
International Conference on Case Histories in Geotechnical Engineering (2004) - Fifth International Conference on Case Histories in Geotechnical Engineering

15 Apr 2004, 1:00pm - 2:45pm

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Sossenkina, Elena; Newhouse, Scott; and Glunt, Matt, "A Dangerous Place to Dig Excavation at the Toe of Saluda Dam" (2004). *International Conference on Case Histories in Geotechnical Engineering*. 15. <https://scholarsmine.mst.edu/icchge/5icchge/session02/15>



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A DANGEROUS PLACE TO DIG EXCAVATION AT THE TOE OF SALUDA DAM

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ABSTRACT

Remedial work on the Saluda Dam will entail excavation at the toe to depths of over 50 ft. Excavation at the toe of a large high hazard dam is an unusual event.

Although statically stable the Dam doesn't meet modern standards for dynamic stability. Based on the assessment of liquefaction potential, the dam requires remediation. The downstream hazard entails consequences of failure of potential loss of life. Due to such consequence, the Regulator called for renovation of Saluda Dam. Engineers evaluated several remedial alternatives. The chosen alternative entails excavation at the toe for construction of new RCC and Rockfill Berms.

Excavation at the toe of so large a dam, impounding so large a lake is a dangerous undertaking. It would be a daunting task even if there were no downstream hazard. The hazard and consequences of failure in this case make it much more so. The consequences of failure demand a high factor of safety. The excavation concept entails powerful questions: How can it be done assuring safety? What factor of safety is sufficient considering consequences of failure? Are there not alternatives to excavation that will effect seismic stability?

ABOUT THE DAM

Saluda Dam located approximately 8 mi upstream of Columbia, South Carolina impounds 41 mi-long Lake Murray. With more than 500 mi of shoreline, water area covering about 78 sq mi and storage capacity of more than 2,100,000 ac-ft of water, Lake Murray is one of the largest lakes on the East Coast. Completed in 1930, the dam is 200 ft high and nearly a mile and a half long. Saluda Dam is a semi-hydraulic fill ("puddle fill") hydroelectric dam. It is regulated by the Federal Energy Regulatory Commission (FERC). Original design and construction did not include any provisions for seepage control.

Figure 1 illustrates the dam's dimensions, geometry, and downstream hazard. The downstream hazard associated with Lake Murray is staggering. An uncontrolled breach through Saluda Dam would cause a downstream flood near the City of Columbia, probably entailing loss of life. Studies indicate that about 120,000 people would be at risk.



Fig.1. *Saluda Dam and Project Overview.*

The dam is earth fill, with no internal seepage control (filter or drain protection), and no cut off. The dam was built by hauling fill to the embankment in rail cars, side dumped into piles on the upstream and downstream portions of the embankment (the two outer shells). These piles were sprayed by monitors, sluicing the fine material into a central sedimentation pool, where it deposited to form a core for the dam.

Figure 2 illustrates this construction method- showing in cross section the sluiced core and the washed soils used to form the core. Near the dam's crest, these sluicing operations were stopped. The final portion of the embankment, within 30 ft of the crest, was constructed of rolled fill. Riprap currently covering the downstream slope of the dam was placed as a remedial measure shortly after first filling to address seepage emerging on the face of the dam.

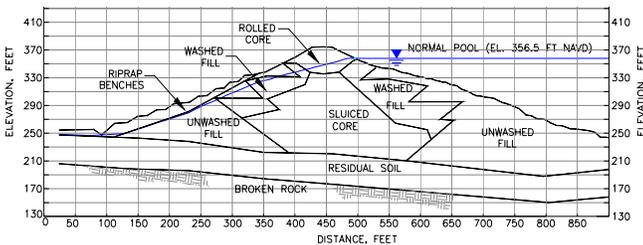


Fig.2. Typical Cross-Section, Existing Dam.

NEED FOR RENOVATION

The dam's construction method comprises its problem- the sluiced fill materials. This material has a loose (or very loose) relative density. Consequently, the dam is susceptible to liquefaction during an earthquake. Figure 2 illustrates the different zones of the embankment distinguished by their placement - washed soils sprayed by monitor to form the sluiced core, the sluiced core itself, and the outer limits of the dumped fill soils that were not sprayed with water during sluicing. The top of the embankment is rolled fill.

Earthquake loads can cause extreme settlement in earth dams, and loss of strength of soils, resulting in a slide within the dam's slope. A large slide or settlement could result in breach of a dam. A breach of Saluda Dam presents danger for people and property downstream, as discussed above.

Paul C. Rizzo Associates (RIZZO) investigated the dam to evaluate the behavior during and immediately after a major earthquake. Based on the analysis, performed in accordance with the current Federal Energy Regulatory Commission (FERC) regulations, there is a significant potential for damage to the dam and potential for a breach under the dynamic forces caused by such an earthquake. Figure 3 illustrates the finite element liquefaction analysis of the dam and FS against slope failure in a post-earthquake condition.

Based on the results of the analyses, the dam requires remediation to comply with current FERC parameters for seismic loading—mainly because of predicted wide-scale liquefaction of the shells. As mentioned, the hazard posed by the dam is very high (the consequences of failure include loss of life). This hazard is the basis for the remediation, prevention of catastrophic flooding associated with failure. Accordingly, the Owner proceeded with remedial measures for

Saluda Dam.

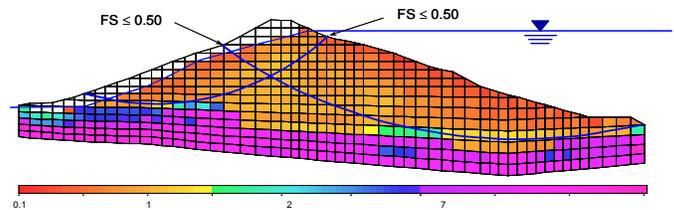


Fig.3. Liquefaction Potential Evaluation. Stability Analysis, Post-Seismic Conditions.

THE SOLUTION

Engineers developed initial solutions that did not require excavation, focusing on renovation of the dam by ground modification. Engineers examined alternatives including: a stability berm at the toe, deep soil mixing, and stone columns. An additional alternative combined deep soil mixing of a portion of the downstream shell of the dam with construction of a stability berm on the downstream slope and toe. All of these ground modification alternatives were discarded as unacceptable.

The Owner and Engineer found the cost excessive, mainly run up by the size of the dam. The Regulator had its own objections based on lack of performance history/data on such techniques as deep soil mixing for fills over 200 ft thick.

RIZZO also evaluated the alternative of draining Lake Murray and rebuilding the existing dam according to modern standards. But the Owner's requirements to minimize impact on the community, and not close the state highway along the dam's crest ruled out this alternative.

Due to problems with alternatives discussed above, the engineering focus turned to two primary remediation alternatives: 1. a massive rockfill berm on the downstream slope; 2. a new RCC gravity dam downstream of the existing dam. Engineers concentrated on the berm, as the more cost effective choice. In successive design iterations the size of the berm became successively larger. Finally design reached a point where building a new dam was more efficient than building the sizeable berm.

Engineers ultimately decided on the solution depicted on Fig. 4, a large new dam built immediately downstream of the existing dam. In this approach, the existing dam is left to impound Lake Murray. The new dam will be "dry," that is under normal conditions there will be a dry gap between the existing and new dams. The new downstream dam will impound water only if a sizeable earthquake were to cause the existing dam to breach (this event may never occur).

As Fig. 4 illustrates, engineers found that a combination of the rockfill and RCC Dams was required. For most of the alignment of the new dam there is sufficient room to build the design rockfill section. However, in vicinity of the powerhouse and the

Saluda River, there is insufficient space for the rockfill slope- its toe would cover the powerhouse and reach the river. Consequently, this portion of the dam compelled an RCC section for required renovation.

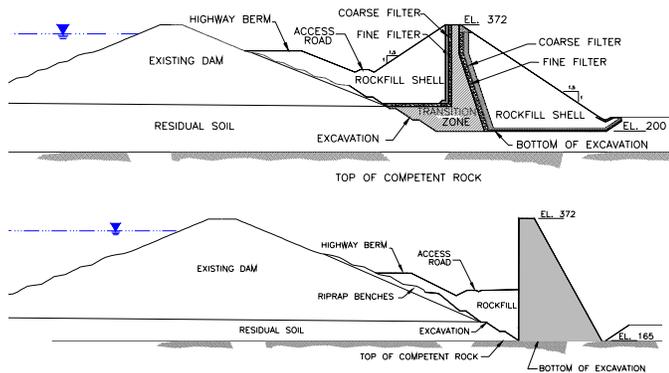


Fig. 4. Proposed Remediation: Rockfill Berm (top), and RCC Berm (bottom).

EXCAVATION

Construction of the remedial, dry dam entails excavation at the downstream portion of the existing dam. Soils susceptible to liquefaction were found in the foundation beneath the proposed new dam. In order to address the risk of settlement and strength loss due to liquefaction during an earthquake, excavation of foundation soils deemed inadequate- not dense enough or strong enough, must be excavated from the footprint of the new dam.

Construction of both the Rockfill and RCC sections shown on Fig. 4 entails excavation. However excavation requirements are different for these two structures. Rockfill excavation will reach a strong soil subgrade while RCC excavation will extend to rock subgrade. Engineers set up a main stipulation for design: No excavation into the existing dam.

Rockfill Section Excavation.

The depth of required excavation beneath the rockfill section posed a challenge. The challenge of this task was finding a balance between two excluding requirements – keeping the existing dam stable (which ideally would mean no excavation at all), and providing a suitable foundation for the new rockfill section, requiring extensive and deep excavation.

The established design criteria are summarized below:

1. No excavation into the original dam was allowed (i.e. upstream of the original dam toe)
2. A minimum depth of excavation of 10 ft was established to prevent piping through existing ground defects, such as tree roots, animal burrows, loose material, etc
3. The excavation depth is the same for the Transition Zone (i.e. core or central portion of the Rockfill Dam)

and downstream shell foundations, that is, no core trench.

4. Excavation Slopes

- Excavation slopes through residual soil were set at 1.5H:1V.
- Excavation slopes through riprap were set at 1H:1V.
- Excavation slopes along the original sluiced embankment fill were set at 2.5H:1V.

RCC Section Excavation

Determining excavation depth for the RCC section entailed the same challenge - balancing foundation requirements of the new RCC section with safety of the existing dam- a balance between extensive excavation and none at all. Engineers decided that the RCC section would require excavation to rock. A more shallow excavation in conjunction with grouting to improve the lower foundation soils was evaluated; however site conditions precluded this choice. For example, rubble and debris within the excavation footprint in vicinity of the powerhouse (left in place after original construction of the powerhouse) made the effectiveness of grout doubtful. Excavation design entailed excavation to sound rock, seepage control for artesian water pressure in the rock zone, and typical dental excavation, cleaning and backfill.

ENGINEERING AND CONSTRUCTION APPROACH

Excavation at the toe of so large a dam, impounding so large a lake is a dangerous undertaking. It would be a daunting task even if there were no downstream hazard. The hazard and consequences of failure in this case make it much more so. The consequences of failure demand a high factor of safety. (The only thing that stands between inaccurate analysis and unexpected failure is a sufficient factor of safety.) The concept entails powerful questions: How can it be done with safety assured? What factor of safety is considered sufficient considering consequences of failure?

Engineers set to work to answer the compelling questions. The basis of excavation design was slope stability. With a computer model of the existing dam in the excavated condition, with the cut slope configuration described above, shear strength parameters from extensive exploration and lab testing, the engineer team set out to determine dewatering and other excavation requirements to provide adequate factor of safety against sliding of the cut slope. Engineers adopted factor of safety for the excavation that matched the service, un-modified condition of the dam. Excavation has been 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 performed on undisturbed samples.

Dewatering to lower head within the dam and foundation is obviously required to maintain the factor of safety during

excavation, as addressed in the next section of the paper. Slope stability analysis performed for 26 cross-sections identified target levels for dewatering. Target levels, or target piezometric elevations within the dam were setup to provide adequate factor of safety against slope failure during excavation.

To further provide safety in excavation, engineers decided to excavate only in a limited area at one time. The new dam footprint was divided into a series of excavation cells. Cells near maximum section, where the dam is tall and excavation is deep were designated as critical. Engineers then established rules governing excavation. Rules require excavation of only one critical cell at a time. More than one non-critical cell may be excavated at once, provided they are separated by a minimum 1,000 ft. Excavation in a limited extent, in cells, should enhance stability in the cut slope by mobilizing soil shear strength in a 3 dimensional aspect, versus a 2 dimensional, plane strain condition.

Excavation and backfill work at each cell will be performed on a round-the-clock basis until the cell backfill reaches the designated backfill elevation- set up around the original ground elevation prior to excavation. Excavation at the toe must be done as rapidly as safety and practicality will allow, so that backfill can be placed as soon as possible.

DEWATERING

The objective of dewatering is lowering head within the existing dam and foundation to the target levels determined from stability analysis. Knowing existing head in the different zones of the dam and foundation prior to excavation, and knowing the required drawn-down target levels from the stability analysis allowed engineers to decide on required methods to dewater the dam and its foundation. Dewatering design was set up around the idealized cross section shown on Fig 2. This idealized cross section has 3 layers: 1. broken rock foundation with artesian head; 2. foundation soil layer (residual soil for all but a small portion of the dam where alluvium is encountered near the river); 3. embankment fill.

The typical dewatering system is illustrated on Fig 5. The components of this system are described below:

1. Deep wells. Deep wells are drilled down into the broken rock layer. Their function is the relief of artesian head in the rock layer. Typical depth of the deep wells ranges from roughly 150 to 320 ft. Nearly 100 deep wells were installed on the project.
2. Eductors. Eductors are used to dewater the embankment fill and foundation soil beneath the embankment. An eductor system uses a venturi to draw groundwater into the well screen and up a riser pipe to the header pipe at the surface. Eductors can lower the water table by as much as 80 ft from the top of the excavation as opposed to approximately 15 ft for a single stage well point system. For most excavations, phreatic head had to be lowered more than 15 ft to reach target level. For this

reason, eductors were a better choice than well points. Eductors on the project range in depth from roughly 30 to 70 ft. More than mile and a half of eductor lines is currently in operation.

3. Vacuum Wells. These wells have the same function as the eductors. They are installed in isolated places where lines of eductors cannot be placed (e.g. within the excavation), or where eductor lines are not as effective as required. Vacuum well depth is typically 20 to 30 ft.

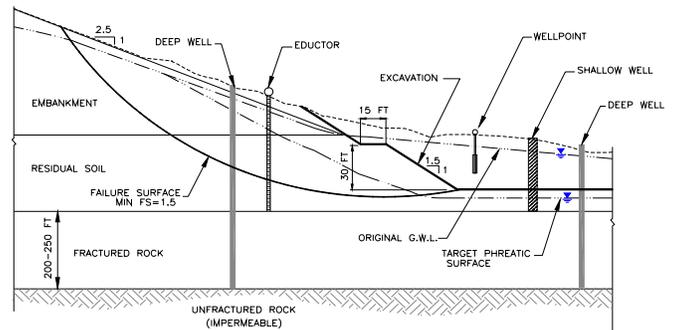


Fig. 5. Typical Excavation Dewatering System.

EXCAVATION INSTRUMENTATION

RIZZO developed a detailed excavation monitoring program to detect any problems with the existing dam during construction activities. The main focus of the instrumentation program is timely measurements of deformation and soil pore water pressure within the embankment and foundation soils and assessment of incoming measurements. Engineers interpret collected data and visual observations and determine if they are within acceptable ranges or indicate a potentially unsafe condition.

The primary instruments to detect and predict slope failure or bottom heave are piezometers and inclinometers. They are supplemented by surface monuments/laser lines. Data from these instruments is used to identify the extent of any movement and to guide subsequent remedial actions.

Inclinometers

Typically, three rows of inclinometers are installed above each excavation cell, as shown on Figure 6, with a total of 65 for the entire dam. These instruments are used to measure subsurface deformations caused by slope movements. An inclinometer consists of a grouted-in grooved casing that is read using a level-sensing probe manufactured by Slope Indicator. Typical depth of inclinometers on the project varies from 50 ft to 140 ft. Most of them extend down to weathered rock. However where the residual soil layer is thick the casing is terminated in competent residual soil. Any movement shown in inclinometers can be verified by means of a laser shot through a line of targets or by GPS surveying of monuments.

Piezometers

Electric vibrating wire (vw) diaphragm piezometers were chosen to monitor pore water pressure within the dam during excavation. Vibrating wire piezometers “pluck” a wire attached to a diaphragm. As the tension in the wire and thus its vibrating frequency vary in proportion to the pore pressure against the diaphragm, the pore pressure can be determined. Engineers selected vw piezometers over other types (such as open standpipe), because of their quicker response time, ability to measure negative pore water pressure, and automating capability. Significant time and cost was saved by choosing to install spring-activated vw piezometers (Model 4500-MLP, Geokon, Inc.) without a sand pack using the “fully-grouted” installation method (Mikkelsen, 2002). Typically, two transducers are deployed per borehole as shown on Fig 6. In total, more than 100 multi-level vw piezometers are placed in this fashion within the dam. Engineers monitor water pressure within the embankment and residual soil layers to ensure dewatered status of the dam and to detect any changes in pore pressure that could indicate a developing failure.

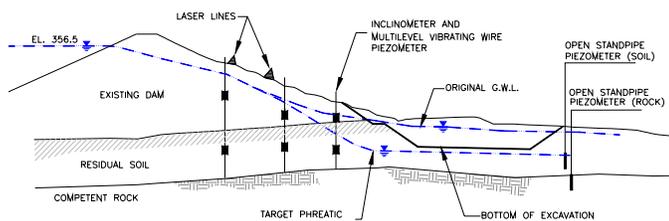


Fig. 6. *Typical Instrumentation Installation.*

Tiltmeters

Tiltmeters will be deployed to monitor movement of structures adjacent to the Saluda Powerhouse. Tiltmeters will be installed during excavation in this area to monitor penstocks and circulating water pipes, and to monitor an existing concrete retaining wall behind the Powerhouse. The penstocks and circulating water pipes are subjected to the full head of Lake Murray. Because the consequences of damaging the penstocks or circulating water pipes are significant, it is important that all structures are closely monitored for potential deformations.

Because of the risk associated with excavation and the consequences of failure, the instrumentation program must operate to obtain, reduce and interpret data as quickly as possible. Engineers have to assess constantly changing, dynamic conditions associated with the fast pace, round-the-clock excavation and draw conclusions in a timely fashion. To accomplish this difficult goal, RIZZO set up a highly automated monitoring system. All vw piezometers in an Active Zone (defined as an open excavation cell and its two adjacent cells) are read using automated methods. Vibrating wire piezometers installed in the dam above the cut are wired to a CR-10 datalogger (Model 8020 MICRO-10, Geokon, Inc.) which converts raw data into pore pressure and then transmits this data

to the construction trailer via radio link. Piezometers nearer to the cut are wired to single-channel dataloggers (Model 8001 LC-1 Geokon, Inc.) which must be downloaded in the field with a laptop computer. The other key feature of the automated system is a wireless computer network (LAN) that covers the entire dam. This wireless network allows an engineer in the trailer to view inclinometer, piezometer, or tiltmeter data directly after it is downloaded to a laptop in the field. Critical time is saved by the ability to see all data in a real-time fashion using the LAN and automated dataloggers.

Excavation Monitoring Plan

The purpose of the plan is ensuring that the existing dam behaves as predicted during excavation, and does not show evidence of impending movement, excessive settlement, erosion due to seepage, or other sign of potential distress.

The plan must have action built in. It is insufficient to simply deploy instruments and watch them. One must know what it is the instrument should tell us, and what we will do as a result of its measurements.

Accordingly, the plan spells out the action levels in response to instrument readings. During excavation, engineers must constantly assess instrumentation data, determining if measurements fall within expected, acceptable ranges or indicate a potentially unsafe condition. As excavation proceeds, engineers expect deformation within the existing dam to a small extent. Engineers must evaluate this deformation, including site observations; the depth, extent, rate, and location of the deformation; and whether the deformation appears to be in response to specific construction activities.

Threshold values of instrumentation measurements are established to indicate appropriate action in response to the measurements. Response action is organized into four levels:

1. Alert State;
2. Warning State;
3. Stop work; and
4. Implement emergency measures such as backfilling the excavation.

The Plan contains the criteria and threshold values defining each of these action levels. Criteria for effects such as piezometer rise, inclinometer movement, rate of deformation and tolerable magnitude of these effects are contained in the Plan. Specific steps for the Engineer, Owner, and Contractor are diagrammed for each of the action levels. Related to the fourth action level, the project has a Construction Emergency Action Plan.

Procedures and Frequency of Measurements

Monitoring is accomplished by two independent methods: 1. visual observations by trained engineers; 2. by measurements

from the instruments discussed above. These two methods are engaged to detect evidence of distress—specifically, movement, high water pressure, settlement, and erosion. Monitoring of an excavation cell begins long before excavation commencement and continues 24 hours a day, 7 days a week after the cell is open. At the initial stages of excavation, every instrument is read at least once per shift. As excavation approaches the planned subgrade elevation, frequency of measurements is increased.

Vital clues as to the dam's behavior and potential failure modes developing can be missed if engineers focus on reading instruments only. To avoid such a scenario, Dr. Ralph Peck (a member of the project's Board of Consultants) has called for a proactive approach including intense observation of the dam to evaluate and predict response prior to indications by instruments. By carefully observing the dam's condition and response, correlating it with construction activities, a much more proactive approach is effected. *Is movement normal reaction of soil mass or beginning of unpredicted, unanticipated slide?* Engineers must answer this fundamental question when early, small movements or water pressure changes are detected.

CONCLUSION

Herman Melville said that "Ignorance is the parent of all fear." Excavation in this project illustrates his remark, a remark about fear of the unknown. If we knew how the dam would behave during excavation, there would be no fear associated with it.

In fact we do not know how the dam will behave. We know only of the consequences of failure. We know by experience that in saturated soil conditions, bad things happen. Slides develop in slopes, soils soften and lose strength, boils and internal erosion develop if the gradient is too high. At the start of construction, whether these troubling things develop remains to be seen. Accordingly, excavation for this project is a daunting task. As engineers explained to the Owner and Regulator as they developed the instrumentation/monitoring program, until the excavation is made we won't know how big the dragon is.

Engineers make predictions about the dam's response to excavation, about its stability. But we cannot wait until after excavation, when the bottom is down to subgrade to evaluate the accuracy of those predictions. Engineering practice is

comprised of making predictions prior to construction, and then making observations during construction to evaluate the predictions' accuracy. The main function of instrumenting and monitoring the excavation in this project is evaluating stability, to ensure that predictions of stability are accurate. If predictions are inaccurate, and stability is in question, we need to know as early on as possible. Instrument data and interpretation are the tools to give us those indications.

To guide in interpreting data and making decisions, engineers prepared a Monitoring Plan. Engineers can change that plan as required as the dam responds to excavation and shows us what to expect. As excavation proceeds, the dam shows us its response; the unknowns, or using Melville's term- ignorance decreases. The fear decreases proportionately.

Our conservative approach to engineering reflects fear of the unknown, manifesting in the factors of safety that we apply, and what we term judgment. Factors of safety reflect what we don't know about the particular structure and foundation that we're analyzing, and must also reflect the consequences of failure. Given the high consequence of failure in this case, appropriate factor of safety was difficult to identify. The only thing that stands between inaccurate analysis and unexpected failure is sufficiently high factor of safety; this tenet is the guideline for setting factor of safety.

A prominent tunneling engineer remarked that "The ground has no commander." Instrumentation and its monitoring must be set up with this facet in mind- to listen to the dam, realizing that it doesn't know how we expect it to behave, and realizing that we cannot command it

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