovered or the seepage is a result of a pocket of water contained within the slope, we had to develop plans and implement procedures on a case-by-case basis. Each time, emergency measures, as stipulated in the Excavation Monitoring Plan, were instituted. These required a temporary suspension of excavation activities to assess the situation. Seepage control measures were installed and seepage rates were monitored. All monitoring activities were completed continuously – night and day – during any open excavation.

Following this first occurrence, we conducted additional research of the as-built drawings of the original Dam. Through this effort, we identified old drainage features and located them in the field. While extreme care was still exercised when water was encountered, knowledge of these existing features provided some level of comfort and helped to adjust expectations during the planned construction.

As stated previously, all rockfill sections were founded on dense, residual soil. After some initial modification of the interpolation procedures, we found this layer fairly simple to predict. Only limited modifications during construction were required. Moreover, the original design was somewhat over-conservative with respect to establishing the depth to dense residual soil. Therefore, most modifications to foundation depth under the rockfill sections allowed the planned excavation depth to be reduced.

**A CASE HISTORY**

Competent rock, on the other hand, can be very difficult to predict and interpret based on borings. The rock surface at Saluda (gneiss and schist) was no exception. Areas within the foundation revealed variations of 100 feet or more in top of rock over horizontal distances of less than 50-feet. Substantial differences were noted between the best-estimate rock surface developed by RIZZO and actual conditions uncovered during remedial construction. These differences caused substantial issues during construction. *Figures 8 through 10* show examples of the wild bedrock conditions encountered during construction.

The planned approach for excavation is shown on [Figure 3](#). As stated previously, the design excavation started from the downstream toe of the original Dam and proceeded from this point down to the planned top of rock. The cut slope was designed with a 1.5H to 1V slope with benches every 30 vertical feet. Dewatering was designed to achieve a 1.5 factor of safety with an open excavation.
Figure No. 8 Cell C-7 Upstream Wall Completed

Figure No. 9 Cell C-9 Foundation
What happens when the top of rock is deeper than planned? Options are a vertical excavation or shifting the Dam downstream. As discussed previously, the Dam was constructed in discrete cells to manage the risks due to excavation. As such, shifting the Dam downstream was not an option after the first segment was constructed. While a vertical (or steeper) excavation carried additional risk, the design for the concrete (RCC) backup dam called for foundation on competent rock. Additional, to achieve the desired foundation excavation while maintaining the safety of the existing Dam, we had complete construction as rapidly as possible to minimize the risks of excavation. But, in some cases, the need for the walls was not known until a substantial portion of the excavation was opened.

The first major problem occurred when an excavation cut slope was over-steepened by the Contractor to reach the desired foundation excavation. The over-steepened slope caused movement on a localized slip surface, resulting in significant surface movement. RIZZO implemented the site-specific Excavation Monitoring Plan and directed placement of emergency backfill to stabilize the slide. Even with the emergency backfill in-place, a 40-foot cut below existing grade remained. Thus, the need to evaluate the problem, develop a solution, and proceed with complete excavation and RCC placement was paramount to avoid additional unnecessary risk. Additionally, the Contractor’s standby charges had the potential to be very significant because continuous 24/7 work was required in the specification. Stopping work effectively stopped three shifts of labor and equipment, not just one.

The solution to the excavation stability problem was the construction of a soldier-pile and lagging wall to allow vertical excavation to the top of rock. Implementation of the solution however, was not as straightforward. The first task required additional borings
along the planned toe of the cut slope to define the new top of rock. These borings, destructively drilled to locate the top of rock, were drilled on 10-foot centers. (Drilling on 10-foot centers would have been almost impossible to justify during design). This defined the height of the planned wall and allowed RIZZO to proceed with the design of piles, anchors and lagging. Following development of the initial design, RIZZO met with the Contractor, which subcontracted the wall construction to a joint venture team of Hayward-Baker/Nicholson.

Initial meetings on cost and constructability revealed several problems with the design – most notable, the current availability of many of the design components. A nationwide steel shortage resulted in significant lead times for steel piles. While a two- to three-month lead time is tolerable on most construction projects, with a 40-foot excavation open below a high-hazard dam and three construction crews and equipment on standby, lead times on the order of days was required.

RIZZO met with the Contractors and requested a summary of piles that were available and readily attainable by either JV partner (Nicholson or Hayward-Baker). Having two of the largest, most well known tie-back wall contractors proved a major plus. RIZZO then re-designed with the available materials, adjusting pile spacing and anchor loads as required to utilize existing material stockpiles.

Following resolution of the initial problem, additional investigation was called for along the remaining length of the planned RCC backup dam. By this time, the Contractor had mobilized and begun drilling for installation of the piles for the wall. We utilized these same resources to advance additional borings to better define the top of rock. Additionally, more analyses and investigations were completed to fully understand the slope failure mechanism and better ascertain the risk involved with excavation.

In the end, RIZZO, working in conjunction with the Owner, decided to spend additional resources and time to construct soldier-pile-and-lagging support walls along much of the planned alignment for the RCC Backup Dam. These walls (about 2800 feet) reduced the safety risk and improved the overall construction schedule. The walls were able to be constructed in advance of dam construction as opposed to delaying dam construction by stopping or delaying excavation activities. Although the cost of the walls was significant, the potential costs for additional construction delay or the serious potential for dam safety risks were far in excess of the cost of the walls.

Close cooperation among the Engineer (RIZZO), the Owner (SCE&G), and the Contractor (Barnard) enabled these most-difficult construction issues to be dealt with in real-time and resulted in a win-win scenario for all parties involved. Safety risks were mitigated (though not eliminated) and construction schedule risks were reduced. Reasonable additional expenditures were made to accomplish the project objectives.