CONSTRUCTION DEWATERING AT SALUDA DAM

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Saluda Dam (Dam), owned and operated by South Carolina Electric & Gas Company (SCE&G), impounds Lake Murray, one of the largest man-made lakes in North America. The Dam is a semi-hydraulic fill structure constructed in 1930 following the typical "puddle dam" construction technology. This type of construction resulted in significant seepage through the Dam upon filling, which required placement of riprap benches and the installation of an extensive network of seepage collection drains on the downstream slope of the Dam to control seepage after initial construction.

The Dam is being remediated to meet changes in earthquake safety criteria as directed by the Federal Energy Regulatory Commission (FERC). The remediation consists of a 5,500-foot-long Rockfill Berm and a 2,200-foot-long Roller Compacted Concrete (RCC) Berm on the downstream slope of the existing Dam. Both the RCC Berm and the Rockfill Berm will serve as the primary water retention barrier in the event of an earthquake induced failure of the existing Dam. Both require a highly competent foundation with the RCC Berm founded on rock. Therefore, extensive foundation excavations into the residual soil or bedrock encountered at the toe of the existing Dam are required to facilitate construction of the Berms.

EXCAVATION GEOMETRY AND PLAN

The cell excavation depths range from a minimum of 10-feet to 67-feet below the existing ground surface. Based on the water surface elevations provided by the existing piezometers, the residual soil is being dewatered to a prescribed depth for all the excavations made for the Rockfill Berm while the entire thickness of the residual soil and the underlying rock will have to be dewatered for the excavations made for the RCC Berm.

The remedial construction consists of 25 separate excavations along the toe of Saluda Dam to construct the RCC and Rockfill Berms. Most of the excavations are limited to a maximum length of 250-feet and widths will range from 110 to 315 feet. To minimize the time that a cell is open at locations deemed "critical" in terms of dam safety, they are being excavated and backfilled by construction crews working 24-hours per day, 7-days per week.

SLOPE STABILITY DURING CONSTRUCTION

To maintain an adequate factor of safety against slope instability for the existing Dam during construction and to provide dry working conditions, the existing phreatic surface (i.e. water levels) within the Dam needs to be lowered substantially by dewatering. These excavations into the residual soil at the toe of the Dam were designed for a factor of safety against slope instability of 1.5 for local, global, breach, and intermediate failure circles. Slope analyses were performed using shear strength parameters of the residual and embankment soils determined by consolidated undrained triaxial compressive strength tests performed on undisturbed samples.

Slope stability analyses were performed for Dam cross sections spaced every 100-feet of the 7,800-foot-long Dam to determine the target phreatic surface levels. The analyses considered the pore water pressures within the excavation slope determined from an interpreted phreatic surface. As determined in previous work by RIZZO, the factors of safety calculated using pore pressures estimated from seepage analyses are 0.1 to 0.2 higher than calculated assuming the pore pressures are simply proportional to the vertical distance from the phreatic surface to the failure surface. Seepage analyses consider the head losses of the water seeping through the Dam, which results in lower pore pressures in most places.

A monitoring program is underway to ensure the global and local stability of the existing Dam and the excavation slopes. This program consists of surveying existing monuments at the existing Dam, measuring inclinometers, and evaluating water level data from piezometers, which are installed along the upstream side of the toe excavation.

Figure 1. Typical Slope Stability Cross Section

DEWATERING SYSTEM

The design criteria for the excavations that terminate in the residual soil (Rockfill Berm) were that the dewatered phreatic surface must be a minimum of five feet below the proposed bottom of the excavation and that the hydraulic head of the underlying fractured rock should provide a minimum factor of safety of 2.0 against a blowout failure. We postulated that a blowout failure could occur if seepage forces from groundwater flowing from the underling rock into the residual soil exceed the weight of the overlying soil.

Our design criteria for excavations that terminate at the contact between the residual soil and the fractured rock (RCC Berm) were that the dewatered phreatic surface within the rock must be a minimum of five feet below the proposed bottom of the excavation. In addition, the groundwater would need to be lowered to a level that ensures the stability of the excavated slope during construction as determined by slope stability analyses.

HYDROGEOLOGIC SETTING

Saluda Dam is located in the Piedmont Region of South Carolina. Igneous and metamorphic rocks characterize the bedrock of the region (LeGrand, 1988). The Saluda Dam site lies within the Modoc Shear Zone, a ductile shear zone within the Carolina Terrane (SCDNR, 1997). Lithologically, the surface below the dam is composed of high-grade metamorphic rocks consisting of quartz-microline gneiss, and quartz-mica schist. These rocks have been impacted into low-grade metamorphic rock by tectonic process. These units show extensive ductile and minor brittle deformation but have been intruded by numerous pegmatities and dikes as well as a small granitic body. These rocks have been subsequently deformed at least twice since their emplacement resulting in folds and additional fractures. These fractures tend to facilitate ground water flow, whereas the dikes and pegmatites tend to inhibit or facilitate ground water flow. In general, fracture flow within the rock mass is highly variable, but where rock is close to the surface, the underlying rock body is tight and where the rock is deeper, well fractured rock resultes in higher permeability. Distinct unfractured and fractured zones in the bedrock occur along the length of the dam. The underlying fractured bedrock generally grades downward into unfractured rock below a depth of about 300-feet.

A characteristic feature of the region is a mantle of residual soil, which covers the bedrock in most places (LeGrand, 1988). The thickness of the residual soil ranges from 0 to 100-feet. The residual soil is predominantly sandy silt with a clayey layer at the top. An old residual soil layer forms an important flow boundary that can significantly affect ground water flow. Where this old soil layer is inclined on the flanks of hills of the pre-Saluda Dam topography, it can significantly affect the flow direction of water within the Dam. The steeply inclined soils near the old riverbed redirect ground water flow toward the river instead of perpendicular to the Dam.

A composite two-media system characterizes the groundwater flow in the region. The underlying bedrock, which tends to be fractured, is the chief avenue for groundwater flow and the overlying residual soil and weathered rock provide and intergranular medium through which recharge and discharge of water from the fractured rocks occur (LeGrand, 1988). The rock controls permeability and the soil controls storitivity. This system allows us to pump water from within the rock and drain water from the overlying soil.

GENERALIZED HYDROGEOLOGIC CONDITIONS

Our generalized interpretation of the hydrogeologic conditions at the Dam and downstream toe is presented on **Figure 2.** To summarize, the conditions at most sections of the Dam can be represented by four hyrdrostratigraphic horizons: embankment materials, residual soil, fractured rock, and unfractured rock.

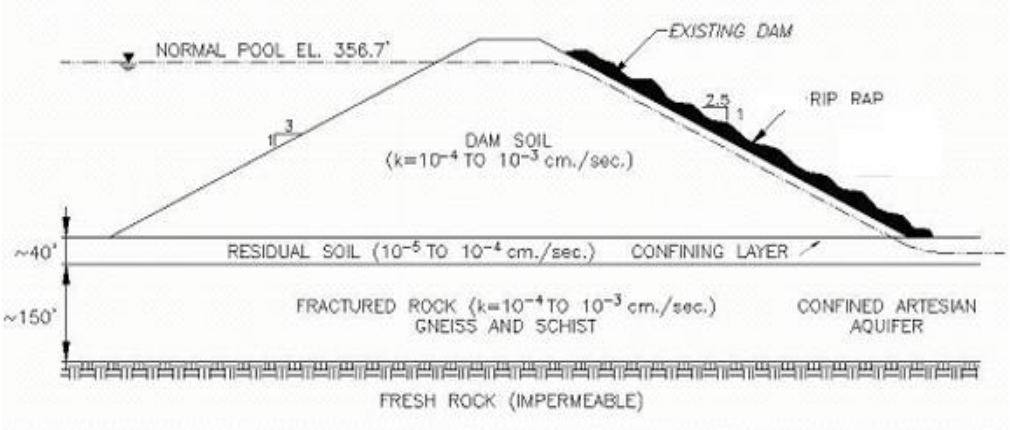

Figure 2. Generalized Hydrogeologic Conditions at Saluda Dam

FIELD INVESTIGATIONS

PUMPING TESTS

Pumping tests were performed at the site at two locations along the downstream slope of the Dam. The hydrostatigraphic horizons evaluated in the pumping tests included fractured bedrock consisting of gneiss ands schist, residual soil consisting of sandy silt, and embankment materials consisting of silty clay to silty sand. The purpose of these tests was to determine the appropriate hydrogeologic data necessary to develop a preliminary design of the dewatering system. Relevant conclusions are summarized as follows:

- Hydraulic communication exists between the fractured bedrock, and sandy residual soils;

- The fractured bedrock and residual soils are one system at the location of the pumping tests and behave like a confined aquifer for all practical purposes;

- Specific capacity values range from 0.28 gallons per minute per foot (gpm/ft) for Pu to 1.27 gpm/ft. The specific capacity values yield maximum sustainable pumping rates ranging from 45 gpm to 206 gpm.

PACKER AND FALLING HEAD TESTS

Packer tests were performed by RIZZO at four in April of 2000 as part of the hydrogeologic study of the site. Two of these tests were in schist, one in gneiss, and one a small intrusive rock (granite). Testing was performed on 5-foot intervals within the fractured schist encountered in two borings.

Falling head tests were also performed at nine piezometers screened within the Dam and underlying residual soils. These tests provided in-situ measurements of the hydraulic conductivity of the residual soil within the screened interval of the piezometer.

DEWATERING ANALYSIS

ANALYTICAL MODELS

Using the method of image wells described in Mansur and Kaufman (1962), four analytical models were used to analyze the dewatering of the excavations: line source, confined aquifer; line source, unconfined aquifer; circular source, confined aquifer; and circular source, unconfined aquifer. These analytical models relate change in head to flow rate for confined and unconfined aquifiers subjected to line or circular sources.

Calculations were performed using all four equations for a line of deep wells spaced at 100-foot on center for a 300-foot-long by 300 foot-wide excavation. A range of equivalent hydraulic conductivities for the residual soil and fractured bedrock aqufier were utilized in the analyses (i.e. 10x10 $^{-4,}$ 5x10-^{4,} and 1.0x10^{-3} cm/sec).

FINITE ELEMENT ANALYSES

As an additional check on the flow rates required to dewater the toe excavations and to evaluate the influence of hydraulic conductivity differences between the embankment soil, residual soil, and fractured rock, a two-dimensional finite element analysis of the Dam and toe excavation was performed using the SEEP2D computer program (Biedenharn and Tracy, 1987). SEEP2D is a two-dimensional finite element groundwater model developed by the U.S. Army Corps of Engineers Waterways Experiment Station to solve steady state seepage problems.

As shown on Figure 3, a 300-foot-wide, 40-foot deep excavation was included at the downstream toe of the Dam to model the proposed excavation at this Station of the Dam.

A “constant head” boundary condition of 358-feet was prescribed along the upstream face of the Dam and along the subsurface materials along the headwater side of the model. A “constant head” boundary condition of 200-feet was prescribed along the subsurface materials along the tailwater side of the model. A “no flow” boundary condition was prescribed along the base of the model. To provide an estimate of the flow required to dewater the excavation, an “exit face” boundary condition was prescribed along the bottom of the toe excavation and the downstream face of the Dam. An “exit face” boundary condition implies that the total head is equal to the elevation head and that the phreatic surface will exit the model along this face. Therefore, the finite element analysis calculates the groundwater that flows into the excavation.

Based on the results of both the analytical models and the finite element analyses, the total flow required to dewater a typical toe excavation ranges from 30 to 300 gpm. The actual flow depends on the hydraulic conductivity of the fractured rock at the location of each toe excavation. The degree of confinement also affects the total flow required to dewater an excavation.

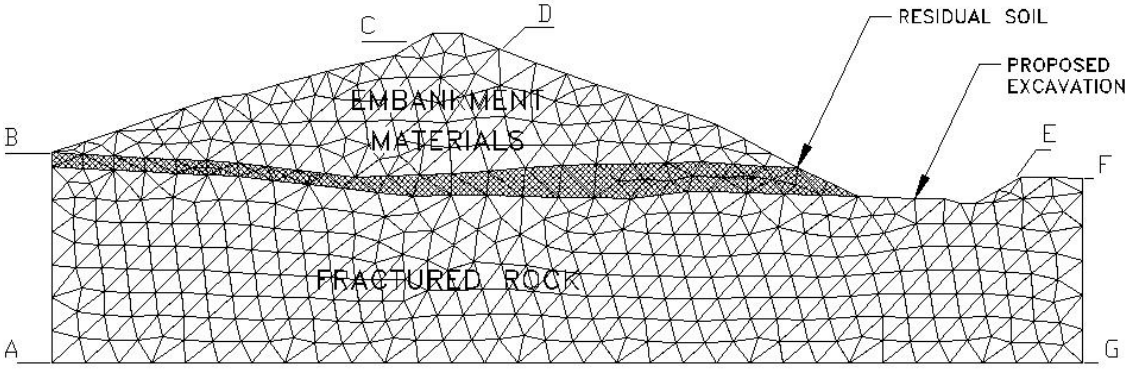

Figure 3. Finite Element Seepage Model

DEWATERING SYSTEM DESIGN

The dewatering system utilized for this Project consists of four components: deep wells, eductors, well points, and shallow wells.

DEEP WELLS

Deep wells are typically used to dewater sand and/or rock formations or to relieve artesian pressures beneath an excavation. They are particularly suited for dewatering large excavations requiring large rates of pumping and deep excavation for dams, tunnels, locks, powerhouses, and shafts (Mansur, 1973). The two major advantages of deep well systems are that they are typically installed outside of the perimeter of the excavation, which eliminates construction interference, and they can handle large volumes of water in one lift.

The purpose of deep wells in the Rockfill Berm excavations is to reduce the hydraulic head in the fractured rock to prevent foundation blowout due to “quick conditions” and to dewater the overlying residual and embankment soils to the maximum extent practical. In the RCC Berm excavations, deep wells are being used to dewater the fractured rock and to dewater the overlying residual soil to the maximum extent practical.

SHALLOW WELLS

Shallow wells are being used in conjunction with educators and deep wells in two specific areas: 1) where a thick layer of residual soil within the excavation zone of several cells was experiencing recharge from adjacent ash ponds, and 2) in thick alluvial deposits in the old river valley. Approximately 30 shallow wells were installed in these two areas. Maximum initial yield is 10 gpm in the shallow wells.

EDUCTORS

The primary advantage of eductors is that an eductor system can lower the water table by as much as 80-feet from the top of the excavation as opposed to approximately 15-feet for a single stage well point system (Griffin Dewatering Corporation, 2001). This is a major advantage at the Saluda site since the water levels for most excavations need to be lowered. The other advantage is that they can be installed outside of the excavation, thus reducing construction interference. The purpose of the eductor system is to remove the water from the overlying residual and embankment soil and to augment dewatering by the deep wells.

WELLPOINTS

The main advantages of utilizing a wellpoint systems are their relatively low cost, their effectiveness, and their versatility and flexibility. In addition, wellpoints are a proven technology because they have been developed and used for more than 50 years. The purpose of the Wellpoint Systems at Saluda is to remove any remaining water not dewatered by the deep wells or eductors, in our case within two excavation cells so far.

DEWATERING CONTRACTING PLAN

The dewatering contract was separated from the main Remediation construction contract to manage risk. Initial discussions with pre-qualified bidders for the main remediation contract indicated that the bidders were exceptionally reluntant to bear the risk of dewatering the excavations at the toe of the existing Dam and the associated slope stability and piping concerns. Consequently, RIZZO undertook full responsibility for the dewatering on a modified design-build basis. Griffin Dewatering was hired on a unit price basis and time and materials basis to work under RIZZO. RIZZO designed, supervised and tested the system using Griffin’s drill rigs and craft labor. In this manner RIZZO was able to consider the effects of dewatering on the safety of the Dam as well as the needs of the main remediation contractor and his schedule.

DEWATERING SYSTEM IMPLEMENTATION

Drilling rigs were mobilized to install deep wells and eductors simultaneously at both the north and south Rockfill Berm areas of the Dam. Field tests indicated that the target phreatic surfaces could not be achieved within the schedule presented by the remediation contractor by deep wells alone; therefore, additional efforts in the field were focused on installing eductors and optimizing their performance.

In general, dewatering wells were planned at about every 100-feet and eductors at about 10 or 20 feet intervals, respectively, along the upstream edge of cell excavations at the Dam. Actual installation of the deep wells and eductors was impeded by the limited available access and by the fact that these were separate operations. The deep wells were usually installed first with a typical drilling time of several days by either a Barber rig or air rotary Odex System. Pumping of deep wells could occur within a week of drilling once development, pump installation, and connection to discharge lines were completed.

Most eductors were installed with Sonic or Versa-Sonic rigs, which use vibration, sound waves and/or water to advance the boreholes. Typically about 150-feet of eductor casing was installed daily per rig, but initial pumping took longer than at deep wells because the rigs were on a bench much longer (which delayed development, installation of eductor bodies, and connection to supply/discharge pipes). At the south portion of the Dam where the excavation cells were deeper and water from downstream ash ponds was recharging the residual soil, both deep wells and eductors were installed on the downstream edge of several cell excavations. However, because the phreatic/groundwater surface within the cell excavations in these areas was responding slower than required to meet the excavations schedule, “sacrificial” deep wells, eductors, and shallow wells were also installed. These wells were lost during cell excavations but deep wells and eductors outside of the excavations will maintain the target phraetic surface until the cells are backfilled. Given more time, the deep wells may have been adequate to dewater these excavations. However, an accelerated remediation contractor schedule resulted in the installation of additional eductors and shallow wells.

CONCLUDING REMARKS

The construction dewatering operations at Saluda Dam has been highly successful despite a series of difficult constraints. Target dewatering levels have been achieved on a schedule consistrent with the main remediation contractor’s schedule and stability of the Dam has been maintained. The overall success of the the program is attributed to a series of factors outlined as follows:

- A flexible design that permitted variable well spacing to resond to changing geologic conditions.

- Use of a modified designer led design-build contractoring procedure.

- Considerable advance testing and a well-developed instrumentation and monitoring system.

- A balanced combination of deep wells and eductors supplement in certain locations with shallow wells and well points.

- Coordination of schedules between the dewatering program and the main remediation contractor's schedule.

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