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INFLUENCE OF STRATIGRAPHIC INTERFACES ON RESIDUAL STRENGTH OF LIQUEFIED SOIL

Jack Montgomery[1]
Ross W. Boulanger[2]

ABSTRACT

Residual strength of liquefied soil continues to be a major source of uncertainty in predicting the seismic performance of embankment dams. Physical, analytical and numerical models have demonstrated that the residual strength is a system response that depends on soil properties, drainage conditions, stratigraphy, stresses, and shaking characteristics. Case history-based residual strength correlations only indirectly account for the effects of these various factors, and only to the extent that their effects were manifested in the case histories used to develop the correlations. Numerical simulations offer a means to explore factors which influence the residual strength but may otherwise be difficult to examine analytically or experimentally. In this paper, numerical simulations are used to examine how undulations in the interface between low permeability layers and liquefiable layers affect the potential for strength loss due to void redistribution. The results of these analyses and subsequent parametric studies provide insight into how geologic conditions may influence the residual strength of a liquefied soil in the field.

INTRODUCTION

The in-situ shear strength of liquefied soil, often called the residual strength (S_r), continues to be a major source of uncertainty in predicting the performance of dams affected by liquefaction. This is most often of concern when analyzing older dams founded on recent alluvium or constructed using the hydraulic fill method. S_r can be significantly affected when drainage of excess pore pressures generated during shaking is impeded by the presence of overlying soil layers of significantly lower permeability. This may lead to localized loosening of the liquefied soil at the interface, or "void redistribution", which could result in S_r being much lower in the field than would be obtained from laboratory tests on samples taken before the earthquake. Current practice relies on case history-based correlations to implicitly account for void redistribution (e.g., Figure 1), but the development of relationships for sands with normalized SPT blow counts greater than 15 is not constrained by the available case history data.

Physical, analytical and numerical models have demonstrated that the S_r is not a soil property alone, but rather is a system response that depends on soil properties, drainage conditions, stratigraphy, stresses, and shaking characteristics. Most design correlations do not directly account for these other influencing factors, although case history based

[1] Graduate Student, Department of Civil & Environmental Engineering, University of California, Davis, CA 95616, jmontgomery@ucdavis.edu
[2] Professor, Department of Civil & Environmental Engineering, University of California, Davis, CA 95616, rwboulanger@ucdavis.edu

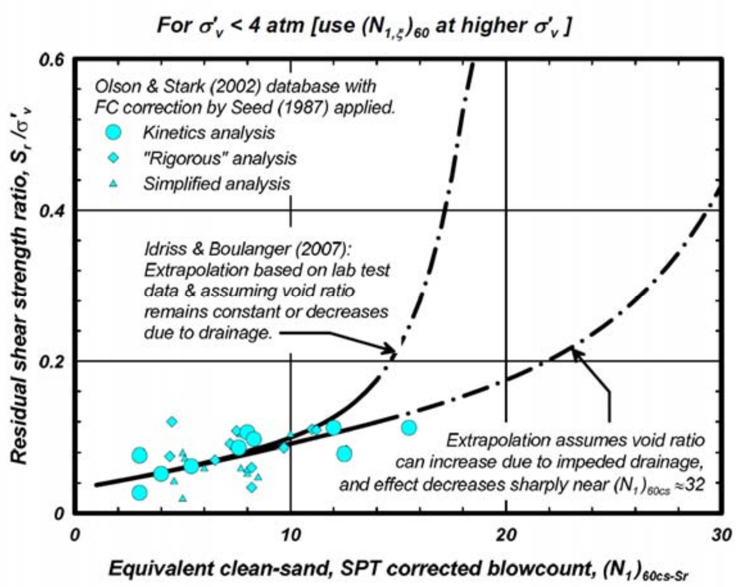

Figure 1. Case history-based residual strength correlations (Boulanger and Idriss 2011).

residual strength correlations do indirectly account for them to the extent that their effects were manifested in the case histories used to develop the correlations (Seed 1987). There is currently a need for more explicit guidance on how to distinguish between cases where the effects of void redistribution may or may not be significant.

Numerical simulations offer a means to explore factors which influence S_r, but may be difficult to examine analytically or experimentally. One of these factors is how the interface between a liquefiable sand layer and an overlying low permeability layer may influence the development of void redistribution. This can help determine whether alluvial deposits with irregular interfaces and stratigraphy (Figure 2a) are as susceptible to strength loss due to void redistribution as hydraulic fill dams which often have planar, continuous interfaces between silts and sands (Figure 2b).

The purpose of this paper is to use numerical simulations to examine how geologic characteristics of stratigraphic interfaces may affect the mechanism of strength loss due to void redistribution. The void redistribution mechanism is briefly reviewed, followed by a discussion of how various characteristics of the stratigraphy may play a significant role. Numerical simulations of a layered infinite slope are then used to examine how undulations in the interface between liquefiable layers and overlying low permeability layers may affect the potential for strength loss due to void redistribution. The potential implications of these findings for engineering practice are discussed.

VOID REDISTRIBUTION

The S_r of a liquefied soil in the field may be significantly affected by the presence of overlying low permeability layers which can impede drainage of excess pore pressures (u_e). Whitman (1985) described situations where localized loosening of liquefied soil may occur due to pore water seepage resulting from the u_e gradients generated during

(a) *(b)*

Figure 2. Interlayered deposits exposed in exploratory trenches in an alluvial deposit (left) and a hydraulic fill dam (right, photo courtesy of Craig Davis, LADWP).

cyclic loading. This phenomenon is often called "void redistribution" and could result in S_r being much lower in the field than would have been obtained from undrained laboratory tests performed on samples of the soil taken before the earthquake. Physical and analytical modeling studies by Kokusho (1999, 2000), Kulasingam et al. (2004), and Malvick et al. (2006) have illustrated the void redistribution phenomena and evaluated several factors (e.g., permeability, density, shaking duration, layer thickness) that significantly affect it.

The mechanism of void redistribution can be illustrated through consideration of a gently sloping alluvial deposit which may be modeled as a layered infinite slope (Figure 3a). The slope contains a potentially liquefiable sand layer which is overlain by a laterally extensive layer of much lower permeability. Cyclic loading from an earthquake may cause high u_e to develop in the sand layer creating an upward gradient. Drainage of u_e will be impeded by the low permeability layer leading to an accumulation of water at the interface and loosening of the surrounding sand (i.e., Point A in Figures 3a and 3b). If water continues to flow upward, the soil at the interface may be loosened to the critical state void ratio leading to a loss of strength and large deformations. In physical models, these deformations are often concentrated in a thin band of soil, referred to as a localization zone, or, in extreme cases, a water film.

Numerical modeling of void redistribution has been performed by several researchers (e.g., Yang and Elgamal 2002, Naesgaard et al. 2005, Seid-Karbasi and Byrne 2007 and Kamai and Boulanger 2013). Seid-Karbasi and Byrne (2007) analyzed a layered infinite slope using a modified version of the UBCSand constitutive model to examine effects of mesh size, density and drainage conditions on the development of void redistribution. Naesgaard et al. (2005) used a similar constitutive model to analyze the Lower San Fernando dam using a simplified stratigraphy with several low permeability layers in the hydraulic fill shells. They showed that the inclusion of the low permeability layers led to void redistribution in the shells and a delayed flow failure of the upstream shell.

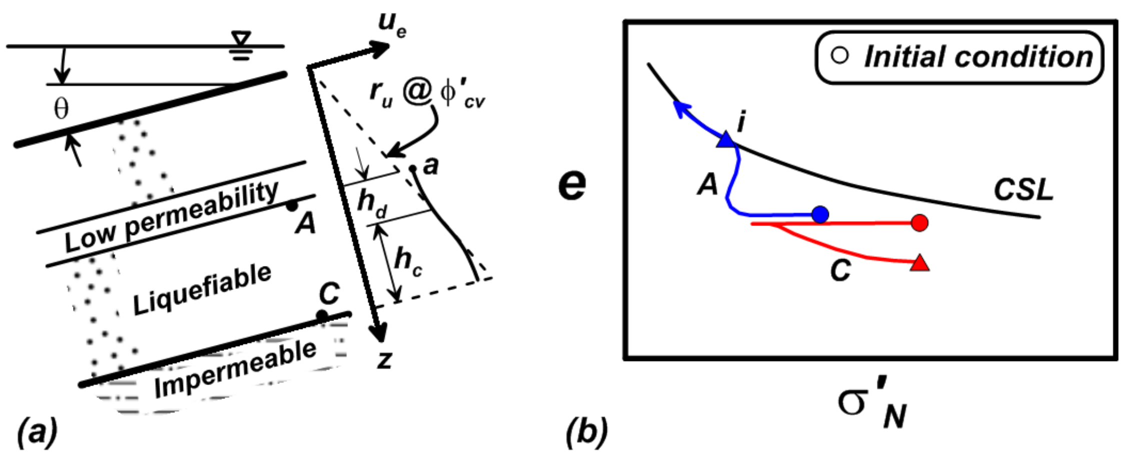

Figure 3. Void redistribution in layered soil profiles (Kulasingam et al. 2004): (a) infinite slope with low permeability layer over a liquefiable sand layer, and (b) void ratio changes for points at the top and bottom of the confined sand layer.

It is not currently practicable to explicitly model void redistribution in routine numerical simulations due to several significant challenges. Some of the hurdles to modeling void redistribution in practice are: the need for constitutive models which include a critical state framework and can capture reconsolidation of liquefiable soils; limitations in the accuracy of numerical simulations at large strains; practical limits to computations at very small scales; and difficulty in adequately characterizing the stratigraphy and properties of heterogeneous deposits. Despite these hurdles, numerical simulations offer the potential for insights that can be used to help guide the interpretation of case histories and physical model test results and the development of practical recommendations for design.

INFLUENCE OF STRATIGRAPHY

One of the significant barriers to explicit modeling of void redistribution is the influence of stratigraphic details on the phenomenon of void redistribution. This has not been extensively studied, but could cause significant differences in the observed behavior between the lab scale, physical model scale, and field scale.

Several types of stratigraphic details can be hypothesized to likely influence the void redistribution phenomenon, including the four examples illustrated in Figure 4:

- Roughness at the interface between the low permeability layer and the liquefiable sand which may impede the development of a contiguous zone of loose sand
- Discontinuities in the low permeability layer which allow high excess pore pressures in the sand to dissipate more freely
- Variability in the thickness of the liquefiable layer which changes the flow pattern and volume of water expelled from the liquefied layer
- Non-homogeneous deposits where soil properties may change with depth such as alluvial environments (e.g., fining upward sequences) or lifts in compacted soils (e.g., looser at the bottom of a lift)

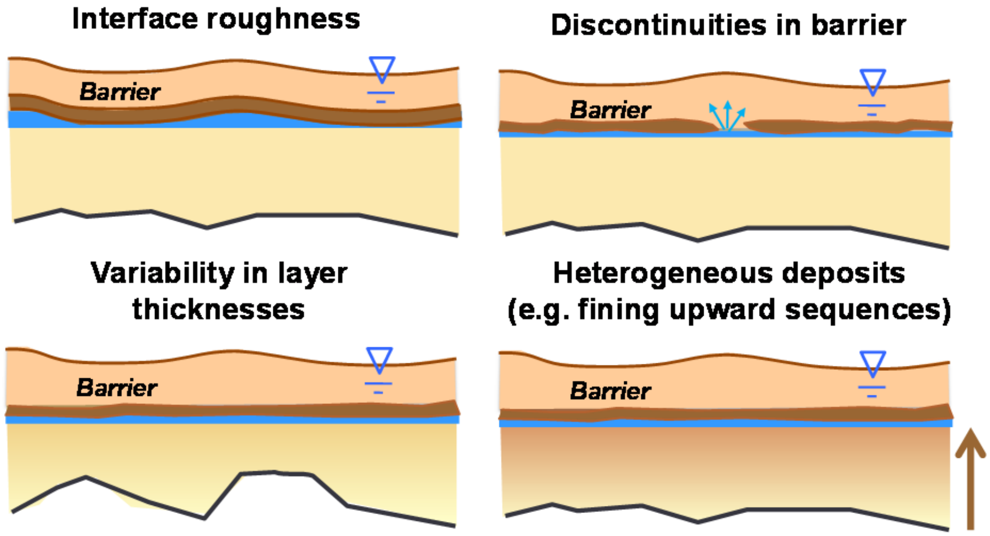

Figure 4. Stratigraphic details which may affect the severity of void redistribution (after Naesgaard et al. 2005).

Each of these effects may be significant for understanding how deformation mechanisms due to liquefaction observed in laboratory experiments (which usually involve relatively uniform model geometries) may differ from those that occur in the field.

Void redistribution can lead to strength loss and large deformations which tend to localize in narrow bands of soil. In analytical models, the thickness of these bands is often assumed to be roughly equal to the thickness of shear bands observed in lab tests. Shear bands in lab shear strength tests on dense sands often have an approximate thickness of 10 to 20 times the mean grain diameter (Vardoulakis and Sulem 1995) which is on the order of 0.2 to 2 cm for typical sands. Natural alluvial deposits rarely have perfectly planar stratigraphic interfaces (e.g., Figure 2) and this roughness may impose an additional constraint on the thickness of the localization zone required to cause instability. The effect of interface roughness on the development of a localization zone has not been studied extensively, and thus numerical analyses offer a potential tool to query the magnitude of these effects.

NUMERICAL SIMULATIONS

Two infinite slope geometries were constructed to examine the role of interface roughness on the response of a layered infinite slope (Figure 5). The first geometry is similar to that used in previous analytical models (e.g., Malvick et al. 2006) and considers an infinite slope with a planar, low permeability barrier layer overlying a layer of liquefiable sand (Figure 5a). The second model uses the same infinite slope, but alters the stratigraphic interface to resemble a sine wave (Figure 5b). This is meant to represent (in a simplified manner) undulations which may develop in coarse-grained alluvial deposits (e.g., ripples or subaqueous dunes on the beds of river channels). The groundwater table in both models is assumed to be at the ground surface with flow parallel to the slope.

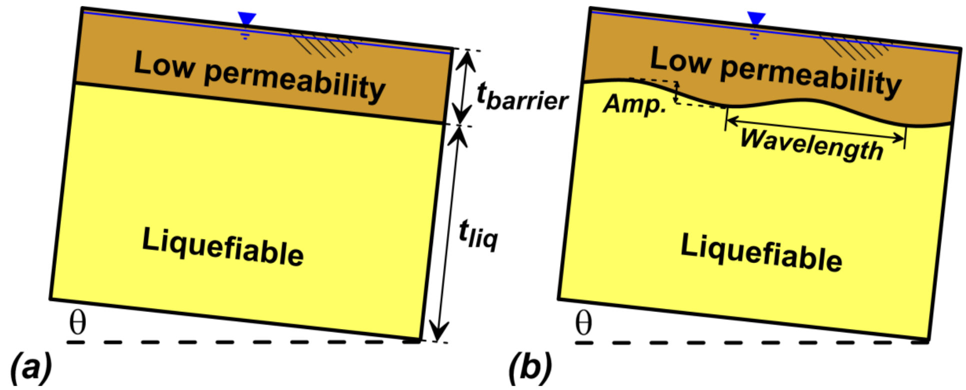

Figure 5. Infinite slope models with (a) planar and (b) “rough” interfaces between the liquefiable sand and low permeability barrier layer.

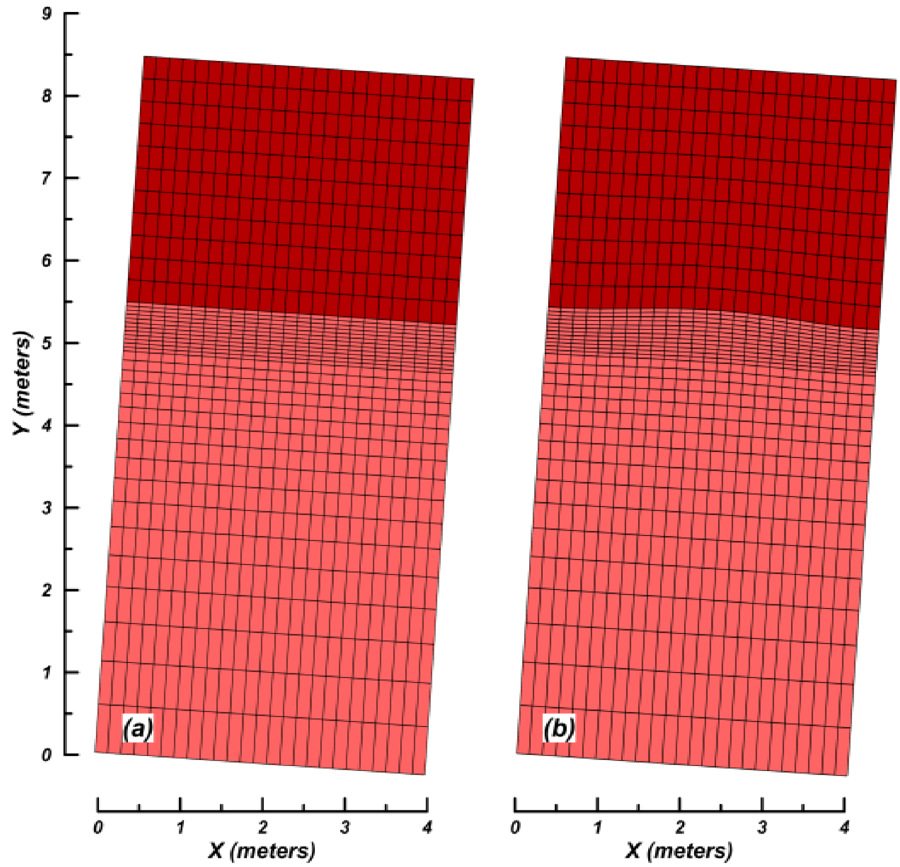

Figure 6. Mesh from FLAC for two infinite slope models showing: (a) a planar interface between the liquefiable sand and low permeability strata, and (b) an interface with an undulation of 12cm.

Numerical simulations were conducted using the commercial software FLAC (Itasca 2011). FLAC was selected due to its widespread use within the dam engineering community and its ability to perform dynamic coupled fluid flow – effective stress simulations. Example meshes are shown for the planar model in Figure 6a and a model with a 12 centimeter (cm) undulation in Figure 6b. Undulation thicknesses of 2, 4, 8 and 20 cm were also examined using a mesh similar to Figure 6b. All models considered a 5.5 m thick sand layer overlain by 3.0 m thick barrier layer. Periodic boundary conditions for both displacements and fluid flow were used on the sides of the model to simulate the infinite slope condition.

Soil layers were modeled using the user-defined constitutive model PM4Sand (Boulanger and Ziotopoulou 2013, Ziotopoulou and Boulanger 2013a) for the sand layer and the Mohr-Coulomb model in FLAC for the barrier layer. PM4Sand was selected because it is critical-state compatible and captures many aspects of sand behavior important to cyclic liquefaction problems. The version of PM4Sand used in this study has additional post-cyclic modifications discussed in detail in Ziotopoulou and Boulanger (2013b). The barrier layer was assigned an undrained strength of 10 kPa.

Simulation Results

Numerical simulations were performed in three phases: static equilibrium, dynamic loading, and post-shaking reconsolidation. During the static phase, stresses were initialized hydrostatically with a groundwater table at the ground surface and flow parallel to the slope. Each model was brought to static equilibrium and then shaken for six seconds using a sinusoidal acceleration time history input parallel to the base of the model with a peak acceleration of 0.15g. The post-shaking reconsolidation feature in PM4Sand (Ziotopoulou and Boulanger 2013b) was then activated and excess pore pressures were allowed to dissipate leading to void redistribution within the sand layer.

Displacement time histories for two models (planar and 12 cm undulation) are shown in Figure 7. The initial relative density (D_r) of the sand was 60% in both models. The ground surface displaces approximately 25 centimeters during dynamic loading in both models. During reconsolidation, the planar model begins to displace approximately 5 seconds after shaking has stopped and deformations quickly become very large indicating a flow failure is likely. The amount of delay between the dynamic loading and the flow slide depends on the permeability, compressibility, and thickness of the sand layer. The model with a 12 cm undulation accumulates a small amount of additional displacement after shaking, but remains stable after excess pore pressures have fully dissipated.

Volumetric strains at the end of the reconsolidation phase for the planar model are shown in Figure 8a. Volumetric strains are highest in the row of sand elements directly below the interface and are uniform across the model which is consistent with the periodic nature of infinite slope problems. This layer undergoes volumetric strains of approximately 7.4% which corresponds to a final D_r of 18% (compared to the initial value of 60%). At this final D_r, the sand becomes unstable and large displacements occur.

Volumetric strains at the end of the reconsolidation phase for the model with the undulation of 12 cm are shown in Figure 8b. Volumetric strains are highest in the row of sand elements directly below the interface, but there is a larger accumulation of strains to the right of the undulation peak. This occurs due to slight sliding of the barrier layer

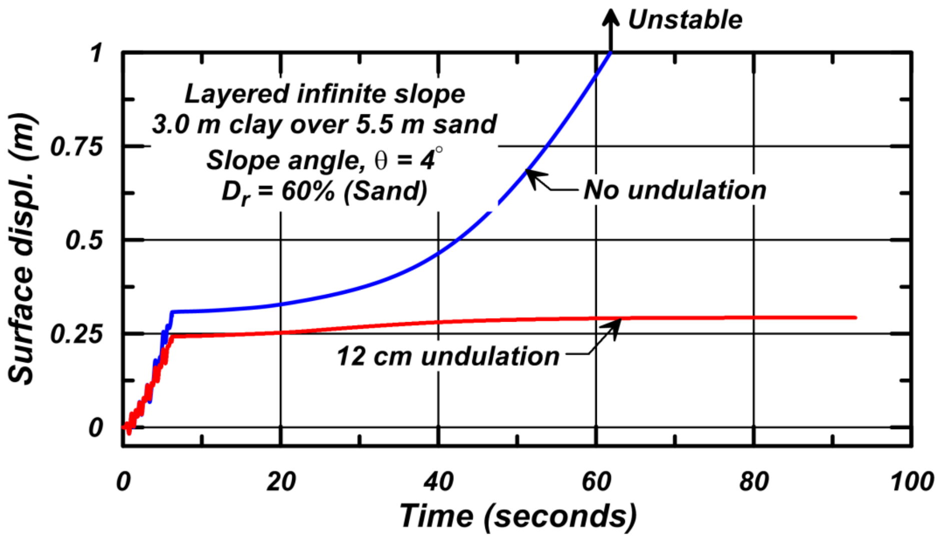

Figure 7. Two time histories showing the final horizontal ground surface displacement for the planar model (Figure 6a) and model with a 12 cm undulation (Figure 6b).

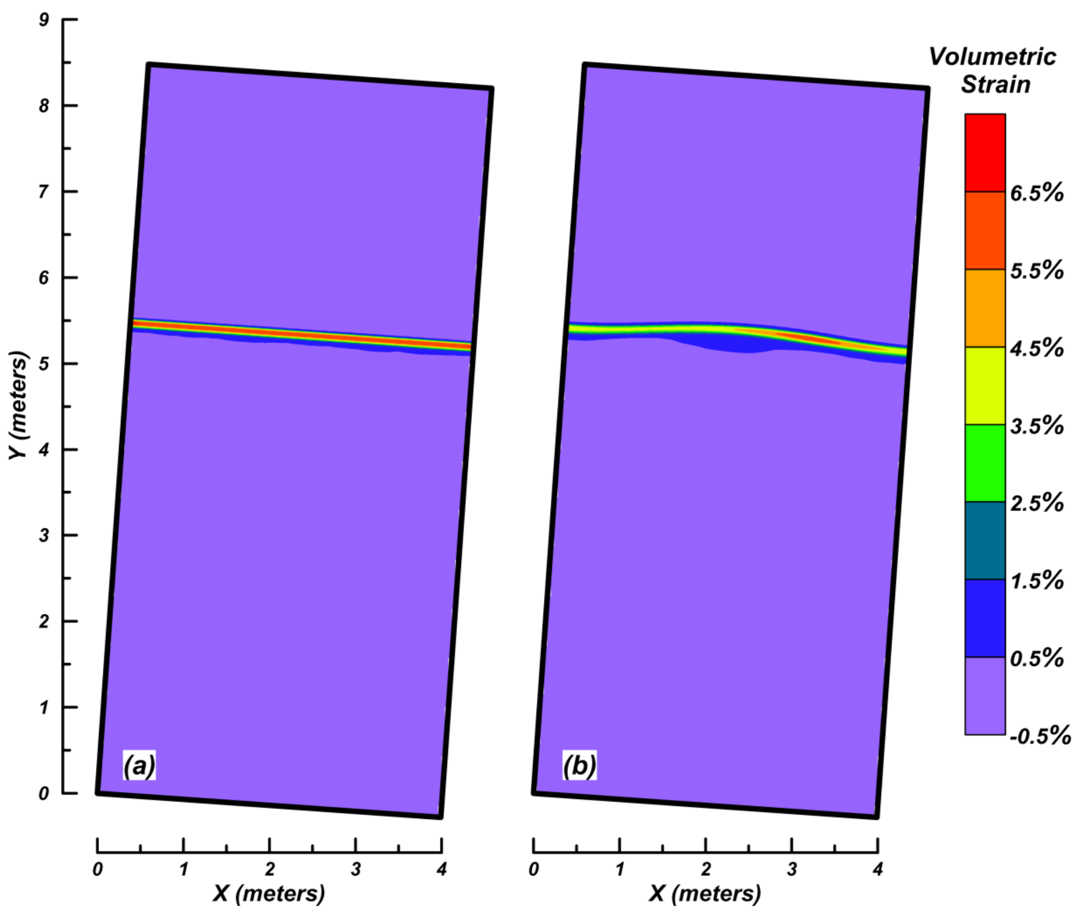

Figure 8. Final volumetric strains for two infinite slope models with a planar interface (a) and an interface with an undulation of 12 cm (b).

which begins to compress the sand to the left of the undulation peak and to unload the sand to the right of the peak. The top layer of elements undergoes average volumetric strains of approximately 6.5% which corresponds to a final D_r of 23% (compared to the initial value of 60%). The reduction in D_r is not uniform across the model and thus a failure plan does not develop and post-earthquake displacements are limited.

The analysis described above was repeated using different amplitudes for the interface undulation and final surface displacements for each model are shown in Figure 9. The results show that as the amplitude of undulation is increased, the amount of horizontal surface displacement decreases significantly. For models with undulation amplitudes greater than 12 cm, only a minor amount of displacement occurs after shaking has ended. For models with undulation amplitudes less than 4 cm, the large surface displacements indicate a flow slide is likely. The limiting amplitude for large deformations will depend of the thickness of the liquefiable layer, D_r, slope angle and shaking characteristics.

Parametric studies examining the effect of mesh size, sand D_r, thicknesses of both layers, permeabilities of both layers, and additional undulation amplitudes are ongoing. The results of the limited analysis presented here are meant to demonstrate the important role geologic details can play when examining localization problems. The results of the parametric analyses will be used to confirm the results shown here for additional cases and offer guidance on the role roughness in the stratigraphic interface plays in the development of void redistribution-induced localization.

CONCLUSIONS

Physical, analytical and numerical models have demonstrated that the residual strength of liquefied soil is not a soil property alone, but rather is a system response that depends on soil properties, drainage conditions, stratigraphy, stresses, and shaking characteristics.

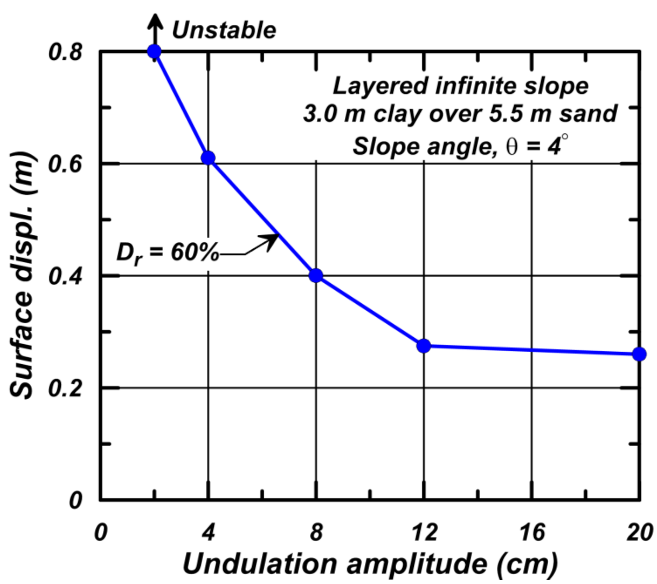

Figure 9. Final ground surface displacement versus undulation amplitude for infinite slope model shown in Figure 6b.

Case history-based residual strength correlations only indirectly account for the effects of these various influencing factors, and only to the extent that their effects were manifested in the case histories used to develop the correlations (Seed 1987).

Numerical simulations were performed to examine how the characteristics of stratigraphic interfaces can affect the mechanism of strength loss due to void redistribution. The numerical simulations are performed using the commercial code FLAC with the constitutive model PM4Sand. This constitutive model provides a critical state framework which is important when analyzing loosening of sands due to void redistribution. Several models for infinite slopes were analyzed with different levels of roughness in the interface between the liquefiable sand and low permeability strata.

The loss of strength associated with void redistribution is greatest for near-planar interfaces between liquefying sands and low permeability strata. These types of conditions are most likely to occur within hydraulic fill dams (e.g., Figure 2b).

The loss of strength associated with void redistribution decreases significantly as the interface becomes more irregular (Figure 9). These types of conditions are observed in many depositional environments, such as the alluvial deposit shown in Figure 2a.

The results of these types of analyses, including parametric studies for mesh sensitivity, provide insights on how geologic conditions are expected to affect residual strengths. Implementation of these types of analyses in engineering practice is still not practicable, but the insights provided can help influence development of recommendations for design.

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