LIQUEFACTION OF EARTH EMBANKMENT DAMS
TWO CASE HISTORIES:
(1) LIQUEFACTION OF THE EMBANKMENT SOILS, AND
(2) LIQUEFACTION OF THE FOUNDATIONS SOILS

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ABSTRACT

Paul C. Rizzo Associates, Inc. (RIZZO) has developed efficient computational tools to evaluate the liquefaction potential of earth embankment dams located within high risk seismic regions. Two relevant case histories are the Saluda Dam and the Santee Cooper East Dam Extension, both structures susceptible to liquefaction, and located in South Carolina. Saluda Dam presents liquefaction risks within the materials that comprise the embankment itself. The earth structure is resting on a layer of non-liquefiable residual soil. On the contrary, the Santee Cooper case presents liquefaction risks within the foundation soils. These facts translate into post-earthquake slope stability processes that are quite different in nature. Remediation strategies are different as well and need to adapt accordingly.

RIZZO has evaluated the liquefaction potential and established remediation plans and designs at each of these two sites. Computational tools developed by the industry and complemented with RIZZO expertise were utilized to identify liquefaction susceptibility both at the foundation and/or within the embankment soils. The remediation concepts between both cases significantly differ. This paper presents the two case histories by comparing their liquefaction analyses results, their feasible remediation alternatives, and their selected remediation concepts. The same in-house computational tool is used to analyze the two cases.

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Paul C. Rizzo Associates, Inc. (RIZZO) has been involved in the evaluation of the liquefaction potential of earth embankment dams located within high risk seismic regions, specifically in the state of South Carolina, where the seismic criterion is controlled by one of the largest earthquakes ever to occur in the northeastern region of the United States, the 1886 Charleston Earthquake. Today, engineers anticipate that a similar earthquake, with an estimated Richter scale magnitude between 7.1 and 7.3, could occur again sometime in the next 650 to 1000 years.

Two relevant cases of dam liquefaction potential are the Saluda Dam (Saluda) and the Santee Cooper East Dam and East Dam Extension (East Dam), both structures susceptible to liquefaction, and located in South Carolina, within the influence area of the 1886 Charleston Earthquake (Figure 1).

Figure 1 – Location of the Saluda and East Dam Projects; for the sites, the Charleston 1886 earthquake’s Mercalli magnitude is estimated between X and IX, and it has been established as the Design Seismic Event (DSE).
Saluda Dam presents liquefaction risks within the materials that comprise the embankment itself. The earth structure is resting on a layer of non-liquefiable residual soil. On the contrary, the East Dam case presents liquefaction risks within the foundation soils. These facts translate into post-earthquake slope stability processes that are quite different in nature. Though both Saluda and the East Dam are earth-fill retention structures, their geometry and characteristics are quite different in nature. Table 1 presents the main features of both projects, including also the volume of water retained. Both reservoirs are essential for local economic activities and should any of them fail, a considerable amount of people downstream of the facilities would be in jeopardy. Liquefaction failures, such as the 1925 Sheffield Dam in Santa Barbara or the 1971 Lower San Fernando Dam, should be prevented at these facilities.

Table 1 – Saluda and East Dam project main features

<table>
<thead>
<tr>
<th>Concept</th>
<th>Saluda</th>
<th>East Dam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Earth Fill Dam</td>
<td>Earth Fill</td>
</tr>
<tr>
<td>Height (ft)</td>
<td>220</td>
<td>36</td>
</tr>
<tr>
<td>Length (ft)</td>
<td>7,800</td>
<td>3,1680</td>
</tr>
<tr>
<td>Lake</td>
<td>Murray</td>
<td>Moultrie</td>
</tr>
<tr>
<td>Lake Surface (acres)</td>
<td>50,000</td>
<td>60,000</td>
</tr>
<tr>
<td>Live Capacity (ft³)</td>
<td>$6.8 \times 10^{10}$</td>
<td>$3.2 \times 10^{10}$</td>
</tr>
<tr>
<td>Dead Storage (ft³)</td>
<td>$1.6 \times 10^{10}$</td>
<td>$1.8 \times 10^{10}$</td>
</tr>
<tr>
<td>Total Capacity (ft³)</td>
<td>$8.4 \times 10^{10}$</td>
<td>$5.0 \times 10^{10}$</td>
</tr>
<tr>
<td>Year built</td>
<td>1929</td>
<td>1941</td>
</tr>
<tr>
<td>Main Use</td>
<td>Recreation, Cooling</td>
<td>Recreation, Water Supply</td>
</tr>
</tbody>
</table>

RIZZO has evaluated the liquefaction potential and has established remediation plans and designs at each of these two sites. Computational tools developed by the industry and complemented with RIZZO expertise were utilized to identify liquefaction susceptibility both at the foundation and/or within the embankment soils. The remediation concepts between both Saluda and the East Dam significantly differ. The following text presents a summary of liquefaction analysis for each case and their results, their feasible remediation alternatives, and their selected remediation concepts.

Liquefaction in Dams

The term liquefaction is used to describe large deformations occurring in a soil mass caused by monotonic, transient disturbance of saturated cohesionless soil (Mogami, 1953). Generation of excess pore pressure under undrained loading is the main ingredient for liquefaction, since it is directly related with a sudden decrease of the effective shear
strength of the soil. In the evaluation of the liquefaction hazard it is required to (a) determine the soil susceptibility to liquefaction, (b) determine the potential for liquefaction to be triggered, and (c) estimate the extent of damage.

The previous concepts apply to any earth retaining structures that is contact with water and located in seismic regions, such as an earth fill dam. In such cases liquefaction potential may exist either in the embankment material itself, the foundation alluvial (in case the dam is resting on soil), and/or the abutments.

**Saluda and East Dam: Susceptibility to Liquefaction**

Saluda and the East Dam are both earth fill water retaining structures, but quite different in nature, as shown by the numbers of Table 1. Both dams give origin to high capacity impoundments, and are therefore classified as high hazard dams. If Saluda Dam would fail, more than 120,000 people would be in jeopardy and water and power provided by the project would be immediately lost. In the case of the East Dam, the damage would reach state wide concerns.

Susceptibility to liquefaction is determined by means of a geotechnical exploration program. The results of such programs indicate that Saluda is a sluiced-core, earth fill dam that is resting on top of a dense, highly compacted, and geotechnically competent residual soil, as shown schematically by the cross section in Figure 2. Some portions of the dam are lying directly on top of bedrock. The height of the largest section is approximately 220 ft and both upstream and downstream slopes have an inclination ranging from three (3) horizontal to one (1) vertical. The fills adjacent to the core are washed fills while the exterior portions remained unwashed. The embankment materials are susceptible to liquefaction, presenting \( (N1)_{60} \) values below four (4). The cross section shown by Figure 2 is obtained from the original 1929 construction drawings,
complemented by various RIZZO’s geotechnical subsurface exploration programs. The relatively elevated location of the piezometric line is the result of the loss of effectiveness of the impervious core and another indication of the susceptibility to liquefaction.

Figure 3 – Typical cross section of the East Dam that is susceptible to liquefaction; in this case, the foundation will present the largest potential.

The East Dam and East Dam Extension (Figure 3) are earth embankment structures constructed from rolled-fill consisting of competent clayey soils. The foundation soils are generally unconsolidated sediments and contain low-blow-count sand and clayey sand layers which are susceptible to liquefaction. The thickness of the low-blow-count sand layers underneath the East Dam and East Dam Extension ranges from 5 feet to 25 feet. A continuous very loose sand layer with \( (N1)_{60} \) less than 4 was encountered along the entire length of both Dams. This layer generally alternates with lenses of medium stiff to stiff clay and layers of medium dense to dense sand. A typical cross section is shown by Figure 3.

**Potential for Liquefaction**

There exists the potential for liquefaction in both dams, as shown by the dynamic quasi-linear FEM analysis shown by Figure 4. The figure presents a graphic representation of the Factor of Safety against Liquefaction \( (FS_L) \) obtained from the coefficient Cyclic Resistance Ratio \( (CRR) \) and the Cyclic Stress Ratio \( (CSR) \):

\[
FS_L = \frac{CRR}{CSR} \tag{1}
\]

The liquefaction potential was determined with the approach developed by Professor H. Bolton Seed and his colleagues at the University of California at Berkeley (1984). Even More recent work concerning the evaluation of liquefaction resistance of soils is
presented in the proceedings from National Center for Earthquake Engineering Research (NCEER) Workshop (NCEER, 1997).

Figure 4 – Liquefaction potential; orange to red elements or squares relate to zones that are likely to undergo liquefaction. It is evident that Saluda is prone to liquefaction within the embankment itself, while at the East Dam it is the foundation alluvial that is at risk.

The CSR is the ratio of the average cyclic shear stress ($\tau_{ave}$) to the vertical effective overburden stress ($\sigma'_v$). The average cyclic shear stress ($\tau_{ave}$) is defined as 65 percent of the maximum computed shear stress in the soil (Seed et al., 1984). The CRR was determined by procedures established in the NCEER Workshop, which focused on evaluating the liquefaction resistance of soils, and was intended to supplement the simplified procedure developed by Seed. These procedures estimate of the capacity or in-situ liquefaction resistance of the soil, as a direct function of the corrected Standard Penetration Test (SPT) blow counts.
The dynamic quasi-linear, finite-element analyses of the Saluda and East Dams are performed using the QUAD-4M computer program (Idriss et al., 1994) to calculate the seismic shear stresses. QUAD-4M computes the dynamic response (based on seismic input record) of an earth embankment or slope in the time domain using a variable-damping, finite-element computational approach. Non-linear stiffness and damping parameters are incorporated into the analysis through the use of equivalent linear, strain-dependent material properties published in the literature. The equations of motion are then solved by step-by-step numerical integration. The input ground motion was a set of six earthquakes with the magnitude and dynamic spectrum to resemble the effects of the 1886 Charleston earthquake.

The control point used for the dynamic analysis (i.e., point where input acceleration time history is applied) is the bottom of the model below the residual soil. Thus, the acceleration time histories to be used in the dynamic analysis are assumed to be the motion of the rock beneath the soils underlying the Dams.

An in-house front-end computer program (Liquefier V1.0) was developed to perform integral liquefaction potential calculations and to perform the post-processing required for the liquefaction analysis. Liquefier V1.0 significantly reduced the amount of time required to do the analysis and greatly reduces the chance for human error. The results of the analysis are equivalent to those shown by Figure 4.

The non-liquefiable portion of the foundation of the East Dam corresponds to stiff and hard clayey soils with higher penetration resistance and adequate capacity to limit increases in pore pressure that could take the soils into an unstable condition. The embankment materials are in good condition as well, and the location of the piezometric line confirms this assertion. The liquefaction potential presents itself in layers of loose sands that surround the clay.

The clear difference in the location of the liquefaction susceptible regions will translate into potential hazards that are both different in nature and extension. Such difference will also show in the possible remediation options for each of these two Dams.

**Extent of Potential Damage**

The final step in the liquefaction evaluation process is to assess the extent of damage involved after the liquefaction triggering phenomena. For the case of an earth fill embankment, it is the post-earthquake slope stability condition that requires close attention. Case histories (Sheffield Dam- 1925, Lower San Fernando Dam125) have corroborated that failure occurs some seconds after the strong motion of the earthquake has finalized. The lag finds its cause on the time it takes for pore pressures to build up amongst the voids of the liquefiable soils.
Post-earthquake slope stability analyses were performed using the UTEXAS3 (Wright, 1991) computer program. Undrained residual shear strength is assigned to embankment or foundation zones that present an $F_{SL}$ lower than one (1). For the Saluda, this strength was usually below 200 psf, a relatively low value that is an indicator of slope stability problems and that results from low $(N_{1})_{60}$ values. Zones with $F_{SL}$ larger than (1) are assigned with a shear strength reduced by the effects of increased pore pressures. Once the strength zones are determined, the slope stability analysis is performed to determine the overall Factor of Safety (FS).

Figure 5 – The hazard potential exists for both cases: (a) Saluda, due to the failure of the embankment; (b) East Dam, due to the failure of the foundation

For the case of Saluda, the FS is less than 0.5. The depth of the failure follows the lower portions of the areas that are shown in red (liquefied zones). Figure 5 shows some typical failures that present FS less than 0.5. The Post-Earthquake condition of this section is
unstable, both in the upstream and downstream slopes. A catastrophic failure may occur after the triggering of liquefaction, resulting in loss of freeboard and severe flooding.

At the East Dam, the critical failure surfaces are the deep wedges in the downstream slope. With respect to the Upstream Slope, the FS is acceptable throughout most portions of the Dam. The Factor of Safety against downstream failure is less than that for the upstream case. Upper sands in the foundation that are susceptible to liquefaction do have higher (N1)60 values (12-15 psf). The residual shear strength does provide the soil with resistance to slope upstream failure.

**Remediation**

In order to be successful, the remediation strategy needs to consider each of the steps of the liquefaction analysis process. A liquefaction hazardous condition may be addressed at the susceptibility to liquefaction itself. For example, removal and replacement of soils is a good example that is commonly applied in the foundation building practice. Evidently, this alternative would be quite costly in a Dam and Reservoir Project. A second approach would be to decrease the potential for liquefaction. In this case, practices such as grouting, soil reinforcement, and drains or stone columns to reduce the amounts of pore pressure increase are usually implemented. Finally, the remediation approach may attack the problem at the damage extent level, as would be the case of containment walls, berms, or other structures.

To decrease the potential for liquefaction it is possible to either perform measures directed to increase the CRR or decrease the CSR. A typical example of increase in the CRR would be densification of soils for the improvement of the penetration resistance. On the other hand, a decrease in the CSR may be attained by increasing the effective vertical stress with overweight material or drains, or by decreasing the dynamic shear stress with modifications in the shape of the liquefiable soil mass.

The following paragraphs and figures present the adopted remediation measures that are currently under implementation at the Saluda and East Dam sites. The measures were selected given the particular conditions at each site, especially the magnitude, shape, and location of the slope stability failure planes, as shown by Figure 5.

**Saluda Dam**

This remediation concept began with the idea of constructing a large magnitude downstream berm like the one shown in Figure 6. The berm would be placed up to an elevation two feet greater than the Normal Pool Elevation (El. 358). This soil structure will create a virtual dam that would prevent crest overtopping in the event of liquefaction of Saluda. The berm would both increase the effective vertical strength at downstream slope and would form a virtual dam that would serve as a containment structure for any
liquefied material. Therefore, this remediation option would both address the potential to liquefaction and the related hazard.

The second and implemented approach considered to move the virtual dam further back. Instead of increasing the effective vertical stress, this option considered the removal of the liquefiable toe and the placement of a new containment structure. This new structure will retain both water and soil flows that could result from the liquefaction triggering. A portion of the new containment structure is a rock fill and another, between Saluda Dam and the powerhouse, is a Roller Compacted Concrete (RCC) Dam (Figure 7). This option addresses the susceptibility and the hazard levels.

Figure 6 – First remediation approach considered for Saluda Dam

Figure 7 – RCC and Rockfill at Saluda Dam; remediation efforts are currently under construction and close to completion
**East Dam**

Remediation of the East Dam Extension should take into account the marginal Factor of Safety against Downstream Slope Failure, the relatively shallow water depth, and the conservative height of the freeboard relative to the depth of the impounded water. Remediation efforts are directed toward possible deep failures on the Downstream Slope, using a combination of (1) vertical drains, (2) stone columns, and (3) downstream berms. In this case, the expected type of slope failure allows addressing the problem directly at the liquefaction potential stage. The solution considers increasing the effective vertical stress by both adding weight over and reducing pore pressure from the potentially liquefiable zones. The purpose is to interrupt the progress of the post-earthquake slope stability failure, which could not be the case with conditions such as those presented in at Saluda Dam. Figure 8 presents a schematic drawing of the remediation approach selected for the East Dam.

![Figure 8 – Remediation concept at Station 40+00 of the East Dam; combination of berms, treated zones, and stone columns](image)

**Conclusion**

Liquefaction may present itself in different forms and magnitudes and it requires a detailed investigation, from susceptibility to hazard potential, in order to elaborate an optimal remediation approach. Such investigation involves field activities, analysis, testing, and interaction with regulators and the community. At Saluda and the East Dam, the process from the first studies to remediation works is taking close to fifteen (15) years.

The two case-histories presented in this paper are good examples that present the different stages of liquefaction analysis in earth fill embankments. The remediation approach is substantially different for each case, basically adapting to the extent and shape of the potential hazard that is generated from the occurrence of liquefied soils.