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EVENT TREE ANALYSIS FOR AT THE SAVANNAH RIVER SITE – A CASE HISTORY

ABSTRACT

At the Savannah River Site (SRS), a Department of Energy (DOE) installation in west-central South Carolina there is a unique geologic stratum that exists at depth that has the potential to cause surface settlement resulting from a seismic event. In the past the particular stratum in question has been remediated via pressure grouting, however the benefits of remediation have always been debatable. Recently the SRS has attempted to frame the issue in terms of risk via an event tree or logic tree analysis. This paper describes that analysis, including the input data required.

PREFACE

Over the years Clyde Baker has been involved with many interesting and varied projects; however the projects that most often come to mind when thinking of Clyde are those associated with the tallest buildings in the world, as evidenced by his recent Terzaghi Lecture. Obviously these projects were filled with many challenges and obstacles that Clyde successfully overcame, but one common denominator in all of them is performance, particularly settlement performance. In that context, this paper attempts to frame a unique settlement issue for critical structures at the SRS in terms of probability of exceedance via a decision or logic tree analysis.

INTRODUCTION

The SRS is a DOE installation located on the Savannah River in west-central South Carolina (see Figure 1). The site has been a mainstay of the DOE defense-related infrastructure since the early 1950s. Currently, SRS is focused on environmental cleanup activities; however critical facilities related to the national defense program are stilled being planned, designed, and constructed. As part of the ongoing environmental and defense-related mission, geologic and geotechnical investigations are and will continue to be performed. Foundation performance, in terms of acceptable settlement, is a key attribute in the design process that requires assessment. An event tree or decision tree analysis provides for a systematic approach to organize or frame particular issues related to a site or a structure, such as settlement. In this particular case, unique subsurface conditions related to compression of "soft zones" within a particular geologic stratum are framed in a way that results in determining the probability of exceeding surface settlement for a given site. This result becomes important in the overall management of the SRS in terms of overall SRS site risk, and therefore, where to spend the precious funds that are seemingly shrinking for the defense-related mission.

BACKGROUND

The analysis of a particular site at SRS can be based on site-specific parameters for the given site or known parameters for neighboring sites, which have been largely studied in the past, or a combination of the two. Probabilities of occurrence (and probability distribution functions) may be applied to parameters of the geologic stratum such as soft zone occurrence, geometry, and compressibility, as well as analytical considerations such as 2 dimensional (2D) and 3D, as applicable.

The results are summarized in the form of a cumulative distribution function of settlement, which can be used to aid decision-makers and engineers in determining the overall site acceptability and risk in terms of settlement. For established sites, the results can be used in a probabilistic design approach to demonstrate regulatory requirements, in terms of overall probability of exceedance, are met, or in a more deterministic approach.

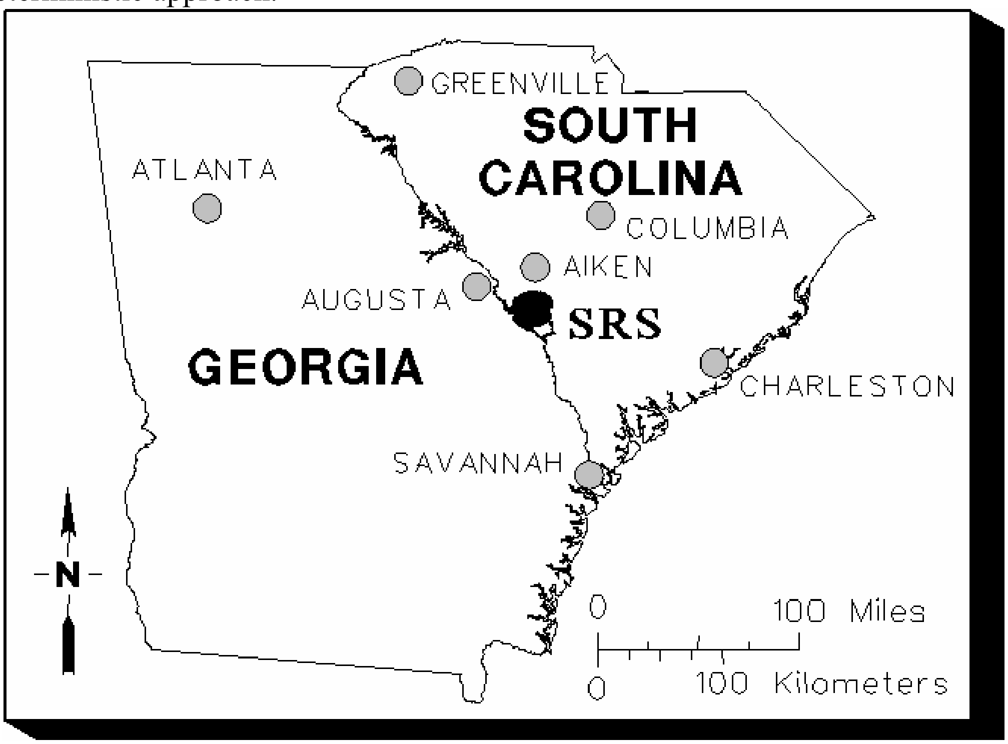

FIG. 1: Location of SRS

This paper will focus on the development of the an event tree, and the input data required, to help decision makers understand more fully the risk involved with regard to structure settlement resulting from these soft soil zones. This paper will not address the merits of soft zone compression itself and resulting surface settlement, and whether or not it is real or perceived.

SOFT ZONE HISTORY

Many past and current investigations have determined that weak or underconsolidated zones of various lateral extent and vertical continuity occur in the sedimentary strata that underlie SRS. Figure 2 is a generalized subsurface profile highlighting the formations and conditions in the central portion of the SRS. These zones occur mostly in the uppermost 30 to 60 meters (100 to 200 foot) section and especially in the lower Dry Branch Formation and the Tinker/Santee Formation. These zones or lenses of quartz sand, calcareous sand, limestone, clay, and marl were deposited during the middle to late Eocene epoch (50 to 35 million years ago) in shallow marine environments. At the SRS these are commonly referred to as soft zones.

Several hypotheses exist regarding the processes responsible for soft zone formation; all share a common assumption that soft zones result from post-depositional and/or early diagenetic changes (in other words, the soft zones were not originally deposited as weak or "low strength" materials). One prevailing idea, which is supported by a substantial body of geologic, geochemical, and mineralogic evidence collected at SRS, invokes the percolation of groundwater and the dissolution of carbonate material and partial replacement by silica over time. This process results in a residuum (soft zone) that is porous but still self-supporting, not unlike a "honeycomb" or sponge-like structure (WSRC, 1999). Typical standard penetration test (SPT) N-values are near 0 to weight of rods, and cone penetration test (CPT) tip resistances are in the range of 475 to 950 kPa (5 to 10 tons/ft^2, tsf). Regardless of the process however, it is clear that these soils are soft and loose and are suspect with respect to potential structure settlement.

At the onset of the early U.S. Army Corps of Engineers (COE) investigation programs at the SRS (early 1950s), the COE recognized that the weaker zones within the Tinker/Santee Formation had to be addressed beneath critical facilities (COE 1952a and 1952b). Thus, possibly due to investigation and analytical tools available at the time, and partly due to schedule concerns (note this was at a time in our history that required immediate action regarding construction of the necessary infrastructure needed to support national defense-related programs), the COE decided to remediate and embarked on an extensive investigation and pressure grouting program (albeit low pressure) of the soft soils beneath the foundations for critical facilities. However, present day exploration and analysis techniques have allowed for more extensive exploration programs, including more sophisticated laboratory testing to more fully characterize these zones, as well as more sophisticated analyses to assess the potential impact these soft zones have on surface or near surface facilities. It is these results that have allowed us to gain a better understanding of these soft zones and resulted in the application of the event tree analysis described herein.

SOFT ZONE SETTLEMENT MECHANISM

The material comprising the soft zone is more deformable and more compressible than the original (unaltered) sediment. In general the materials consist of very loose and very soft fine sands, silty fine sands, clayey fine sands, silts and clays of various combinations. The *in situ* vertical effective stress acting on the soft zone is less than the vertical effective stress at the same depth in a region that does not contain a soft zone. In other words, the dissolution and partial replacement by silica *in situ* and the subsequent redistribution of vertical overburden stress have created a zone in which the vertical effective stresses are less than would be computed by simple summation of overburden effects. Since the existing vertical stresses acting on the soft zones are less than the apparent geostatic stress (P'_{0G}), these soils may be described as "underconsolidated" with respect to the vertical stress at an equivalent depth in unaltered matrix soils (non-soft) surrounding the soft zones.

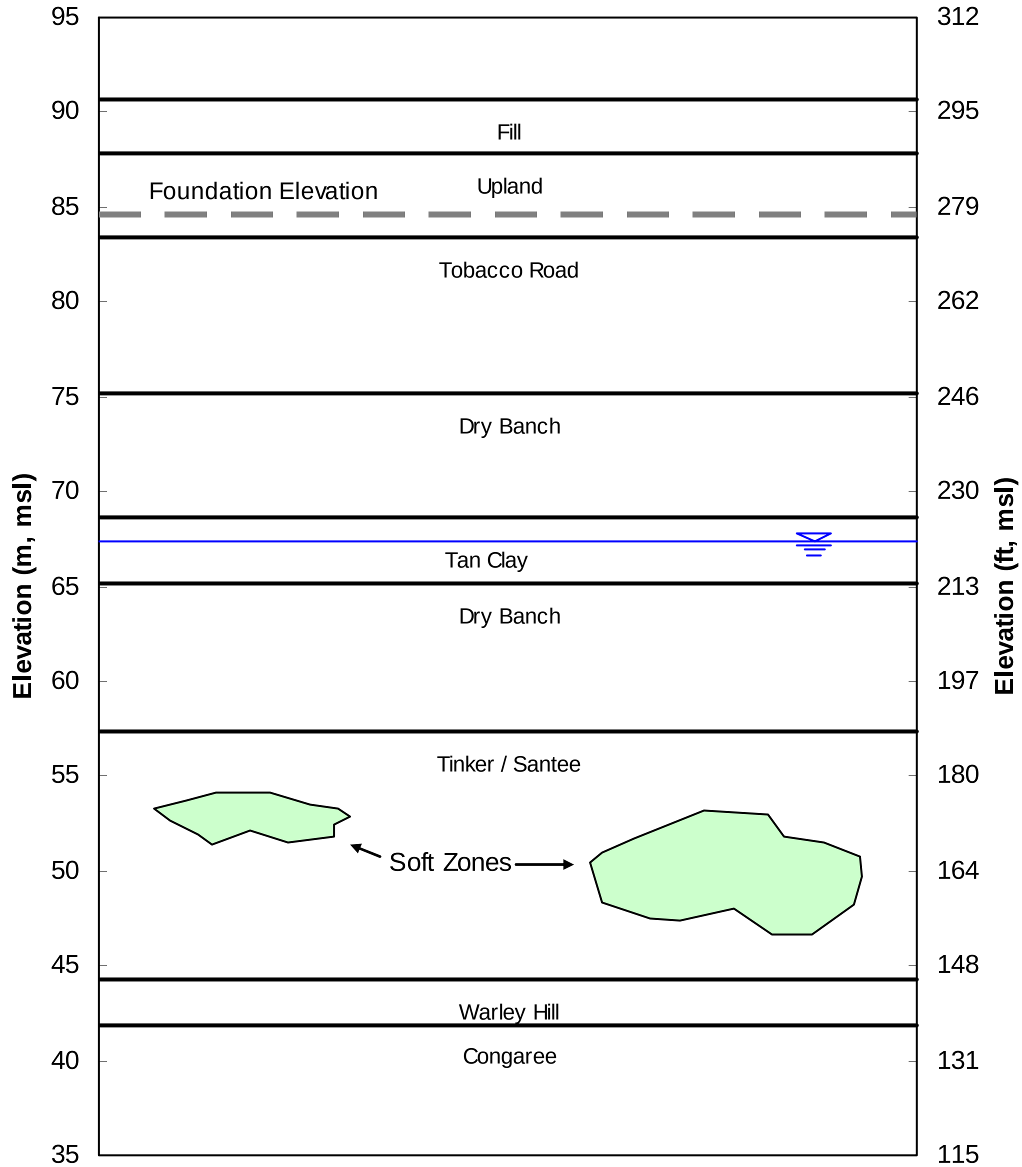

FIG. 2: Generalized Geologic Profile

Even though the soft zones are "underconsolidated" with respect to geostatic stress, they are assumed to be normally consolidated within their stress regime (i.e., within the area/volume of stress redistribution or arching). The condition of lower-than-geostatic stress is possible because of the relatively strong matrix soils (carbonates) surrounding the soft zones and the relatively density of overlying sands (in this case, sands of the Dry Branch Formation). Thus, when a consolidation test is performed on an intact specimen of soft zone soil (which, admittedly is difficult to obtain), the preconsolidation pressure (P_C) determined is assumed to be the effective vertical stresses acting on the soft zone (i.e., OCR of 1 within the soft zone stress regime).

However, the P_C computed for a soft zone will be less than the geostatic stress (P'_{0G}), hence the term “underconsolidated”.

In general, it is thought that under static conditions the soft zones are too small laterally and too deep to have an affect on surface structures. Based on measured settlement data and actual performance of the many facilities at the SRS since construction began in the early 1950s, this has been found true. However, what cannot be quantified in detail is the effect that a seismic event would have on the state of apparent equilibrium within and around the soft zones below the SRS. Thus, for the design of critical facilities, it has been assumed (for the past 20 years or so) that the full overburden pressure is transferred to the soft soils at depth following the design basis earthquake, and that the settlement at depth propagates to the ground surface. This basic design assumption and the general simplified computational philosophy have been utilized at SRS for a number of years. The simplified analytical philosophy relies on consolidation theory to determine soft zone settlement at depth and on empirical correlations used in the soft ground tunneling industry to propagate the compressions at depth to the ground surface. Figure 3 depicts this generalized approach.

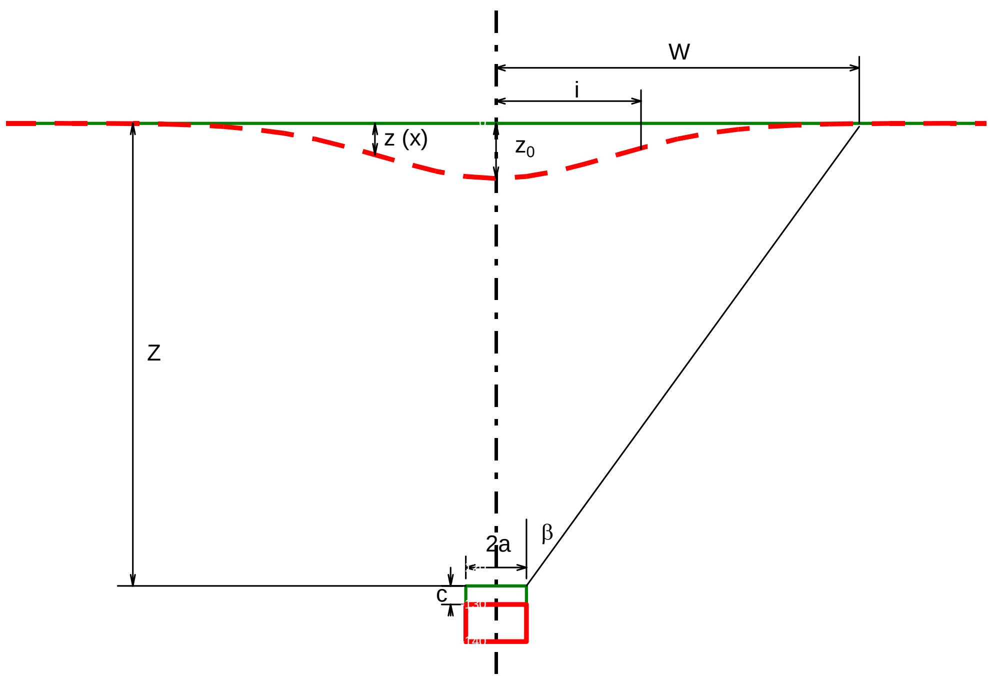

FIG. 3: Propagation of Subsurface Settlement to the Surface Level

Where, the surface settlement profile is shown as the inverted normal (Gaussian) distribution curve, Z is the depth from the ground surface to the top of the soft zone, W is the half-width of the surface settlement trough, i is s the inflection point, z_0 is the maximum surface settlement, c is the vertical displacement at the level of the soft zone, a is the half-width of the soft zone, and β is the settlement propagation angle. In addition, past studies at SRS have also relied on more sophisticated numerical models (e.g., FLAC and finite element analysis) to compute compression at depth and propagate it to the ground surface. However, the simplified studies have resulted in more conservative estimates of surface settlement and are more easily implemented and understood. The soft zone and settlement evaluation associated with the even tree analysis and described herein are based on the simplified empirical tunnel methodology mentioned above.

Soft Zone Parameters

To implement the simplified approach, several soft zone and soil parameters are required;

1. Presence. Do they exist at a particular site?
2. Thickness. How thick is the soft zone, can it affect surface structures?
3. Depth. Is the soft zone shallow enough that it will impact surface structures? Is it located in the Tinker/Santee Formation? Note, soft zones are by definition located within the Tinker/Santee Formation or the lower Dry Branch Formation (Eocene-age deposits of sands, calcareous sands, limestone and marl) surrounded by strong matrix soils (carbonates and dense sands).
4. Lateral extent, length and width. Is the soft zone large enough to affect surface structures? Is it discrete (can be characterized in 3D) or is it lenticular (characterized as plain strain, 2D)?
5. Compressibility. What is the existing state of stress and what are the compressibility parameters?
6. Angle of propagation (β). Although not a specific soft zone parameter, it is an important parameter of the soils above since if settlement were to occur at depth, β would determine the extent of settlement at the ground surface (or foundation level).

At the SRS the presence, thickness, extent, and depth of soft zones is determined by the exploration results; namely by identifying weak zones within the Tinker/Santee Formation. Conservative criteria established previously are low SPT N-values (< 5 bpf, including weight of hammer and weight of rod events) and low CPT tip resistances ($q_t \leq 1450$ kPa, [15 tsf]). To a lesser degree, fluid loss during drilling, drilling tool drops, and other drilling anomalies have also been used as indicators.

The compressibility characteristics of these soils are difficult to determine simply because of the difficulty in obtaining quality samples for testing. In most cases a fixed-piston type sampler has been used with very careful handling procedures being implemented. In this paper the compressibility (strain, ε) of the soft zones is defined as follows;

$$\varepsilon = \frac{C_c}{1+e_0} \times 100\%$$

where, C_c is the compression index and e_0 is the initial void ratio.

The angle of propagation is the angle at which the settlement at depth is propagated upwards to the ground surface. At the SRS, a value of 33° has typically been utilized, based on comparisons with similar soils below the water table reported in the tunneling literature (e.g., US DOT 1976).

Each of these attributes lends themselves to event tree analysis. Each can be quantified, to a degree, or estimated based on SRS site-specific experience.

EVENT TREE ANALYSIS

Applicability of an Event Tree to Soft Zones

The use of an event or logic tree has become somewhat routine for complex engineering problems (e.g., dam safety evaluations). If nothing else, it forces the analyst to think through the problem at hand in a more logical way, laying out the specific steps/events required to solve the particular problem at hand from start (initiating event) to finish (outcome or consequences). For the soft zone settlement issue at SRS, the event tree can be used as a screening tool during initial site selection or preliminary analysis of a new site, or as a specific design tool once the detailed exploration for a given site has been completed and knowledge of the soft zone parameters discussed above is better defined. In either case, the results would frame the resulting structure settlement in probabilistic terms.

The event tree uses the following soft zone parameters or categories as branches within the tree: geometry (2D versus 3D model application), depth, thickness, width, angle of settlement propagation (β), and strain (ε).

The event tree will be used to determine the probability of occurrence of settlement given a range of input parameters. The results can then be used in a fully probabilistic analysis of the structure, or more simply to put into context the probability of exceeding a particular value of settlement given an initiating event. In addition, in the context of a preliminary siting study or preliminary engineering, subsequent subsurface explorations can be used to further define the extent and/or properties of the soft zones for additional refined analyses.

CASE HISTORY

Soft Zone Presence

In the specific case history given below, for conservatism the presence of a soft zone is assumed to exist; thus it is given a weighting of 1.0. However, if this were a Greenfield site, the weighting could have been developed based on historic data in the project area. As an example using the identifying criteria previously described for the CPT, cumulative distribution plots of the soft zone presence in the project area were generated. Of 381 CPTs analyzed for soft zones, 217 (57%) encountered a soft zone (i.e., $q_t \leq 1450$ kPa, [15 tsf]). Thus, for a Greenfield site, the analysis could have been carried out with a weighting of about 0.6 and 0.4, presence and non-presence.

Soft Zone Geometry (Model application)

Previous analysis of soft zones at SRS considered the soft zones as tunnel-like (lenticular) features, and thus the analysis was carried out assuming plain strain conditions. With the increase in analytical capabilities, the soft zone settlement analysis has evolved to allow for the analysis of the soft zones as 3D objects if supported by detailed site characterization. Typically, this is usually difficults because of the amount of exploration required. However, over the years many explorations holes have been advanced for numerous facilities onsite, and if soft zones are known to exist, additional holes are sometimes advanced to "chase" the soft zones. Thus, in some cases, sufficient data are available to identify and constrain soft zones. In any case, it is generally believed that soft zones more often exist as isolated pockets, and therefore should be analyzed with a 3D methodology.

When soft zones are identified, through a field investigation, as being isolated pockets, the 3D approach may be utilized. However, for the event tree analysis, engineering judgment is still used to assess whether a soft zone should be analyzed with the 2D or 3D methodology. The consideration of soft zones as 2D features produces more conservative estimates of settlement. For this event tree case history, soft zone geometry weightings of 0.75 (2D) and 0.25 (3D) are used.

Soft Zone Thickness and Depth

For this case history the soft zone thickness was determined as the summation of material with a CPT tip resistance (q_t) of $\leq$ 1450 kPa (15 tsf), within the Tinker/Santee formation. This is a conservative assumption as all of the soft zone intervals within a given CPT are considered to behave as one continuous soft zone even though in most cases individual continuous soft zones over the entire SRS are thin, on the order of two fee and less. Figure 4 presents the results, for the specific case history, in terms of a cumulative distribution plot. Based on the data shown the following weightings were assigned to the respective thicknesses; 0.45, 0 to 0.6 m (0 to 2 feet) thick; 0.4, 0.6 to 1.7 m (2 to 5.5 feet) thick; and 0.15, 1.7 to 5 m (5.5 to 16.3 feet) thick.

The depth of the soft zone is assumed to be the shallowest occurrence of a soft zone interval within a given CPT in the Tinker/Santee formation. This is a conservative assumption, as the soft zone is considered to act as a continuous layer at the shallowest depth encountered (i.e., closet to the ground surface or foundation level). Figure 5 illustrates the cumulative distribution plot of the soft zone depths for this case history. Based on the data shown the following weightings were assigned to the respective soft zone depths; 0.45, 33.5 to 27.4 m (110 to 90 feet) deep; 0.35, 39.6 to 33.5 m (130 to 110 feet) deep; and 0.2, for depths greater than 39.6 m (130 feet).

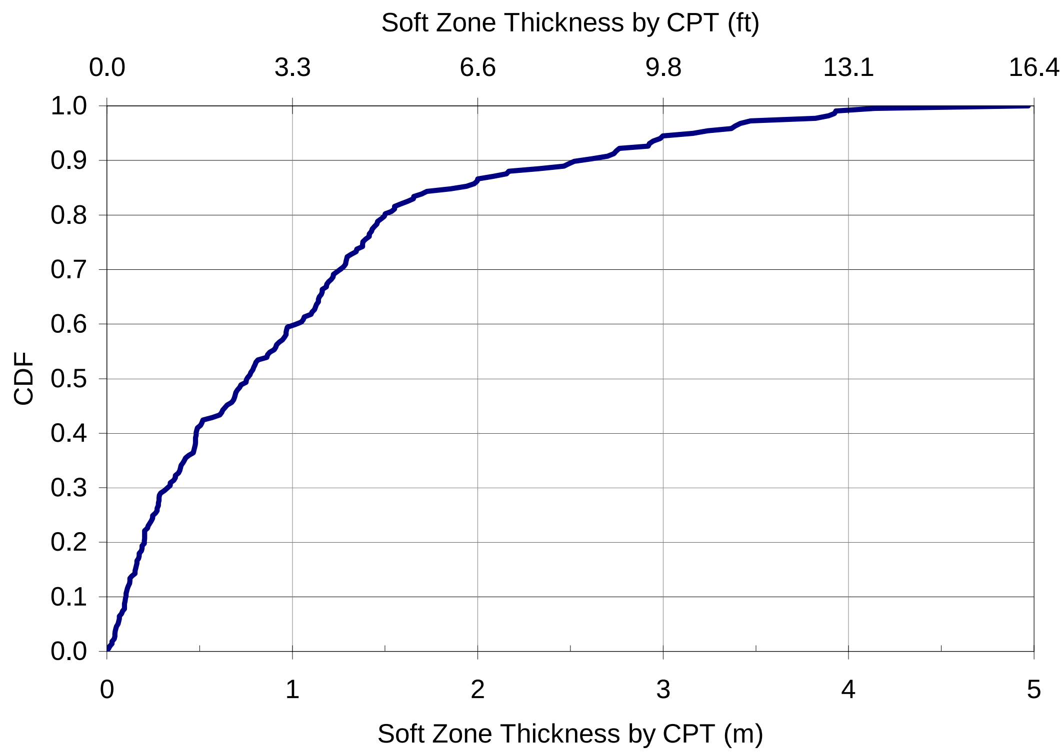

FIG. 4: Cumulative Distribution Plot of Soft Zone Thickness

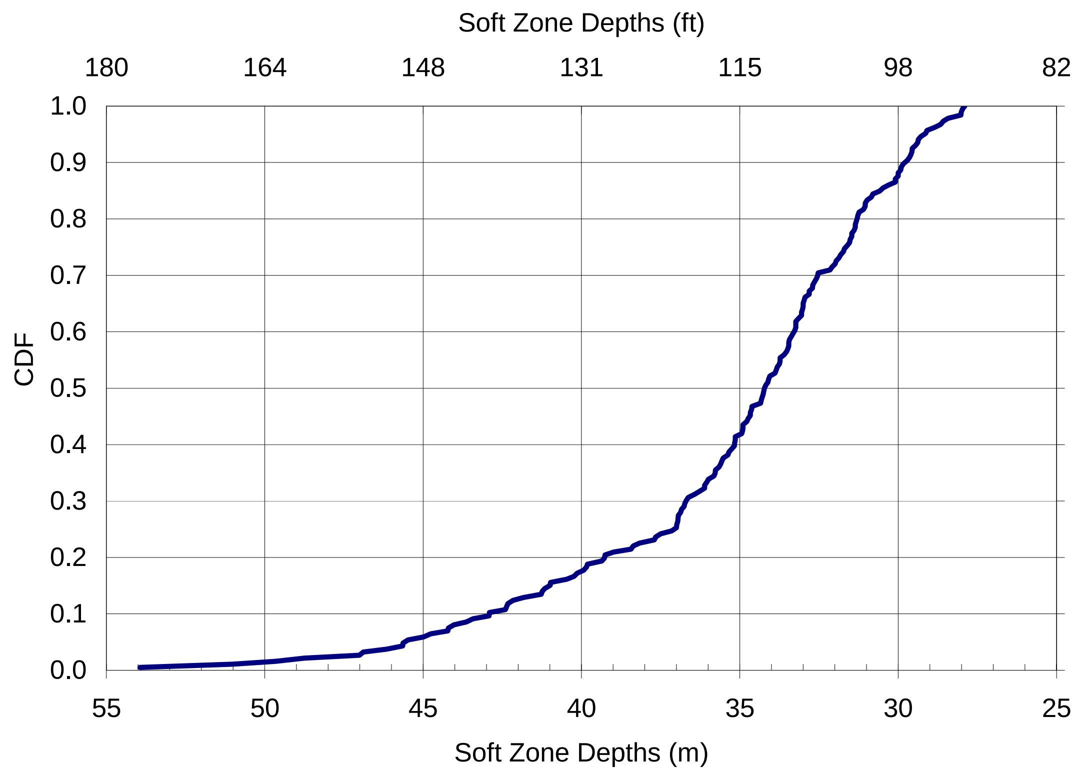

FIG. 5: CDF of Soft Zone Depths

Soft zone width

A review of previous SRS investigations reveals that soft zone widths are generally ≤ 15.2 m (50 feet). Previous numerical modeling efforts supports this conclusion, as larger soft zones would tend to settle over time, and since there is no known indication of surface settlement, maximum soft zone widths of approximately 50 feet are reasonable. Using a recent, densely investigated site as a model of typical soft zone geometry at the SRS, widths of soft zones thicker than 6.6 m (2 feet) were found to range from 3.3 to 15.2 m (10 to 50 feet) (corroborating the above conclusion). Using some engineering judgment and the explorations carried out for this case history site, weightings of 0.1, 0.4, and 0.5 were applied to soft zone widths of 3.3, 7.6m, and 15.2 m (10, 25, and 50 feet), respectively. The weighting of the expected widths maybe further refined or broadened based on additional investigation density.

Angle of Propagation (β) in Overlying Soils

The angle of settlement propagation, β (measured from the vertical), was estimated from studies relating measured surface settlement above soft ground tunnels in similar soils (US DOT 1976). According to Cording et al (US DOT 1976) for rock, hard clay and sands above the water table, β falls between 11° and 33°. For sands below the groundwater table, β is in excess of 50°. For clayey soils β is generally between 26° and 50°, depending on the stiffness. At the SRS and study area in question, the soils in the upper 40 m (130 feet) are generally classified as SC soils that for the most part are overconsolidated and relatively strong (except for the soft zones). Thus, for soils above and below the water table, β is expected to range from 26° to 50°, with the most likely β angle ranging from 33° to 41°. Using engineering judgment, weightings of 0.1, 0.4, 0.4, and 0.1 were applied to β angles of 26°, 33°, 41°, and 50° respectively.

Soft Zone Compressibility

Soft zone compressibility is the most difficult parameter to measure and it turns out to be the most important parameter in determining settlement. Because soft zone soils are difficult to sample, limited data are available from any given area on SRS. Thus, previous results from the entire SRS have been utilized to develop a cumulative distribution plot of strain. Figure 6 depicts the results from that evaluation. The computed strain ranges from near 0 to 27%. Based on Figure 6, and utilizing engineering judgment, weightings of 0.6 was selected for strains up to 5%; 0.2 for strains between 5 and 8%; 0.1 for strains between 8 and 15%; and 0.1 for strains 15 and 27%.

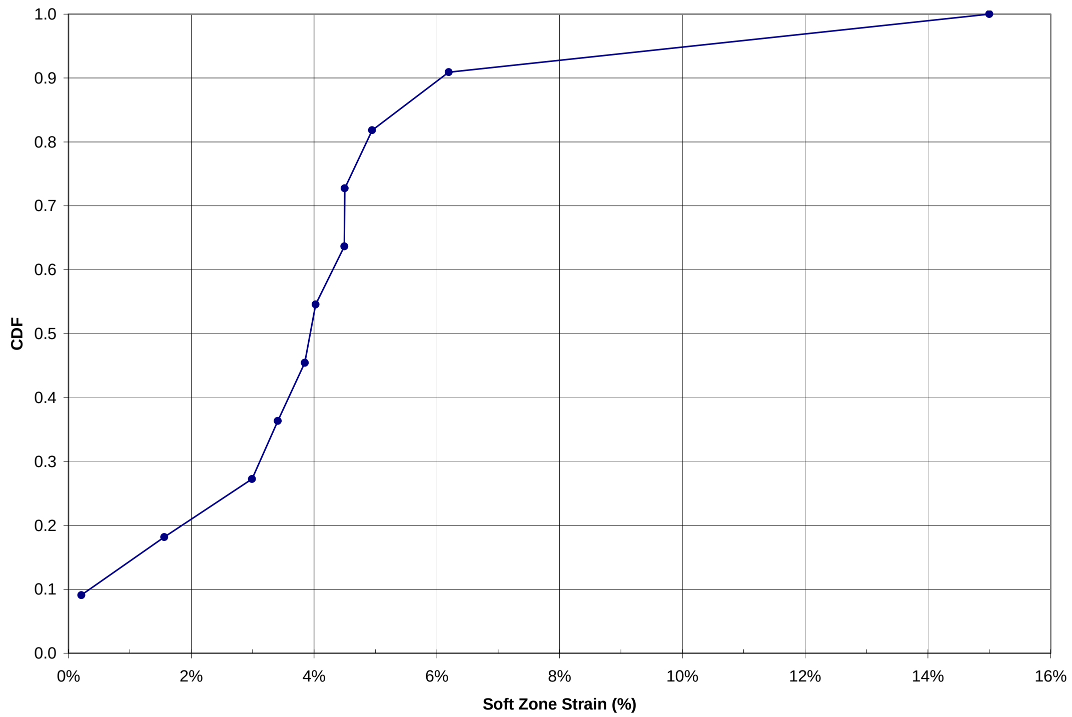

FIG. 6: Cumulative Distribution Plot of Soft Zone Strains

Settlement Computation

With the geometry and data given above, settlement can now be determined. The event tree assumes both 2D and 3D soft zone settlement methods. The maximum settlement (z_0) for a 2D soft zone analysis (WSRC 2007) is;

$$z_0 = 2c\frac{a}{W} \qquad \text{(Eq. 1)}$$

where

c = soft zone compression at depth (thickness × strain)
a = soft zone half width
W = Depth × tan β + a (W is surface settlement profile half-width)
β = angle of propagation

For a 3D soft zone analysis the maximum settlement is computed as follows; (WSRC 2007)

$$z_0 = 4c\left(\frac{a}{W}\right)^2 \qquad \text{(Eq. 2)}$$

where

W = Depth × tan β + (2 / $\sqrt{\pi}$) × a

In traditional soft zone settlement analysis, both the 2D and 3D methods generally use a 1.5 m (5 feet) grid spacing (1.5 m [5 feet] intervals of width) and superposition to model soft zones; i.e. a 7.6 m (25 feet) wide soft zone is modeled using 5 soft zones with W = 1.5 m (5 feet). For simplicity of computation, the computed settlement within the logic tree analysis considers the grid spacing to be the width of the soft zone, i.e., one soft zone (no superposition), i.e. 7.6 m (25 feet) wide soft zone is modeled as one soft zone with W = 7.6 m (25 feet). See Figure 7. The use of a 1.5 m [5 feet] grid produces slightly higher values of settlement, thus the results of the logic tree analysis were adjusted to match the results of 2D and 3D methodologies considering 1.5 m (5 feet) grid spacing.

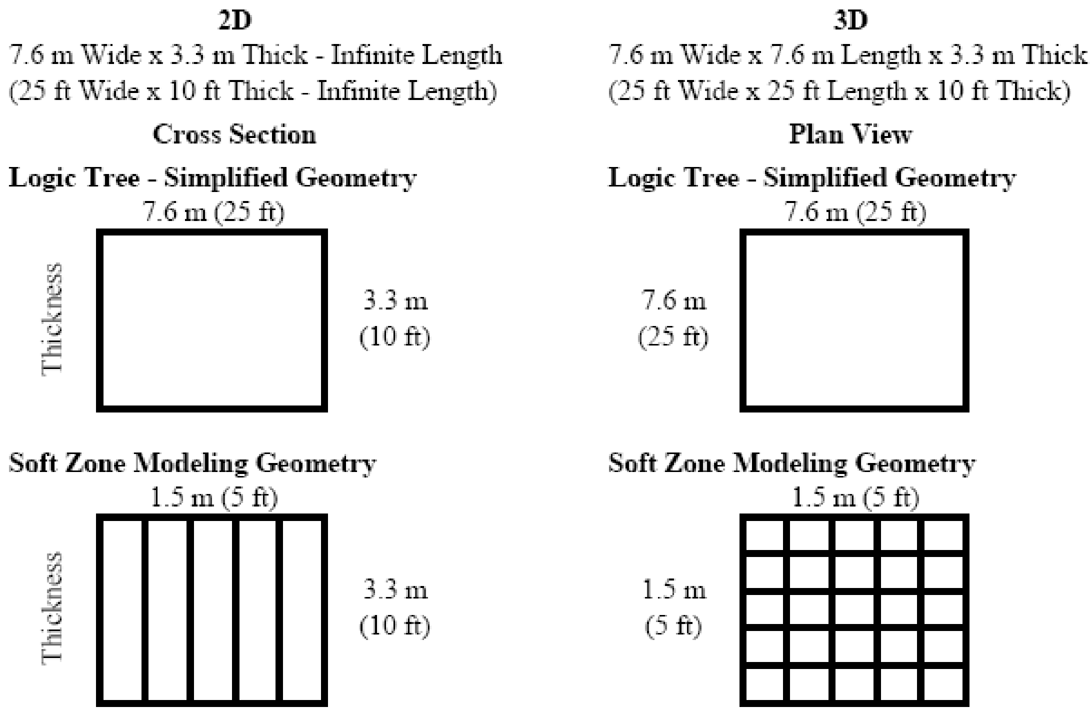

FIG. 7: Soft Zone Settlement - Method Comparison

LOGIC TREE CONSTRUCTION

The event tree has 864 outcomes (leafs). One such branch is shown on Figure 8. In that example, a 3D soft zone, 27.4 m (90 feet) deep, with a thickness of 5 m (16.3 feet), 3.3 m (10 feet) wide, an overlying angle of propagation of 50°, and a compressibility of 8% has a probability of occurrence (neglecting the initiating event) of 0.25 x 0.45 x 0.15 x 0.1 x 0.1 x 0.2 or 0.00003375 (3.375×10^{-5}). The associated settlement resulting from this combination of parameters is 0.0033 m (0.13 inches).

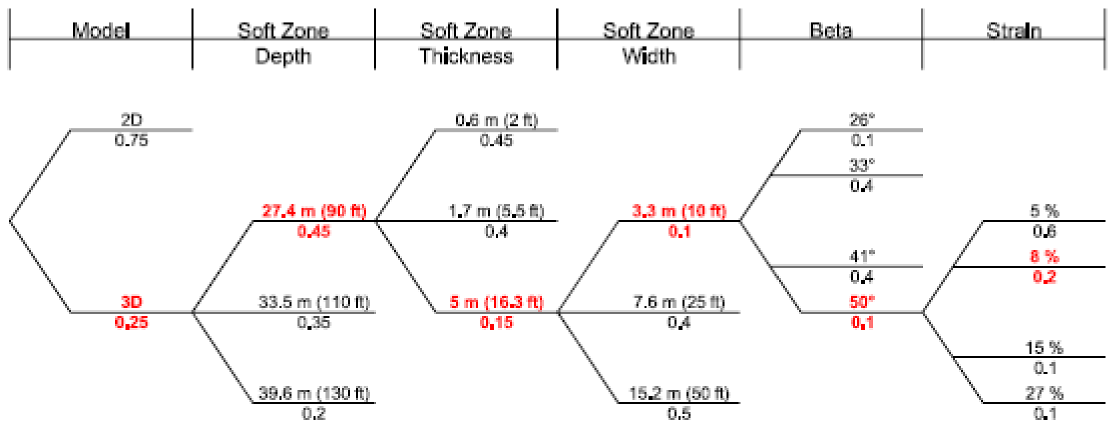

FIG. 8: Event Tree Construction

The settlement and probability of occurrence are computed for all leafs (outcomes) of the event tree. Following all possible branches for the event tree given in Figure 5, there are a total of 864 possible outcomes. The results are shown in the form of a cumulative distribution of settlement shown on Figure 9. This can be analyzed through specifically designed software or the use of a customized spreadsheet.

The results, given in Figure 9 for this particular site (case history), show that the probability of exceeding about 7.6 cm (3 inches) of settlement from soft zone compression at depth is approximately 1 in 5 (20%). This event in and of itself could be characterized as “unlikely” or “occasional”. If we consider that the initiating event is an earthquake with an annual probability of exceedance of 4 x 10^{-4}, then the probability of exceeding about 7.6 cm (3 inches) of settlement is on the order of 8 x 10^{-5} per year (0.008% per year).

As a comparison, a deterministic soft zone settlement analysis utilizing conservative site-specific parameters for soft zone geometry, thickness, depth, width, strain, and β results in a computed settlement for design of approximately 7.6 cm (3 inches).

A value not presented in the logic tree is the weighted average (the summation of probability of exceedance × settlement for all branches of the logic tree). The weighted average for this case is about 5.5 cm (2.15 inches), which corresponds to approximately a 70% chance of not being exceeded (a probability of ≈ 30% of being exceeded).

The actual settlement, as calculated through a deterministic approach using reasonable but not overly conservative parameters, for a particular facility is about 7.1 cm (2.8 inches) (MACTEC 2003). Based on the logic tree analysis presented in this paper, the deterministic settlement corresponds to a probability of being exceeded of less than about 20%. Given the probability of the initiating event, these results show that the probability of the structure exceeding a settlement of about 7.1 cm (2.8 inches) is about 8 x 10^{-5} per year. In this particular case, designing for a deterministic settlement of 7.1 cm (2.8 inches) was considered reasonable and was eventually accepted. It should be noted that in past analyses for similar facilities more extreme (presumably more conservative) soft zone parameters have been utilized. Thus, one positive outcome from this type of analysis is a consistent design approach in terms of a specific settlement percentile to use for structure evaluation.

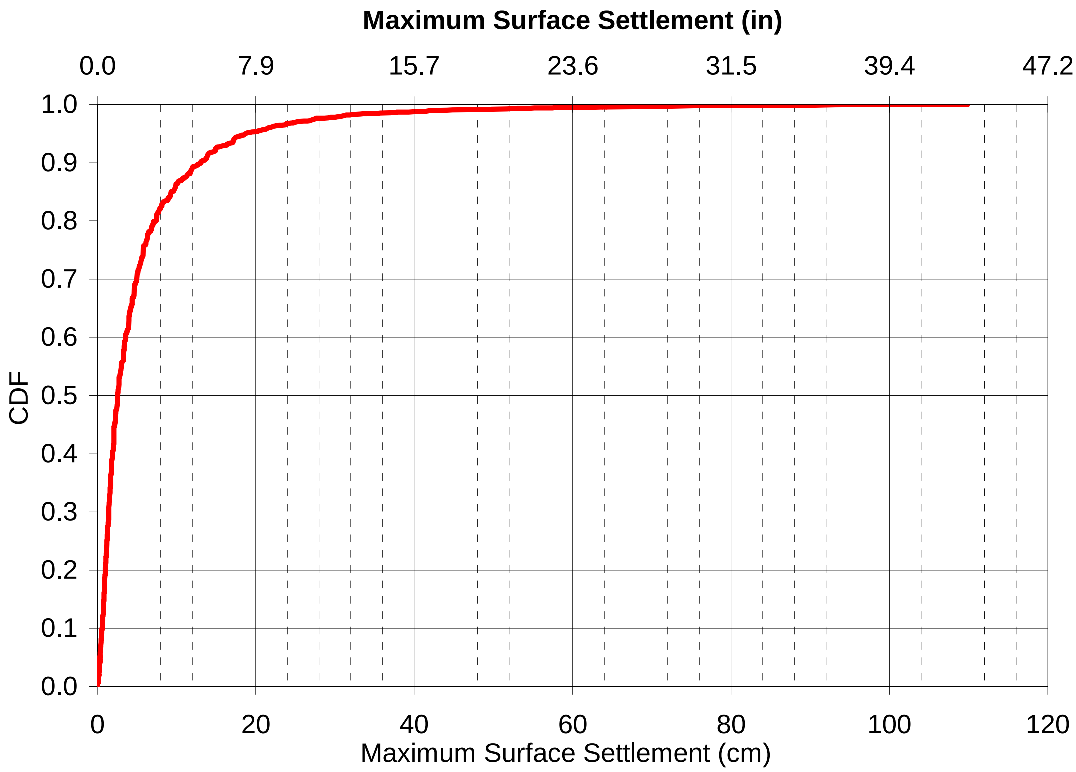

FIG. 9: Cumulative Distribution Plot of Surface Settlements

CONCLUSIONS

At the SRS use of the event tree for soft zone settlement evaluations is still in its infancy. However, it has proven to be an effective tool to put into perspective the probability of a structure exceeding a specific amount of settlement. What it has also accomplished is to allow more realistic estimates of soft zone parameters to be considered, not just the "most conservative" or the "most onerous" results. There is now a recognition that, although extreme settlements can still be designed for, there is a price to pay, and using maximum or extreme values for soft zone parameters may not be appropriate.

The results from the event tree analysis may be used to expand on the results of a deterministic approach for a particular site or may be used as an exercise to aid in a sighting process. Either way, the logic tree analysis can prove to be a valuable tool for decision makers. However, what the event tree does not do is attempt to determine the probabilities at which settlements should be determined; that determination is left to the end user.

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