NUMERICAL MODELING OF LIQUEFACTION-INDUCED LATERAL SPREADING

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SUMMARY

During liquefaction, a shear-induced dilatancy mechanism may be one of the major factors that dictate soil behavior. As shear strain accumulates, this dilative tendency results in instants of excess pore pressure drop, sharp acceleration spikes, and associated regain of shear strength and stiffness in the liquefied soil. These phenomena are documented in an increasingly large body of research studies, including downhole-array earthquake records, and laboratory and centrifuge experiments. A new constitutive model based on the multi-yield plasticity concept is developed to accurately reproduce the above characteristics of soil liquefaction. The constitutive model is incorporated in a fully coupled soil-fluid Finite Element program. Calibration was performed for medium density sand based on laboratory tests and centrifuge experiments. The centrifuge experiments included a series of tests to investigate liquefaction effects under a soil embankment. An Internet site (http://casagrande.ucsd.edu) is now available for execution of a one-dimensional version of this Finite Element program. A comparison study conducted on this website demonstrates significant difference in soil response between level-ground and sloping sites, due to the strong influence of soil dilatancy. This study also shows dilatancy as an important mechanism in limiting soil lateral spreading during liquefaction.

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.

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 and Dobry 1998, Dobry and Abdoun 1998, and 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

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liquefaction-induced lateral spreading due to dynamic (earthquake) excitation. After calibration, predictive simulations were conducted and compared to a series of centrifuge experiments exploring the effects of liquefaction below an overlying soil embankment [Adalier 1996, Adalier *et al.* 1998]. A 1D version of the computational program (*CYCLIC 1D*) has already been set up on the Internet (http://casagrande.ucsd.edu) for interested researchers to use.

CYCLIC LATERAL SPREADING MECHANISM

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

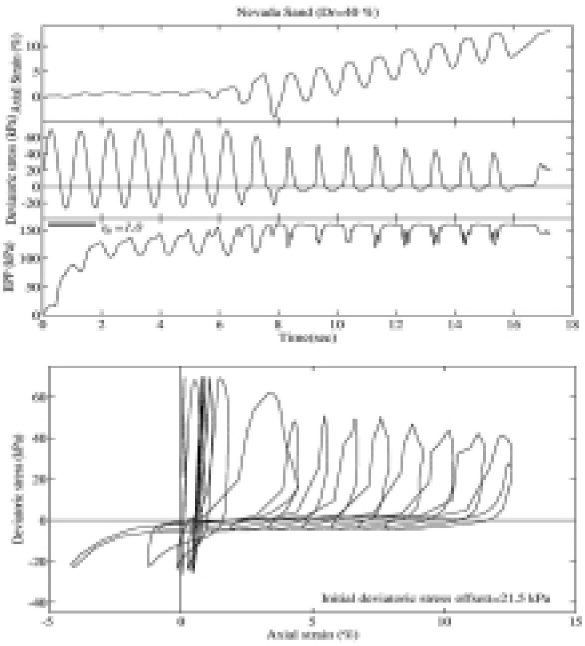


Figure 1: Stress, strain and EPP histories during an undrained stress-controlled cyclic triaxial test of Nevada sand (Dr 40%) with an imposed static deviatoric stress (after Arulmoli et al. 1992).

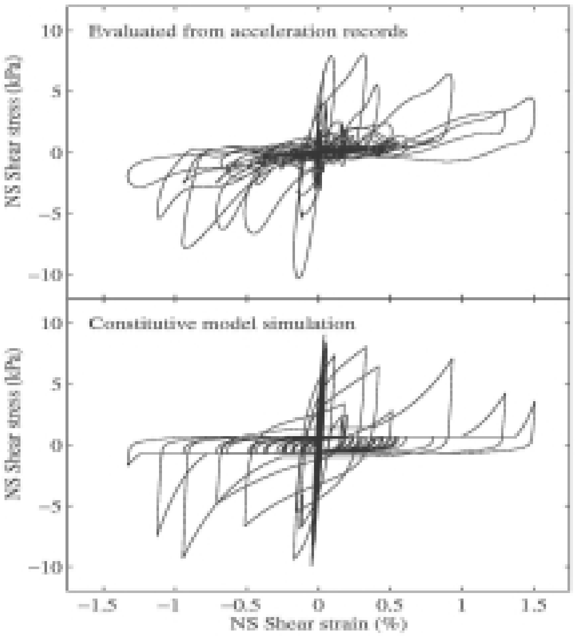


Figure 2: Wildlife-Refuge NS shear stress-strain histories during Superstition Hills 1987 Earthquake (evaluated from accel. histories and computed, Elgamal et al. 1995).

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 1999], based on the original framework of the multiple-yield-surface plasticity concept [Iwan 1967, and Mroz 1967], implemented by Prevost [1985] for frictional cohesionless soils. It was modified [Parra 1996, Yang 1999] from its original form [Prevost 1985] to model the shear stress-strain features discussed above, including the biased accumulation of cyclic shear strains due to the presence of a locked-in driving 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. The model parameters for medium density (Dr $\approx$ 40%) Nevada sand response were calibrated by extensive laboratory tests [Arulmoli *et al.* 1992] and centrifuge experiments [Parra 1996, Yang 1999].

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]. Predictive simulations were conducted using *CYCLIC* [Parra 1996] and compared to a series of centrifuge experiments (Figure 3) exploring the effects of liquefaction below an overlying soil embankment [Adalier 1996, Adalier *et al*. 1998]. Figure 4 shows a satisfactory match between computed and experimental results.

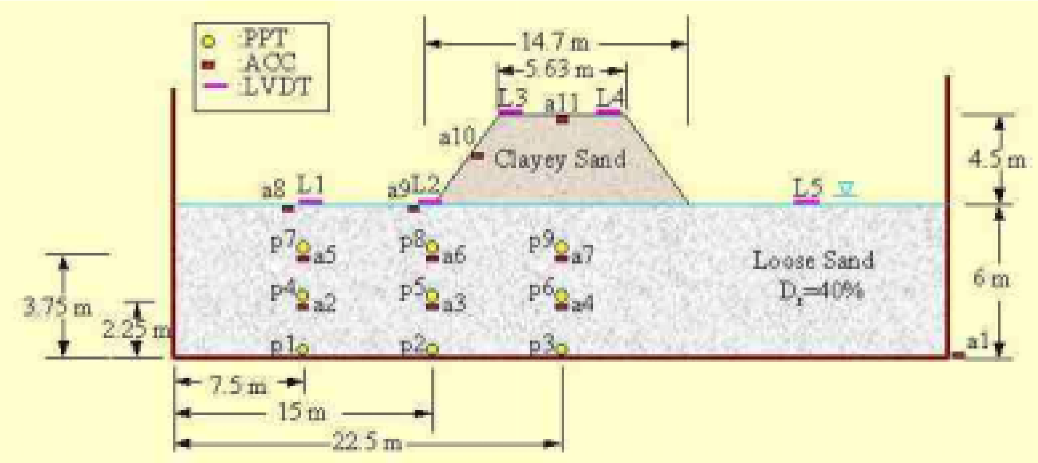


Figure 3: General configuration and instrumentation Centrifuge Test #1 (No remediation, after Adalier 1996).

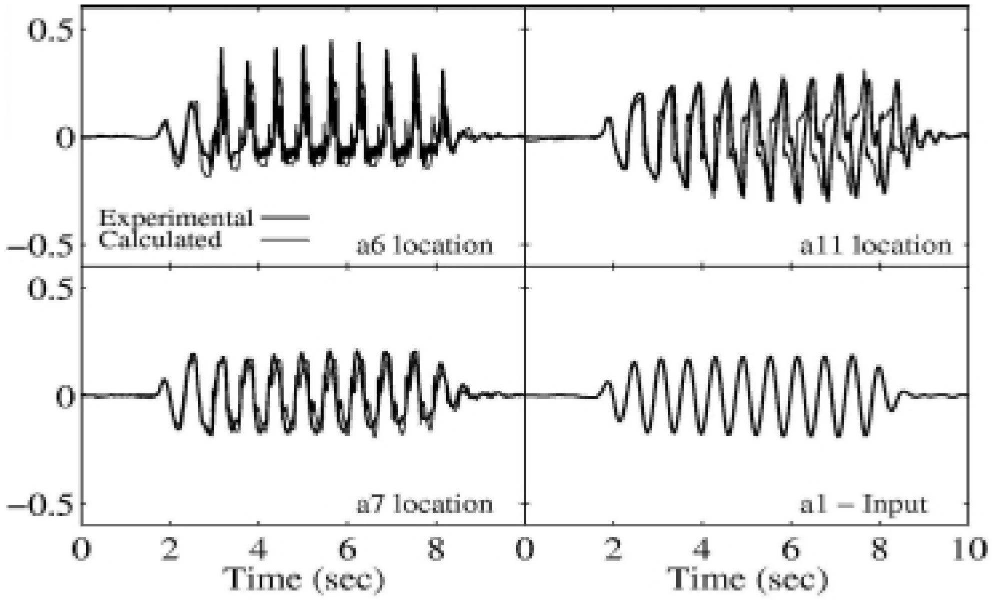
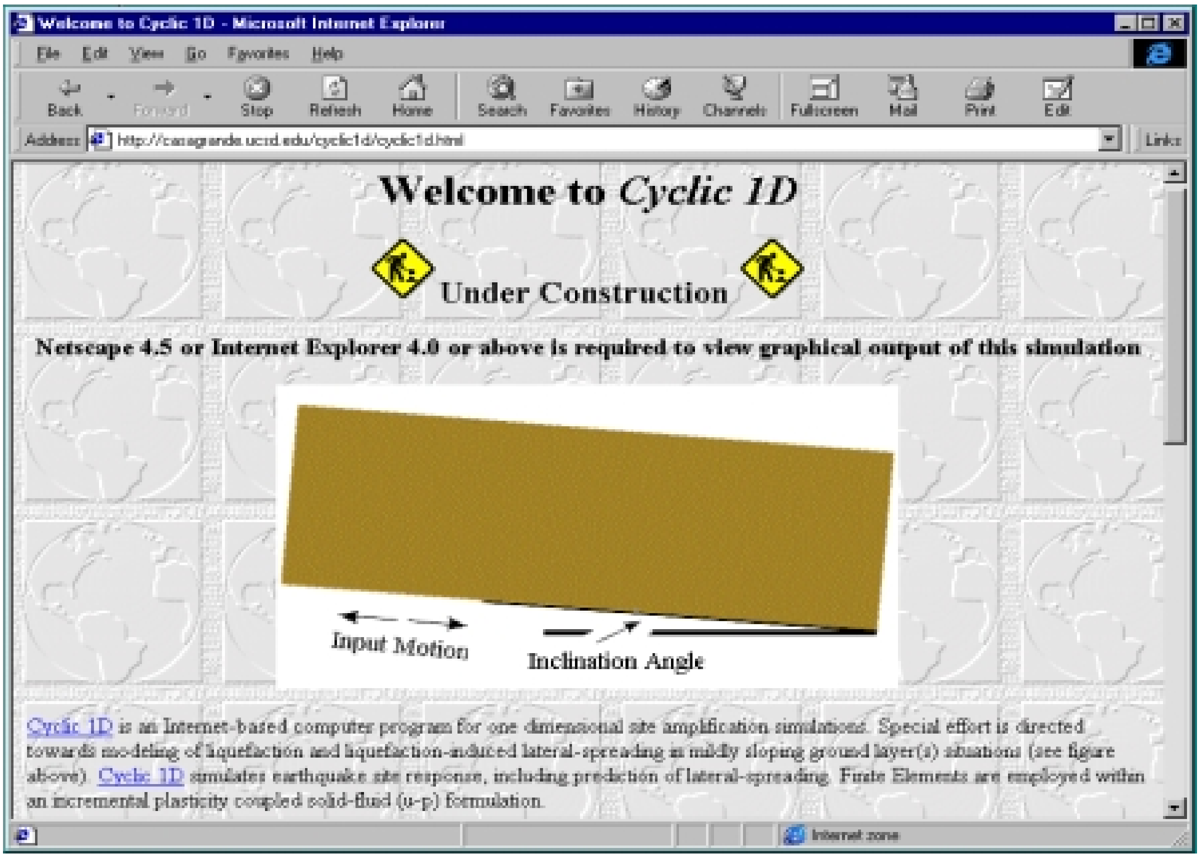


Figure 4: Calculated and experimental horizontal acceleration histories for Test #1 (see fig. 3, 0.2g peak input, representative results, after Parra 1996).

CYCLIC 1D

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)**. The *CYCLIC 1D* website is displayed in Figure 5. 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.



Welcome to *Cyclic 1D*

Under Construction

Netscape 4.5 or Internet Explorer 4.0 or above is required to view graphical output of this simulation

Cyclic 1D is an Internet-based computer program for one dimensional site amplification simulations. Special effort is directed towards modeling of liquefaction and liquefaction-induced lateral-spreading in mildly sloping ground layer(s) situations (see figure above). Cyclic 1D simulates earthquake site response, including prediction of lateral-spreading. Finite Elements are employed within an incremental plasticity coupled solid-fluid (u-p) formulation.

Figure 5: *CYCLIC 1D* liquefaction simulation web site(http://casagrande.ucsd.edu)**.**

Results of two 1D numerical simulations executed on the *CYCLIC* 1D website are discussed below. Both cases simulate the dynamic behavior of a 10 m medium dense (Dr≈40%) clean Nevada sand stratum, subjected to cycles of base excitation. In the first case the soil profile is level, and the input excitation has a peak acceleration of 1.0 m/sec/sec (Figure 6). In the second case, the same input motion is used, but the soil profile is inclined by 4.0 degrees (to simulate a mildly inclined infinite-slope situation). The purpose of this study is to manifest the significance of the above discussed cyclic-mobility mechanism (particularly the soil dilative behavior) on the development of liquefaction-induced lateral spreading .

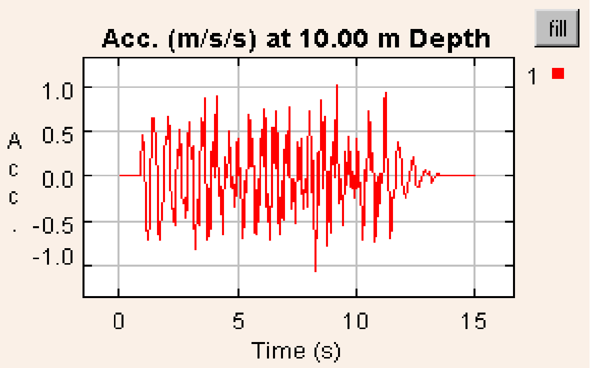
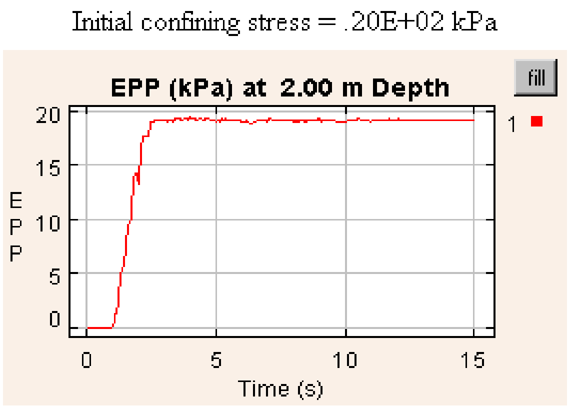


Figure 6: Base input excitation.

In the level ground case, liquefaction is quickly reached in all but the deepest part of the stratum, and the high level of excess pore pressure remains throughout the shaking phase (Figure 7). This significant buildup of excess pore pressure results in: i) loss of effective confining stress and shear strength (Figure 8), ii) degradation of shear stiffness (Figure 9), and iii) quick decrease and eventually disappearance of lateral acceleration amplitude near ground surface (Figure 10). It is also seen that in the level ground case with uniform cycles of excitation, acceleration spikes are symmetric, with negligible permanent lateral deformation (Figure 11).

In the inclined stratum case, soil is subjected to the same symmetric cyclic base excitation (Figure 6) superposed on a static locked-in shear stress (due to the 4 degrees inclined self-weight component of the ground). The presence of this static driving force results in the accumulation of significant permanent lateral deformation (lateral spreading) in the down-slope direction (Figure 12) and in a pattern of asymmetric acceleration spikes (Figure 13). Although excess pore pressure initially builds up much like the level ground case, post-liquefaction behavior is completely different. The p-q diagram (Figure 14) shows strong soil dilatancy as the stress path travels along the failure (or phase-transformation) line during liquefaction. This pattern of cyclic mobility results in: 1) instantaneous increase of confining stress and shear strength (Figure 14), 2) corresponding pore pressure drops (Figure 15), 3) associated regain in shear stiffness (Figure 16), and 4) appearance of asymmetric down-slope acceleration spikes (direct consequence of this stiff dilative shear stress-strain response) at ground surface. Thus, the above dilative mechanism may prevent an otherwise excessive amount of lateral spreading from accumulating.



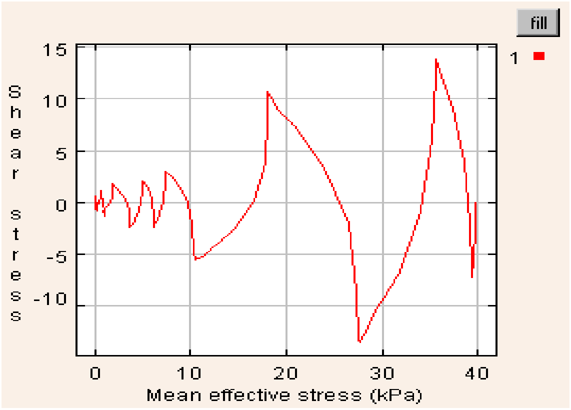
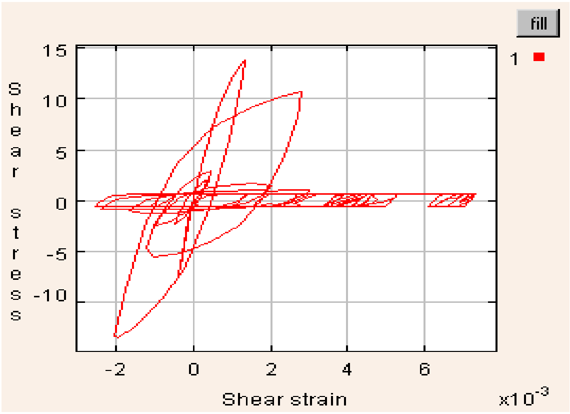


Figure 7: (level case) Excess pore pressure history at 2.0 m depth.

Figure 8: (level case) Shear stress vs. mean effective stress at 5.0 m depth.



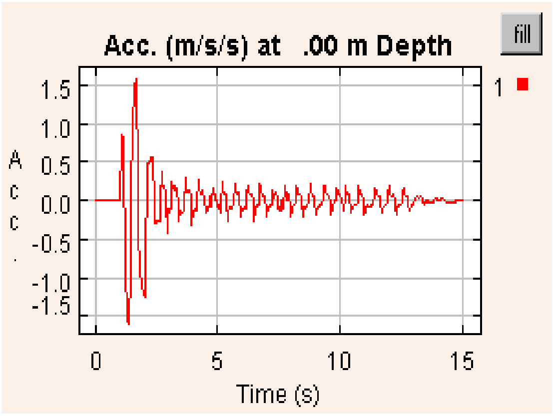
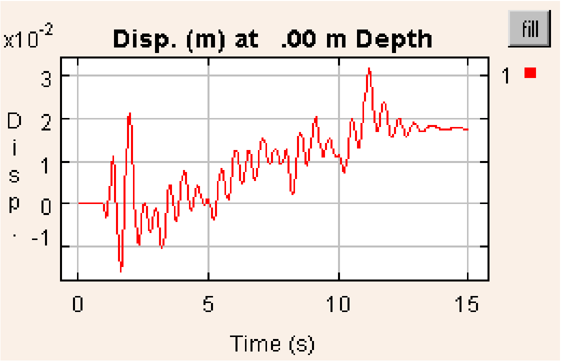


Figure 9: (level case) Shear stress-strain history at 5.0m depth.

Figure 10: (level case) Surface acceleration time history.



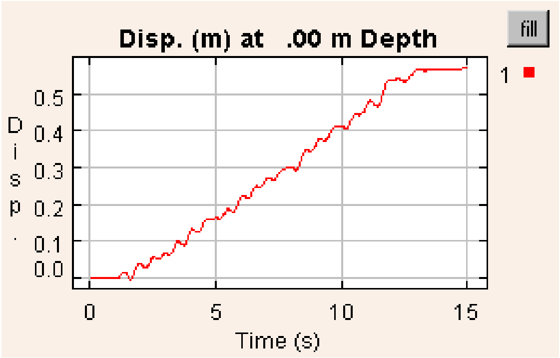
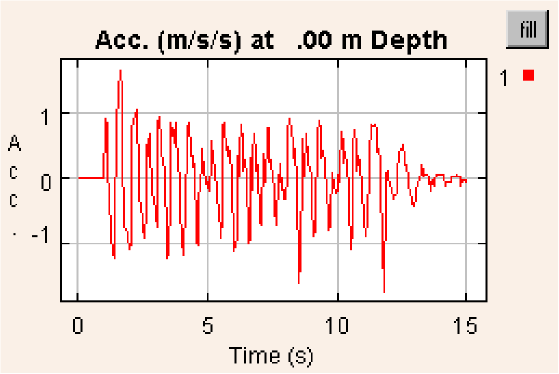


Figure 11: (level case) Surface lateral displacement time history (relative to the base) .

Figure 12: (inclined case) Surface lateral displacement time history (relative to the base).



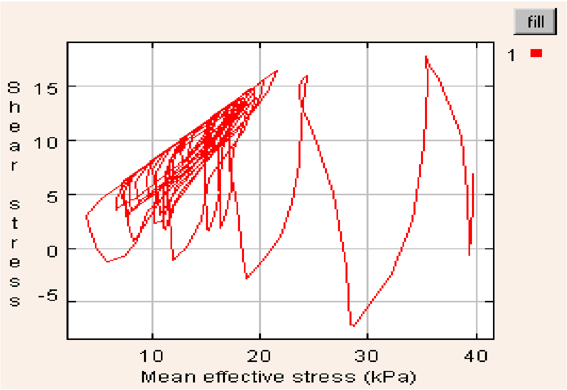
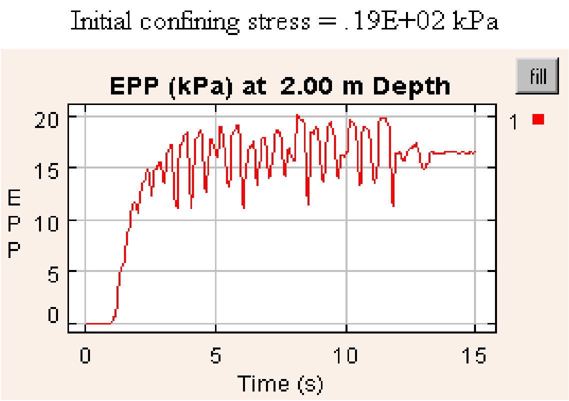


Figure 13: (inclined case) Surface acceleration time history.

Figure 14: (inclined case) Shear stress vs. mean effective stress at 5.0 m depth.



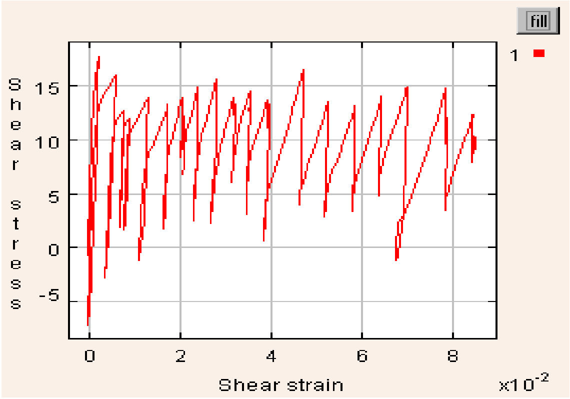


Figure 15: (inclined case) Excess pore pressure history at 2.0 m depth.

Figure 16: (inclined case) Shear stress-strain history at 5.0m depth.

CONCLUSIONS

A new constitutive model is developed to model the cyclic shear behavior of liquefied soil. The underlying mechanisms are based on observed (medium-dense cohesionless soil) response during earthquakes, centrifuge experiments and cyclic laboratory tests. The salient model response characteristics were illustrated in the form of level and mildly sloping site responses. An Internet site (http://casagrande.ucsd.edu) is available for using the developed constitutive model (within a fully-coupled solid-fluid finite element program) to conduct seismic simulations of level and sloping seismic site response.

ACKNOWLEDGMENTS

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