UNDRAINED BEHAVIOR OF LIQUEFIED SOIL

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Project Objectives:

The objective of this study is to analytically relate the post earthquake undrained stress-strain-strength behavior of liquefied sand to its initial (pre earthquake) state, thereby allowing the designer to predict the potential resistance of such liquefied sand to sustained or monotonically increasing (post earthquake) static loads. Currently, the only way to assess the mobilized undrained behavior of liquefied saturated sand (stress-strain and stress path) under monotonic loading is via laboratory testing (a black box approach). Such behavior has been assessed experimentally by several researchers interested in the varying resistance of saturated sand under undrained monotonic loading after being liquefied under cyclic loading corresponding to the free-field shaking of the earthquake (Fig. 1). Such post earthquake characterization is important relative to such problems as slope stability and post earthquake behavior of both shallow and deep foundations (footings and piles).

The present work has been fashioned to deal with sands of different properties (gradation, density, particle shape, etc.) under different levels of confining pressure (representing varying overburden and depth below the groundwater table). The validity of the proposed work is to be verified by comparison with observed results of Nevada, Ione, Ottawa, Banding and Fraser River sands. The work conducted will allow the assessment of the stress-strain-strength behavior of liquefied sand under different scenarios of loading. The simplicity of this approach will make it an attractive general method for characterizing the undrained behavior of liquefied sands with no need to run extensive experimental tests.

Concepts Implemented:

The undrained behavior of isotropically consolidated saturated sand under monotonic loading is characterized by a change in the excess porewater pressure which, in turn, leads to different forms of undrained (liquefaction) reponse (Fig. 2). Such behavior featuring a positive build up in excess porewater pressure, yields a contractive response. The growth of the excess porewater pressure continues until reaching a stable value corresponding to the lowest value of undrained resistance of the sand, known as its steady state strength. Moreover, the sand shows continuous large deformation under constant effective confining pressure, constant shear stress, and constant rate of shear strain. Such behavior of sand is known as complete liquefaction (Fig. 1). However, liquefied sands may exhibit a large increase followed by a decrease in the excess porewater pressure which results in dilative response (Fig-2). Such behavior is a consequence of the higher relative density of the sand.

Based on field data (earth-dam failure due to soil liquefaction) Seed and Harder (1990) have provided a relationship (Fig. 3) to assess the undrained residual strength of liquefied sands (S_r) from the standard penetration test (SPT) corrected blowcount, $(N_1)_{60}$. However, a very large difference between values at the upper and lower limits at a particular $(N_1)_{60}$ value affects the assessment of S_r tremendously. In addition, a higher peak of undrained resistance is ignored in the case of the partially liquefied sand, while greater resistance at lower strain is attributed to the sand in the case of complete liquefaction.

The current work has been developed to deal with sands with different particles (well rounded, subrounded, subangular, or angular) under different levels of confining pressure. The validity of the work presented and the equations formulated are verified by several comparisons with observed results of Nevada, Ione, Ottawa, Banding and Fraser River sands. The work conducted allows the assessment of the strength of liquefied soil under different scenarios of loading that simulate axial compression, lateral compression-axial extension or direct shear (Fig. 4) by relating other loading scenarios to the axial compression soil behavior. The simplicity of this approach makes it an attractive general method to characterize the undrained behavior of sands with no need to run extensive experimental tests.

The response of liquefied soil (saturated sand) under undrained conditions is predicted in the current research work based on its drained behavior or effective stress response. As a result, the peak and residual strengths of particular liquefiable soil will be calculated (Fig. 2). The designers always desire the evaluation of the degraded strength of soil due to soil liquefaction under seismic loading. Such liquefied soil resistance is related to the scenario of loading (axial compression, lateral compression-axial extension or direct shear) as seen in Fig. 4.

The current research work is based on the following stages of research:

1. Experimental test data using different types of sand to prove the concepts of calculating the undrained behavior of sands from its drained response (Norris et al. 1997).
2. The formulation of isotropically consolidated rebounded soil (Ashour and Norris, 1999).
3. The formulation of axially drained sheared rebounded soil (Ashour and Norris, 1999).
4. The assessment of the excess porewater pressure in saturated sands under seismic (cyclic) loading (Seed, 1979).

The formulation employed in this study is based on extensive experimental work performed on different kinds of sands (published in the literature or performed at UNR lab). Only soils that tend to decrease in volume during shear, i.e. contractive soils, suffer the loss of shear resistance that results in liquefaction. However, even contractive soils are not susceptible to liquefaction unless the driving shear stresses are large enough. Soils that tend to exhibit a net increase in volume due to the imposed shear stresses, i.e. dilative soils, are not susceptible to liquefaction because their undrained strength is equal to or greater than their drained strength. It is known that liquefaction may occur in silts, and quick clays as well as sands and silty sands.

The evaluation of the deviatoric stress - axial strain or shear stress – shear strain response of liquefiable soil provides the designer with the resistance and strain of soil according to the mechanism of soil failure or loading scenario as observed with laterally and axially loaded piles (i.e. the p-y and t-z curves), bridge abutments, slope stability, soil lateral spreading and shallow foundations.

Tasks and Activities Accomplished:

- **Task 1:**
  Analyze laboratory test data published in the literature or provided via the tests performed at the University of Nevada Reno geotechnical lab. The data search and collection has been extended to cover several types of sands with reliable and accurate descriptions of sand properties.

- **Task 2:**
  Upgrade and modify the formulations developed by Ashour and Norris (the project PIs) to account for the effect of fines on the undrained behavior of liquefiable soils. Such work has required the modification of the previously developed formulations for
  1. Isotropically consolidated-rebounded sand
  2. Isotropically consolidated sand under axial compression loading

- **Task 3:**
  Assess the combined excess water pressure induced by the earthquake (free-field) and the induced or applied deviatoric stress (near-field post earthquake loading).

- **Task 4:**
  Develop a relationship between different loading scenarios to predict the steady state strength of a liquefied sand based on its drained behavior under axial compression loading.

- **Task 5:**
  Building a computer code (program) with graphics user interface to facilitate the data entry and the plotting of results.

  Data required to implement the technique developed:
  - Peak ground acceleration (a_{max}) and the magnitude of the earthquake to evaluate the excess porewater pressure (R_u) induced by cyclic loading (Seed et al. 1983).
  - Soil properties:
    Effective unit weight of soil
    (N1)60 (or Relative density, Dr)
    Angle of internal friction (φ)
    Particle shape or roundness (ρ)
    Percentage of fines (passing the # 200 sieve)
    Drained axial compression strain at 50% strength, ε_{50} (%)
    Uniformity coefficient (Cu)

- **Task 6:**
  Verify/validity the developed technique based on available data from task 1.

References:

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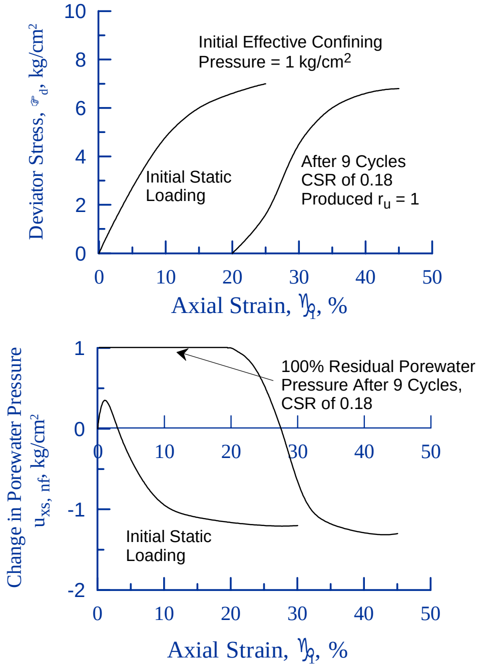

Fig. 1 Behavior of fully liquefied Sacramento sand (Seed 1979)

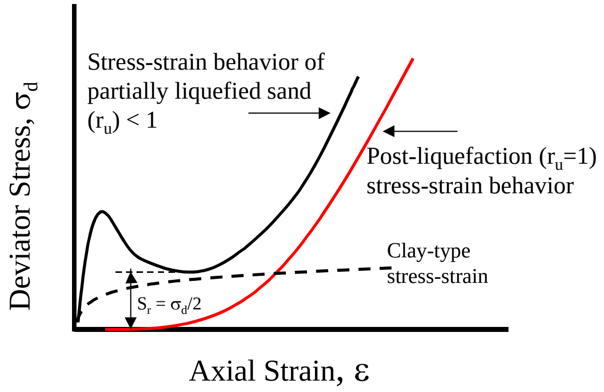

Fig. 2 Stress-strain pattern of partially and completely liquefied soil

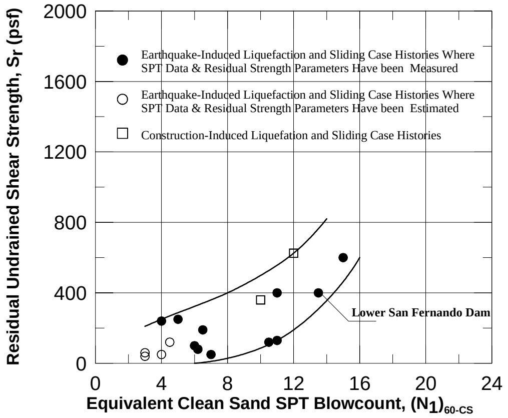

Fig. 3. Blowcounts Vs. residual strength (Seed and Harder, 1990)

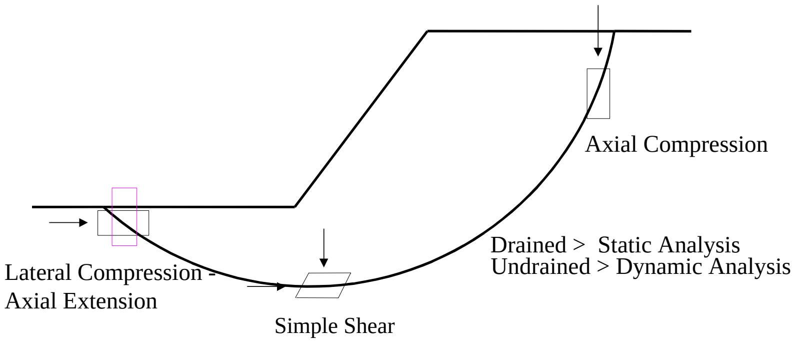

Fig. 4 Different loading scenarios of soil as simulated in the triaxial test