Modeling of Liquefaction-Induced Shear Deformation

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ABSTRACT: A constitutive model is developed to reproduce salient aspects associated with seismically-induced soil liquefaction (medium to dense clean cohesionless soils). Attention is mainly focused on the deviatoric (shear) stress-strain response mechanism. Soil cyclic shear behavior during liquefaction is modeled to display a significant regain in stiffness and strength with the increase in deformation during each cycle of applied load. This behavior appears to play a major role in dictating the magnitude of shear deformations as observed in laboratory tests and manifested in acceleration records from earthquakes and centrifuge experiments (clean sands and non-plastic silts). Constitutive model parameters are selected to represent medium, medium-dense and dense clean cohesionless soils. Using these parameters, the resulting model response is presented under simple-shear cyclic loading situations. Further modeling accuracy may be achieved based on a more thorough understanding of the underlying physical processes.

KEYWORDS: Liquefaction, cyclic-mobility, sand, constitutive modeling, earthquake, plasticity

1. INTRODUCTION

During liquefaction, recent records (Holzer *et al.* [9], Zeghal and Elgamal [23], Youd and Holzer [22]) of seismic site response 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 (Figure 1), 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 (*e.g.,* Seed and Lee [16], Casagrande [2], Castro [3], Castro and Poulos [4], Seed [17]). For the important situations of biased strain accumulation due to an initial locked-in shear stress, 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 (*e.g.,* Dobry *et al.* [5], Taboada [19], Dobry *et al.* [6]), shake-table tests, and cyclic laboratory sample tests (Arulmoli [1]). A thorough summary has been compiled (Elgamal *et al.* [8]) of the relevant: i) seismic response case histories, ii) recorded experimental (centrifuge, shake table and laboratory) response, and iii) constitutive models developed to simulate this phenomenon.

In the following pages, illustrations of the above-described shear stress-strain mechanisms are presented. Thereafter, the constitutive model is discussed, and the salient model response characteristics are presented.

2. CYCLIC LOADING MECHANISM

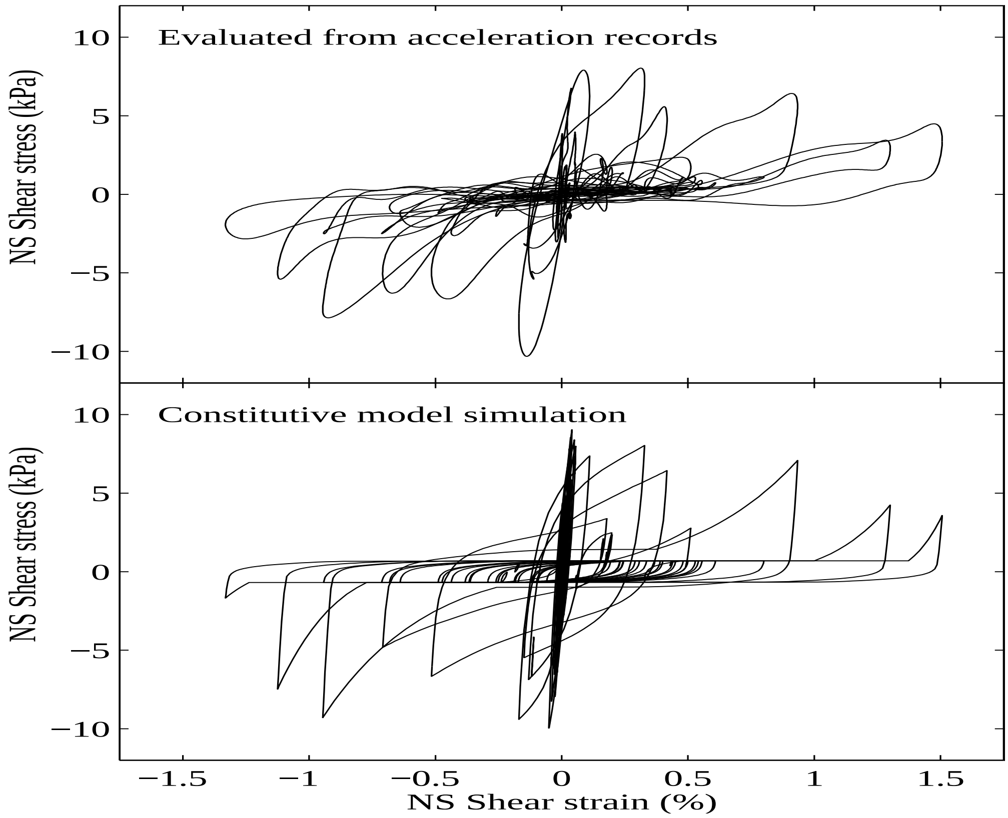

Figure 1: Wildlife-Refuge NS shear stress-strain and effective-stress histories during the Superstition Hills 1987 Earthquake (evaluated from acceleration histories and computed, after Elgamal et al. 1995).

A thorough review of available relevent literature has been presented recently by Elgamal *et al.* [8]. An illustration of the dilative-tendency mechanism observed in undrained cyclic laboratory tests is shown in Figure 2 (Arulmoli *et al.* [1]). Similar response (Figure 1) was observed (Zeghal and Elgamal [23]) at the US Imperial County Wildlife Refuge site (1987 Superstition Hills earthquake records). Currently available constitutive models that reproduce important aspects of the above shear mechanism include those by Iai [10], Iai *et al.* [11] and Tateishi *et al.* [20].

One-dimensional shear stress-strain histories (e.g., Figure 3) calculated from recorded centrifuge experiment acceleration and LVDT records (Dobry *et al.* [5], Dobry *et al.* [6], Taboada [18], Elgamal *et al.* [7], Taboada and Dobry [19]) also display a similar response mechanism. Figures 2 and 3 depict the mechanism of accumulation of cycle-by-cycle deformations. Accuracy in reproducing this mechanism is among the most important goals of the developed constitutive model.

3. CONSTITUTIVE MODEL

The model framework follows the procedures developed by Prevost [15], based on the multiple yield surface plasticity concept (Iwan [12], and Mroz [13]). It was modified (Parra [14], Yang [21]) from its original form (Prevost [15]) to model the shear stress-strain features discussed above (Figs. 1 - 3). Special attention was given to the deviatoric – volumetric strain interaction under cyclic loading; in particular during loading – unloading – reloading near the yield envelope (Parra [14], Yang [21]).

4. MODEL RESPONSE

Figures 4 and 5 illustrate the mechanism of model response. These figures depict a simulation of a biased cyclic shear stress - strain history. A static driving “locked-in” shear stress was simulated by applying load cycles in the range of 0.0 kPa to 60 kPa (Figure 4). Under this loading history, gradual pore pressure buildup and liquefaction occurs (i.e., effective confinement approaches zero, Figure 5). During liquefaction the model reproduces a stable cycle-by-cycle accumulation of shear deformation, along the lines of the experi-

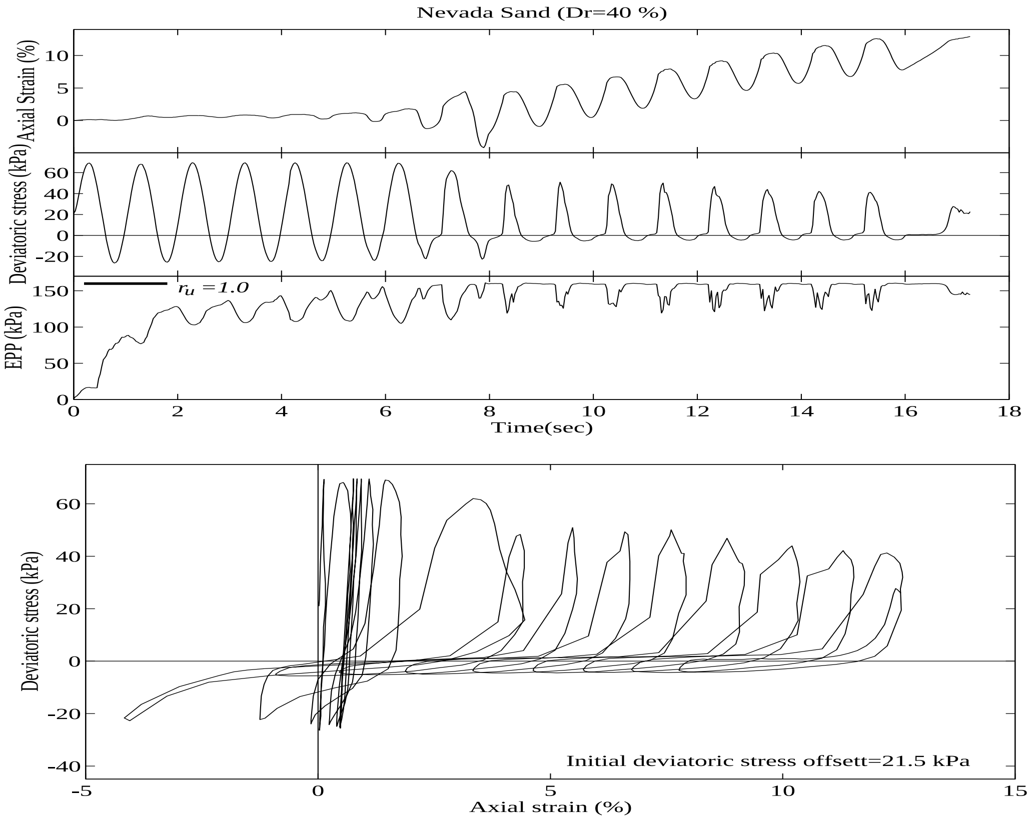

Figure 2: Stress, strain and EPP histories during an undrained stress-controlled cyclic triaxial test of Nevada sand ($Dr = 40$ %) with an imposed static (initial) deviatoric stress (after Arulmoli et al. 1992).

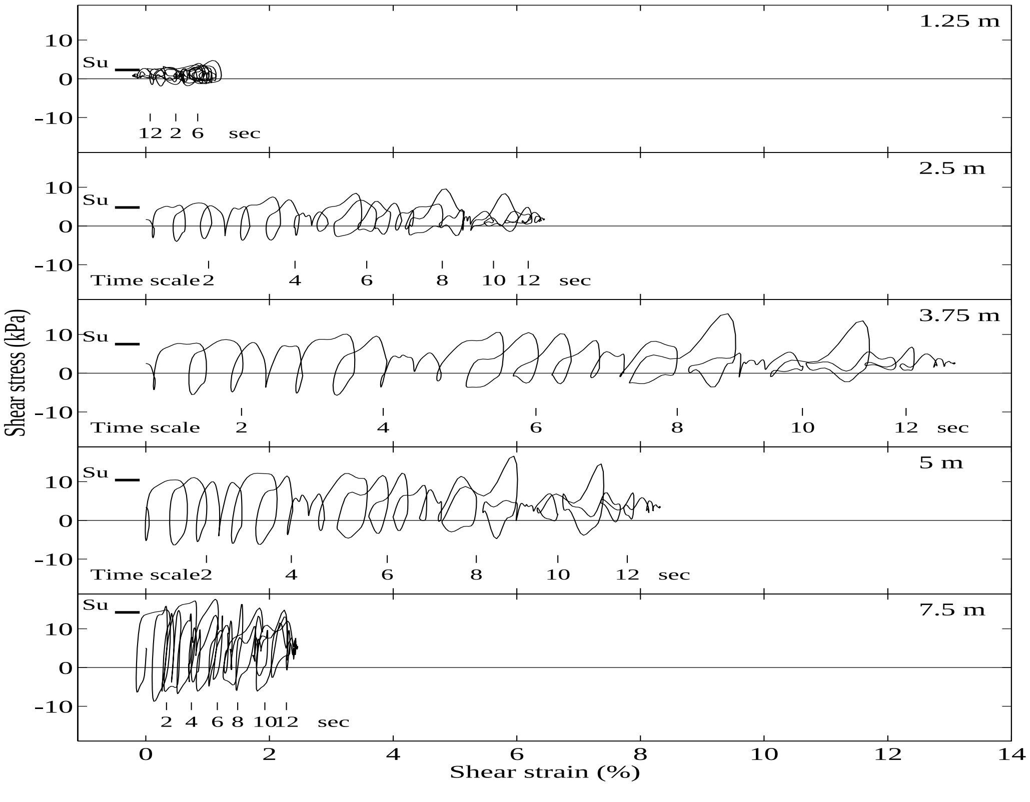

Figure 3: RPI Model 2 shear stress-strain histories with superposed static stress due to inclination (Taboada 1995, Dobry et al. 1995, Elgamal et al. 1996).

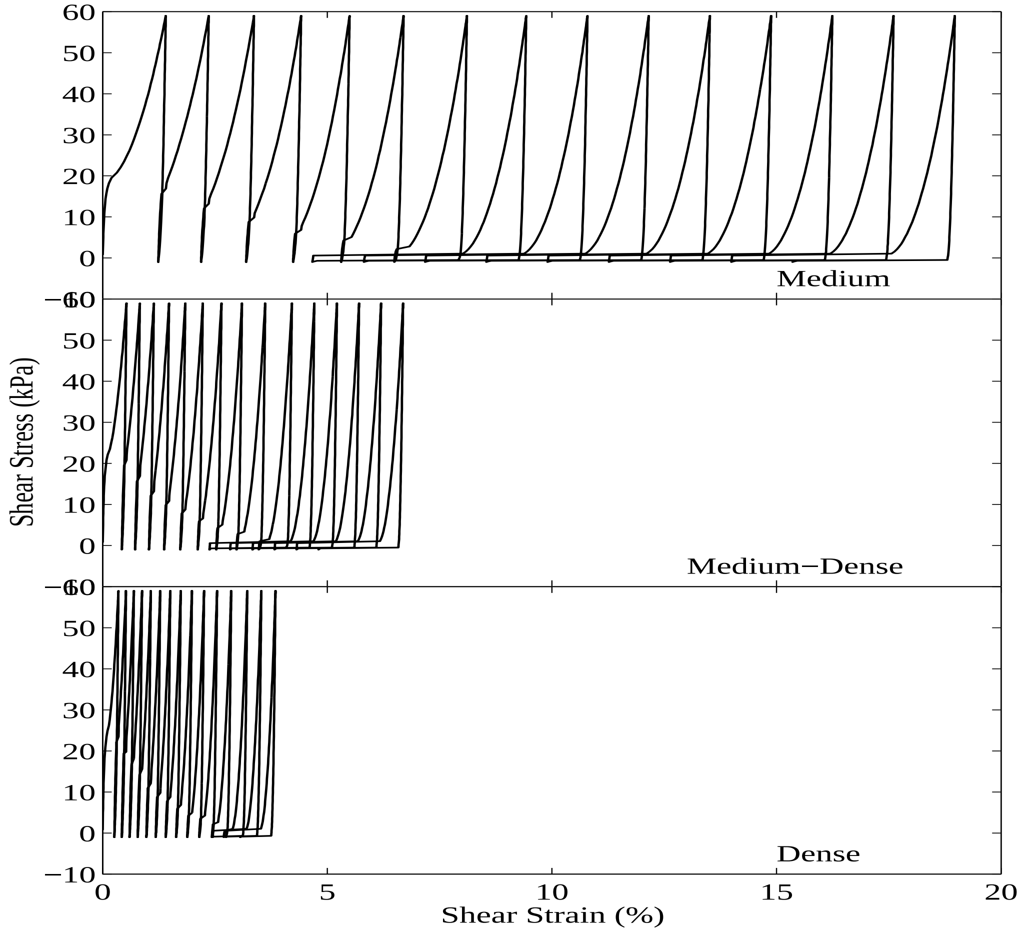

Figure 4: Simulation of undrained biased cyclic simple shear tests.

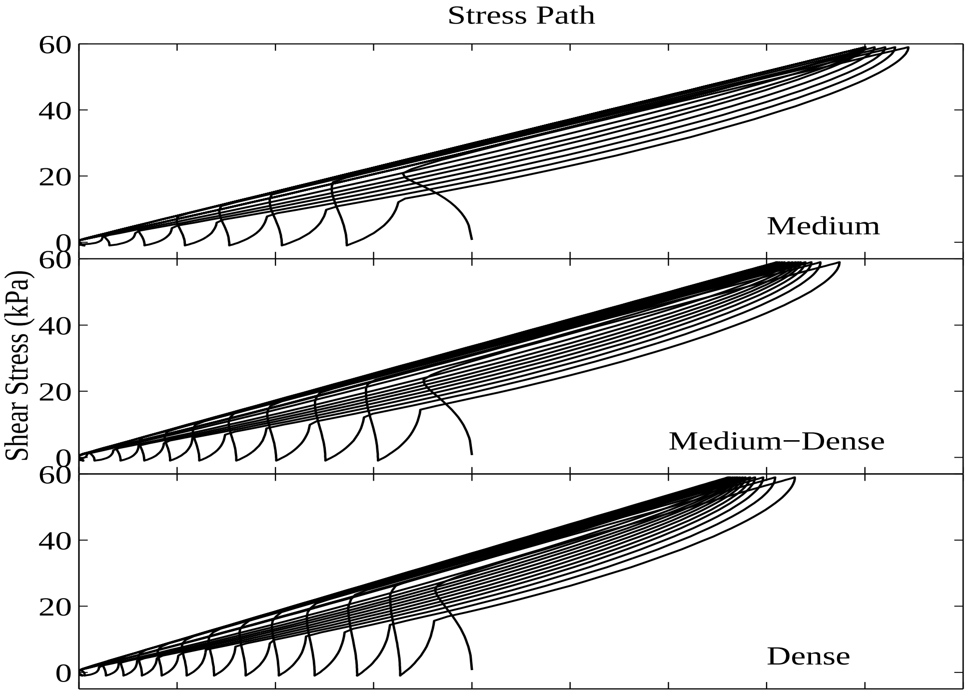

Figure 5: Computed stress path during undrained biased cyclic simple shear.

mental response of Figure 2. For engineering applications, three performance scenarios were selected to represent clean medium, medium-dense and dense sand (or silt) situations (relative density in the range of about 40% to 90%). In Figure 4, maximum accumulated cycle-by-cycle shear deformations are about 1.3% (medium), 0.5% (medium-dense) and 0.3% (dense).

The medium sand response was calibrated by extensive laboratory tests (Arulmoli *et al.* [1]) and centrifuge experiments (Parra [14], Yang [21]). At this point, the deformation characteristics for the medium-dense and dense situations are qualitative (motivated by the literature review in Elgamal *et al.* [8]). Further data is needed to refine the estimates of the proposed model, particularly for the medium-dense and dense sand situations.

Additional Remarks

1. A "damage" parameter can allow the model to reproduce stiffness and strength degradation (as a function of total accumulated plastic strain) as depicted in Figure 1.

2. Note that loose cohesionless soils will possibly display a dominant contractive response with little dilative tendency and much increased level of accumulated shear deformations. Such deformations can be reproduced by the developed constitutive model (among many others). However, the emphasis placed on the deformation ranges of Figure 4 reflects the interest in: i) estimation of deformations that might be objectionable despite the absence of a flow-failure (performance-based design assessments), and ii) applicability to liquefaction countermeasure effectiveness (e.g., by densification). In this regard, the accurate estimation of very large flow-failure deformations is not a primary goal, since loose soils (that may be vulnerable to flow-failure) are unacceptable from a practical engineering point of view.

5. SUMMARY AND CONCLUSIONS

A new constitutive model is developed to model the cyclic shear behavior of clean cohesionless soils during liquefaction (emphasis on medium to dense sand scenarios). The underlying mechanisms are based on observed soil response during earthquakes, centrifuge experiments and cyclic laboratory tests. A range of response characteristics (pore pressure buildup and accumulated deformations) is proposed as a first step towards a performance-based liquefaction design methodology.

6. ACKNOWLEDGMENTS

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