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ABSTRACT

During liquefaction, strength and stiffness degradation in sloping liquefied soil may lead to significant cycle-by-cycle shear strain accumulation. Accuracy in quantifying the magnitude of accumulated permanent shear strain is the key to satisfactory modeling of liquefaction-induced lateral spreading. Commonly used stress-space constitutive models may not be easily calibrated to reproduce the observed magnitudes of permanent shear deformation, since the shear flow phase is often accompanied by a minor change in shear stress magnitude. In a newly developed constitutive model, the observed large post-liquefaction shear-strain accumulation is accomplished by introducing a perfectly plastic zone into a multi-yield surface stress-space framework. After the perfectly plastic strain accumulation phase, the tendency for dilation may result in significant regain in shear stiffness and strength. This aspect of soil behavior is also modeled within the aforementioned constitutive model framework. This new model is integrated in an effective-stress fully coupled two-phase (solid and fluid) Finite Element computer code. In this paper, results of numerical simulations conducted using this computational program are discussed. A one-dimensional version of the program is now available on the Internet for on-line execution (**http://casagrande.ucsd.edu**).

KEYWORS

Liquefaction, Dilatancy, Lateral Spreading, Soil Plasticity, Constitutive Model, Finite Element Analysis, Embankment, Earthquake, Cavitation, Polarity

INTRODUCTION

During liquefaction, recent records of seismic site response (Holzer *et al.* 1989, Elgamal and Zeghal 1992, Zeghal and Elgamal 1994, Youd and Holzer 1994) have manifested a possible strong influence of soil dilation during cyclic loading. Such phases of dilation may result in significant regain in shear stiffness and strength at large cyclic shear strain excursions, leading to: i) associated instances of pore-pressure reduction, ii) appearance of spikes in lateral acceleration records (as a direct consequence of the increased shear resistance), and most importantly, iii) a strong restraining effect on the magnitude of cyclic and accumulated permanent shear strains. This restraint on shear strain has been referred to as a form of cyclic-mobility in a large number of pioneering liquefaction studies (Seed and Lee 1966, Casagrande 1975, Castro 1975, Castro and Poulos 1977, Seed 1979). For the important situations of biased strain accumulation due to an initial locked-in shear stress (e.g., lateral spreading), this pattern of behavior may play a dominant role in dictating the extent of shear deformations (for clean sands and silts).

Currently, the above-mentioned effects are thoroughly documented by a large body of experimental research (employing clean sands and clean non-plastic silts), including centrifuge experiments (Fiegel and Kutter 1992, Taboada 1995, Elgamal *et al.* 1996, Taboada and Dobry 1998, Dobry and Abdoun 1998, Balakrishnan and Kutter 1999), shake-table tests, and cyclic laboratory sample tests (Arulmoli 1992). A thorough summary has been compiled (Elgamal *et al.* 1998) of the relevant: i) seismic response case histories, ii) recorded experimental response (centrifuge, shake table, and laboratory), and iii) available constitutive models to simulate this phenomenon.

In the following sections, the main characteristics of the above-described shear stress-strain mechanisms are presented. The framework for a newly developed computational constitutive model and the salient model response characteristics are outlined. This computational framework is integrated into a general two-dimensional (2D) solid-fluid coupled, effective stress Finite Element program. The program (*CYCLIC*) was calibrated based on laboratory and centrifuge experiment results, designed to investigate the characteristics of liquefaction-induced lateral spreading due to dynamic (earthquake) excitation. This program has been employed extensively in numerical studies of soil systems such as layered sloping ground, remedied earth embankment (liquefaction countermeasures), and quay wall-soil interaction. In this paper, results of a numerical study of a waterfront embankment are presented and discussed. A 1D version of the computational program (*CYCLIC 1D*) is currently available for execution over the Internet at (**http://casagrande.ucsd.edu**).

CYCLIC LATERAL SPREADING MECHANISM

A thorough review of available relevant literature on the lateral spreading response mechanism in clean sands and silts has been presented recently (Elgamal *et al.* 1998). An illustration of the dilative-tendency mechanism observed in undrained cyclic laboratory tests is shown in Fig. 1 (Arulmoli *et al.* 1992). Similar response (Fig. 2) was observed (Zeghal and Elgamal 1994, Elgamal *et al.* 1995) at the US Imperial County Wildlife Refuge site (1987 Superstition Hills earthquake records, see Holzer *et al.* 1989).

Fig. 1 depicts the mechanism of accumulation of cycle-by-cycle deformations. This cyclic mobility mechanism can significantly reduces the total accumulated shear strain due to liquefaction. Accuracy in reproducing such response is among the most important goals of the developed constitutive model.

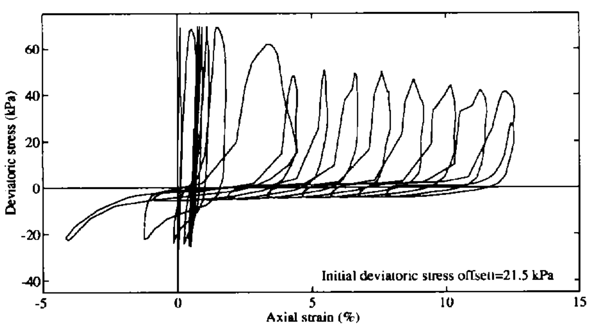

Fig. 1 Stress-strain history during an undrained stress-controlled cyclic triaxial test of Nevada sand (Dr=40%) with an imposed static deviatoric stress (Arulmoli et al. 1992).

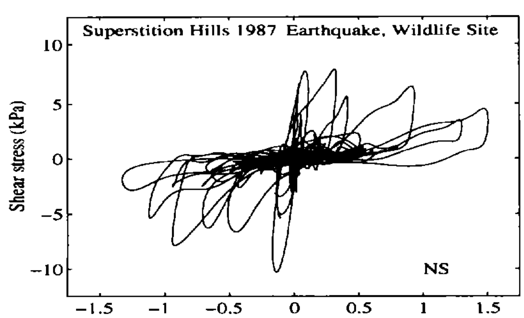

Fig. 2: Wildlife-Refuge NS shear stress-strain histories during Superstition Hills 1987 Earthquake (evaluated from acceleration histories, Zeghal and Elgamal 1994, Elgamal et al. 1995).

LIQUEFACTION CONSTITUTIVE MODEL

Currently available constitutive models that reproduce important aspects of the above-mentioned dilative shear mechanism include (Iai 1991, Iai *et al.* 1995, Kramer and Arduino 1999, Tateishi *et al.* 1995, and Cubrinovski and Ishihara 1998). An additional new constitutive model was developed (Parra 1996, Yang 2000), based on the original framework of the multiple-yield-surface plasticity concept (Iwan 1967, and Mroz 1967), as proposed and implemented by Prevost (1985) for frictional cohesionless soils. This model was modified (Parra 1996, Yang 2000) from its original form (Prevost 1985) to represent the shear stress-strain features discussed above, including the biased accumulation of cyclic shear strains due to the presence of an imposed static shear stress. Special attention was given to the deviatoric - volumetric strain interaction under cyclic loading; in particular during loading - unloading - reloading near the yield envelope (Figs. 3 and 4).

Commonly used stress-space constitutive models may not easily reproduce the mechanism of liquefaction-induced permanent shear strain accumulation, since the shear flow phase (Fig. 3, phase 1-2) is often accompanied by a minor change in shear stress. In the new model, accumulation of perfectly plastic strain (Fig. 3, phase 1-2) is directly controlled by introducing a *perfectly plastic zone*, which is a function of strain-space state parameters (Yang 2000). Furthermore, non-associative loading-unloading flow rules were devised (Parra 1996) to reproduce the observed strong dilation/contraction effects (Fig. 3, phases 2-3, 3-4). The model parameters for medium density (Dr ≈ 40%) Nevada sand were calibrated by extensive laboratory tests (Arulmoli *et al.* 1992) and centrifuge experiments (Parra 1996, Yang 2000).

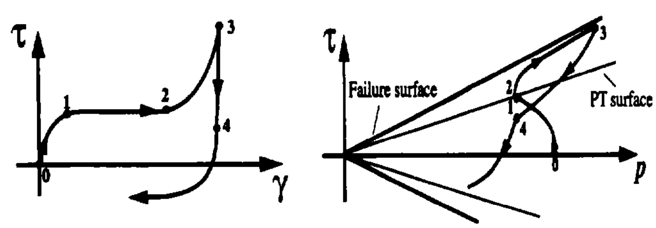

Fig. 3 Response characteristics of the new constitutive model: typical shear stress-strain response and effective stress path (Parra 1996, Yang 2000).

A step-by-step shear stress-strain history was generated (Fig. 4) to illustrate the employed *perfectly plastic zone* (PPZ) logic. For simplicity, the effect of confining pressure is not included (each step below corresponds to a sub-plot number in Fig. 4):

1. Initially, the PPZ is symmetric or isotropic. Once the phase transformation (PT) envelope is reached during a loading phase, perfectly plastic strain is developed within this initial PPZ.

2. Beyond the boundary of the initial PPZ, dilation takes place. The PPZ is enlarged accordingly.

3. Upon unloading, the PPZ is further expanded to the right by the same amount of shear strain experienced during unloading (such that $\gamma_1 \leq \gamma_{1_{max}}$, a user defined level of strain), allowing for additional perfectly plastic strain to develop upon possible reloading.

4. Reloading reaching PT surface and resulting in perfectly plastic strain, until the PPZ boundary.

5. The PPZ translates with the current strain point towards the right, up to the level γ of step 2.

6. Further straining during dilation enlarges the PPZ (similar to Step 2).

7. Unloading causing the PPZ to continue the expansion of step 3 up to a total amount of $\gamma_{1_{max}}$, and thereafter translate to the right, allowing for additional perfectly plastic strain to develop upon possible reloading. However, the combined expansion and/or translation is limited by $\gamma_{1_{max}}$, and further unloading does not alter the PPZ.

8. The PPZ follows the strain point towards the left with the size unchanged (biased loading).

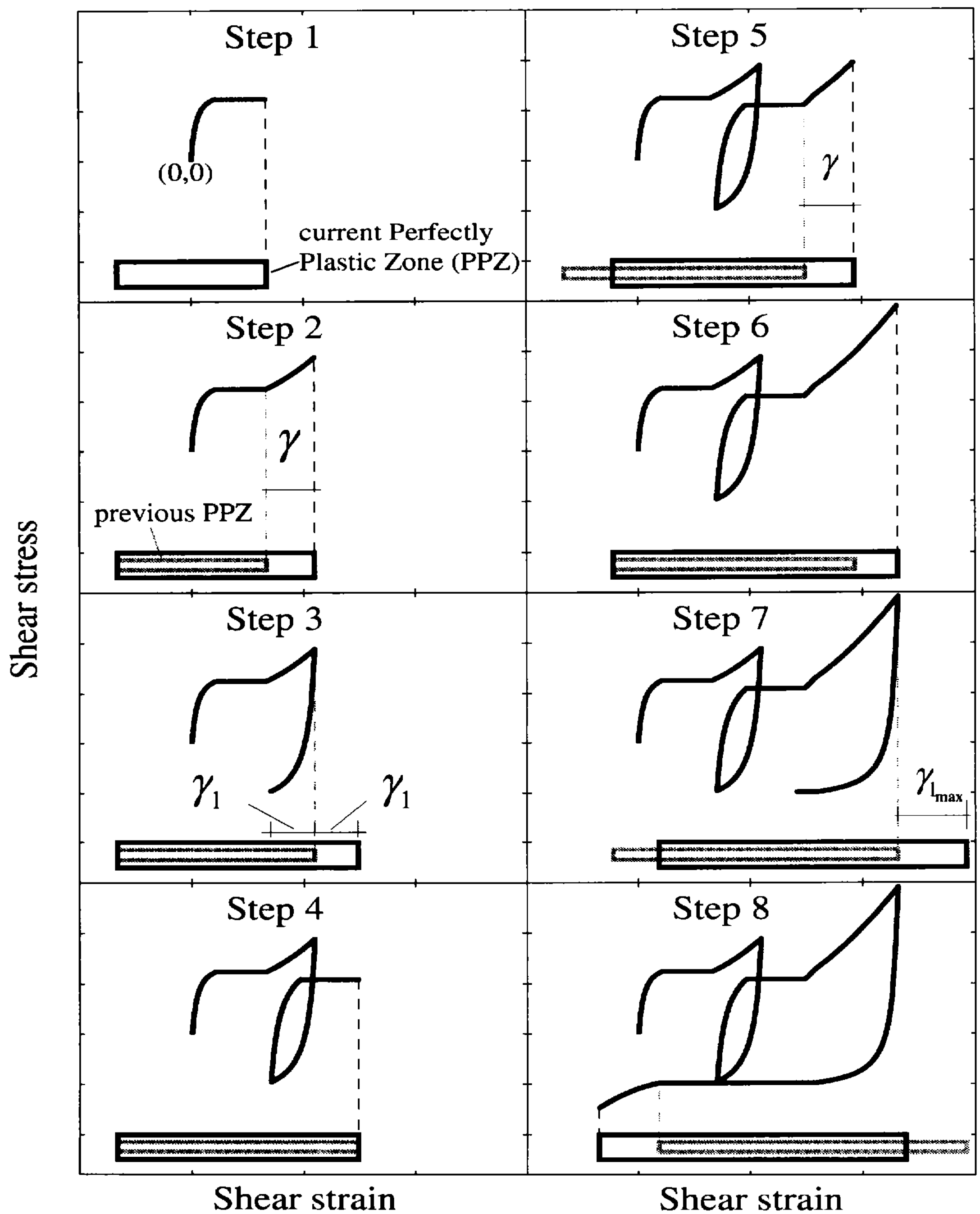

Fig. 4 Illustration of Perfectly Plastic Zone logic.

APPLICATION: 2D ANALYSIS OF A WATERFRONT EMBANKMENT

CYCLIC: A Solid-Fluid Coupled Finite Element Procedure

The new constitutive model was integrated into a general purpose 2D (plane strain and axisymmetric) finite element program *CYCLIC*. The finite element formulation implemented in *CYCLIC* is based on a fully coupled solid-fluid approach (known as u-p formulation), following the procedures developed by Chan (1988) and Zienkiewicz *et al.* (1990). *CYCLIC* has been employed extensively to study soil behavior in conventional laboratory tests and dynamic centrifuge experiments. In the following, results of a numerical study of a waterfront embankment using *CYCLIC* are presented and discussed.

Modeling Procedure

A numerical investigation of a waterfront embankment was conducted (Yang 2000). The site consisted primarily of liquefiable sands with a clay seam and a rock dike (Fig. 5). In the constitutive model, Nevada Sand properties (based on extensive calibration, Parra 1996, Yang 2000) were employed for sand with a Poisson's ratio ν of 0.4. The clay seam was modeled essentially as a pressure insensitive material with a relatively low shear stiffness. The rock material was modeled using the same sand model but with higher shear stiffness and very large permeability. A 4-node quadrilateral element was used for both the solid and fluid phases. The input acceleration was prescribed along the base and side boundary nodes in the horizontal direction. The boundary conditions for the fluid phase dictated an impervious base and lateral boundaries, with prescribed fluid pressures enforced along the surface nodes. These prescribed fluid pressures were evaluated depending on the water level at each individual surface node. Additional modeling details are described in Yang (2000).

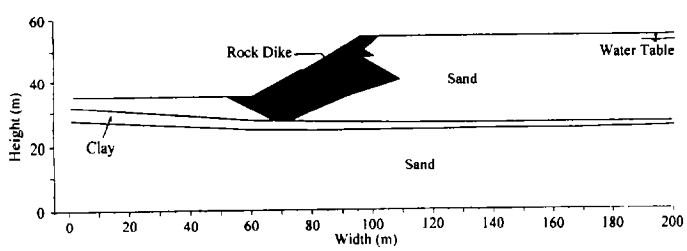

Fig. 5 Earth embankment (modified from Earth Mechanics 1998)

Results and Discussions

In this analysis, one of the horizontal acceleration time histories recorded at the Rinaldi Receiving Station during the 1994 Northridge (Los Angeles) Earthquake (Fig. 6) was used as input motion. This is a representative near-fault record with a rather strong velocity pulse (Fig. 6). The peak acceleration is 0.88g. In order to study the polarity effect of this acceleration pulse on the model response, two simulations were conducted, one using the original record (denoted Case O in the following) and the other with reversed polarity (denoted Case R in the following). Fig. 7 shows the finite element model mesh before and after a shaking event.

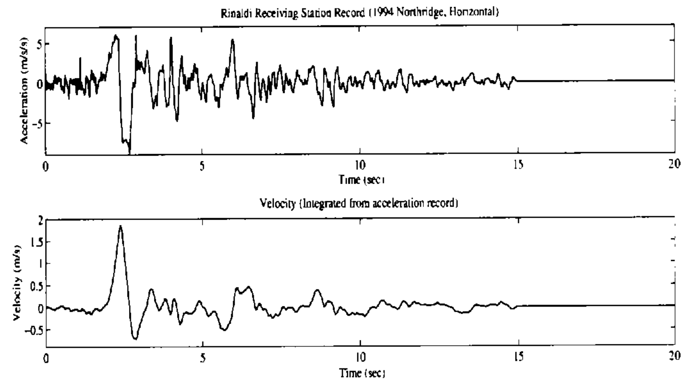

Fig. 6 Rinaldi Receiving Station recorded acceleration and integrated velocity histories (1994 Northridge Earthquake, Horizontal).

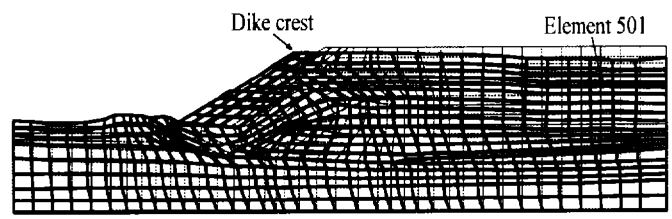

Fig. 7 Undeformed vs. deformed embankment mesh (deformation not to scale, Yang 2000).

Figs. 8 and 9 depict the computed horizontal and vertical displacement histories at the dike crest for these two cases. The polarity effect of input excitation is evident in Fig. 8, in that the two displacement curves are out of phase. For example, at the instant of the large velocity pulse arrival (2.5 seconds), the dike crest in case O quickly moved 0.8m down-slope, whereas in case R the movement was 0.5m up-slope. In both cases, a maximum horizontal displacement of about 3m was observed (Fig. 8). Although the difference was not significant in the final crest lateral displacement, Case R predicted a maximum vertical settlement of 0.5m, compared to a predicted 0.3m settlement in Case O (Fig. 9).

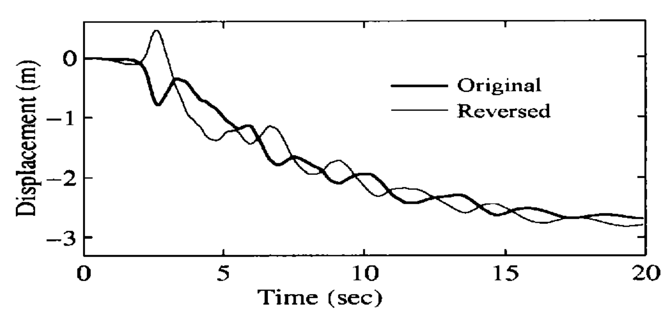

Fig. 8 Lateral displacement histories at dike crest.

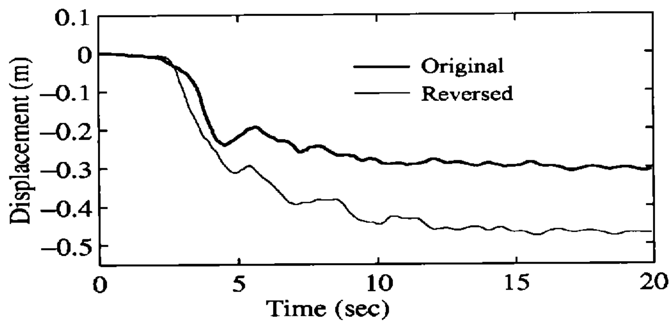

Fig. 9 Vertical displacement histories at dike crest.

Strong dilation tendency induced by the intense shaking also caused cavitation (i.e., pore water pressure dropping to −1 atmospheric pressure, Casagrande 1975) in many elements. For example, element 501 (Fig. 7) in Case O experienced cavitation at about 2.5 seconds (Fig. 10), when the peak velocity occurred (Fig. 6). In Fig. 10, the two excess pore pressure curves are also clearly seen to be out of phase. For example, at the instant of cavitation in case O, the same element was showing a strong pore pressure increase in case R.

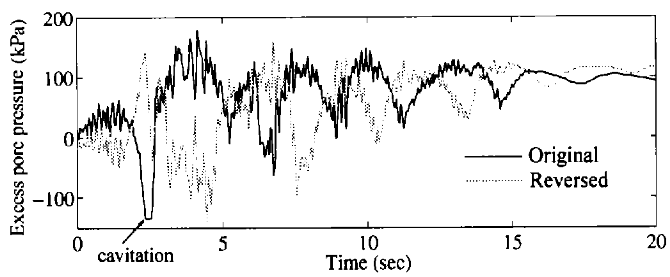

Fig. 10 Excess pore pressure histories at Element 501.

CYCLIC 1D WEB-SITE

A site amplification computer code (*CYCLIC 1D*) that includes the above-described constitutive model is currently available for execution using commonly available Internet browsers such as Internet Explorer or Netscape Navigator (**http://casagrande.ucsd.edu**). Currently, the user can: i) define element height (the soil stratum consists of 10 elements), ii) choose a stratum inclination angle, and iii) select/scale from a set of base input earthquake motions. Upon completion, computed results are displayed graphically, and can be downloaded electronically (Elgamal and Yang 2000).

SUMMARY AND CONCLUSIONS

In clean medium to dense sands, a possible strong influence of soil dilation on liquefaction-induced lateral deformation was shown. This mechanism is documented in a large body of experimental research (on medium-dense cohesionless soil) including earthquakes records, centrifuge experiments and cyclic laboratory tests. A new constitutive model was developed to reproduce such cyclic shear behavior during liquefaction. In order to accurately predict post-liquefaction lateral spreading, a "perfectly plastic zone" scheme was devised and described in detail. The constitutive model was incorporated into a solid-fluid coupled finite element code *CYCLIC*, which was employed to study the dynamic behavior of a waterfront embankment, including the influence of input motion polarity and near-fault effects on the model response. Currently, a web-site (**http://casagrande.ucsd.edu**) is available for using the new constitutive model (within *CYCLIC*) to conduct seismic simulations of level and sloping site response.

ACKNOWLEDGEMENTS

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