

On Suitability of Element Tests to Represent Constitutive Response of Liquefiable Soils

Majid T. Manzari, Ph.D., M. ASCE¹, Karma Yonten, Ph.D.²

¹ Department of Civil and Environmental Engineering, The George Washington University, 800 22nd St, NW, Washington, DC 20052; e-mail: manzari@gwu.edu

² Formerly, Department of Civil and Environmental Engineering, The George Washington University, 800 22nd St, NW, Washington, DC 20052; e-mail: kyonten@gwu.edu

ABSTRACT

Calibration and validation of constitutive models and numerical modeling techniques used in analysis of soil liquefaction and its effects are often based on extensive comparisons with the results of element tests and centrifuge experiments. While good quality experimental data are available to understand and quantify the stress-strain-strength response of liquefiable soils in monotonic and cyclic drained/undrained element (triaxial and direct simple shear) tests, the results of these experiments are often less repeatable when the soil approaches liquefaction state and relatively large deviatoric strains suddenly develop within a few cycles of loading. The main source of these less repeatable patterns of soil behavior appears to be instability rather than the attainment of a state of material failure. The goal of this paper is to investigate the role of instability on the stress-strain response of liquefiable soils by using a critical state sand plasticity model that is enriched with an internal length scale representing the potential shear bands that may develop during monotonic or cyclic loading conditions. Through a series of numerical simulations, it is shown that the global stress-strain response measured in the element tests is a good approximation of the soil constitutive response before an unstable condition such as shear banding or liquefaction develops in the soil specimen.

INTRODUCTION

Laboratory element tests are widely used to investigate the stress-strain-strength behavior of soils. Many features of soil mechanical behavior under monotonic and cyclic loading conditions are often inferred from the results of these tests. Dependence of shear-induced volume change response (dilatancy) on the initial confining stress and void ratio, concepts of critical state, phase transformation, flow liquefaction, and cyclic mobility in saturated sands, have all been inferred from and supported by the results of element tests on soils. The validity of these inferences is based on the assumption that the soil specimen tested in these tests remains as a uniform material

under one stress/strain state. It has long been recognized, however, that variability of soil density within the specimen, the imperfections caused by boundary conditions, and development of unstable stress state may lead to the violation of this basic assumption. In many monotonic triaxial shear tests, the soil specimen may reach a bifurcation state that is usually manifested in form of the localization of shear strains within a narrow band. Such phenomenon has long cast significant doubt on validity of the stress-strain curves, obtained from the global stresses and strains measured at the boundary of the specimen, beyond the peak shear stress. Several questions arise as the results of these observations: 1) Is there a true material softening or the entire post-peak response of the soil is caused by shear localization? 2) Can we calibrate a constitutive model by using the results of element tests with complicated boundary conditions such as those in Direct Simple Shear Test? 3) Does shear localization play a role in cyclic testing of sandy soils that are susceptible to liquefaction?

The main objective of this paper is to briefly address the last two questions by discussing the results of numerical simulations of cyclic direct simple shear and cyclic biaxial tests on a liquefiable soil.

RESPONSE OF A LIQUEFIABLE SOIL IN DIRECT SIMPLE SHEAR TEST

Direct simple shear test is widely used in evaluation of liquefaction resistance of sands. Significant research has already been reported on assessment of the effect of boundary conditions on the measured response of soils during simple shear tests (e.g., Wang et al., 2004). Here a strain-controlled cyclic simple shear test on Toyoura sand is considered. A fully coupled effective stress formulation allowing for re-distribution of pore pressure and void ratio within the soil specimen will be used. The constitutive model (Manzari and Dafalias, 2005) is a micropolar extension of the original critical state two-surface plasticity model proposed by Manzari and Dafalias (1997) and Dafalias and Manzari (2004) which has been used to investigate post-failure response of sands (Manzari and Yonten, 2011-a&b). The original model has been calibrated for a variety of standard sands including Toyoura sand and is shown to capture the essential features of sand stress-strain-strength characteristics in monotonic and cyclic loading conditions. Here the micropolar model is employed to analyze the response of Toyoura sand in direct simple shear (DSS) test. A specimen of Toyoura sand with the height of 25 mm and length of 80 mm is first subjected to vertical stress of 1,000 kPa and then subjected to cyclic shear strain loading ranging between 0.2 and 0.4 percent.

Figure 1 shows the stress paths and “shear stress”-“shear strain” curves calculated at three different locations within the specimen: first one near the left vertical boundary, second one at the center of the box, and the last one near the right vertical boundary. All these points are selected in the mid height of the specimen. Average responses computed from the boundary forces and displacements of the shear box are also shown for comparison. It is noted that the

stress-strain curves obtained near the left and right boundaries are significantly different from that obtained in the center of the specimen. These differences are mainly caused by lateral boundary conditions that are inevitable in a direct simple shear test.

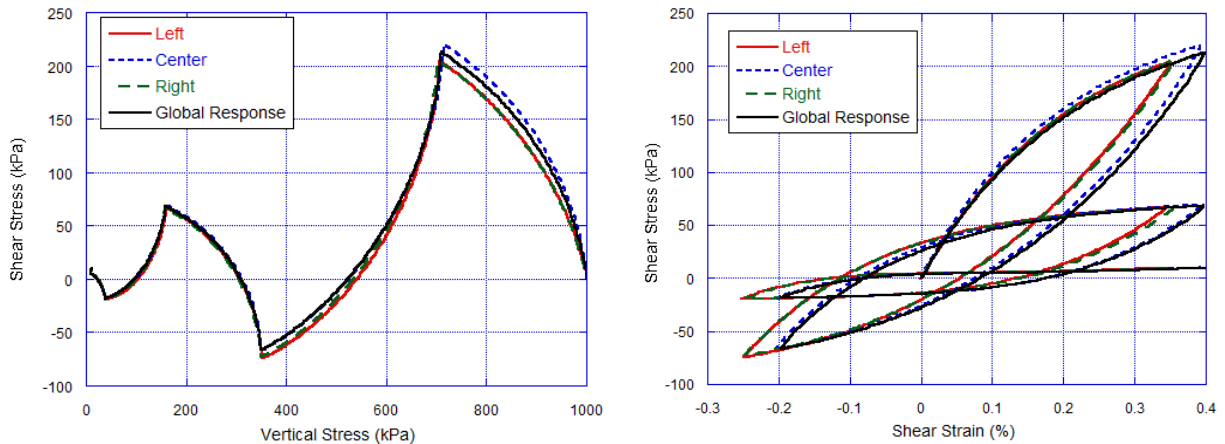


Figure 1. Comparison of shear stress vs. shear strain responses computed at three locations within the soil specimen with the global response obtained from boundary forces.

There are also small differences between the responses obtained near the two vertical boundaries. But these differences are mainly due to the very small variability of initial void ratio distribution within the specimen, and depending on the location of the reported stresses and strains, may also be caused by non-uniformity of stresses and strains during the shear loading cycles. Figure 2 shows the non-uniformity of shear strain distribution within the soil specimen during one of the shear load cycles.

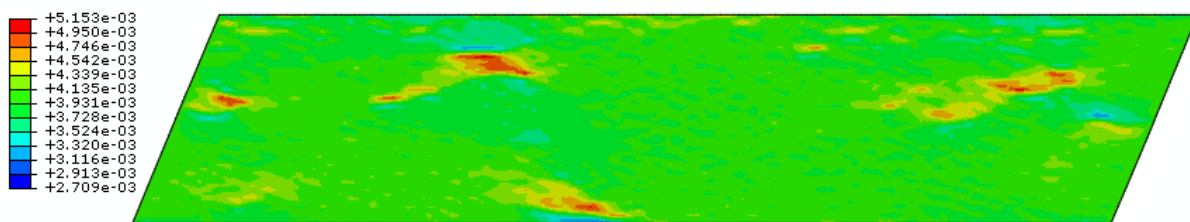


Figure 2. Contours of shear strains during a cyclic DSS test

The results shown in Figure 1 suggest that while the global stress-strain response obtained from the boundary forces is not identical to the stress-strain response of the soil in the central portion of the specimen, it provides a good approximation of the actual stress-strain response of the soil in that region.

RESPONSE OF A LIQUEFIABLE SOIL IN CYCLIC BIAXIAL SHEAR TEST

A second set of numerical simulations are presented to demonstrate the effects of small variation of void ratio and possible triggering of shear localization on the soil stress-strain response. Here

a biaxial specimen of Toyoura sand is subjected to strain-controlled cyclic loading. The axial strain ranges from -1% to 1%. A slightly varying field of void ratio was introduced in the specimen to mimic the natural imperfection and heterogeneity of prepared specimens. The specimen is first consolidated with an effective confining stress of 100 kPa and upon cyclic loading develops significant excess pore pressure leading to a near liquefaction state. During the loading, a clear shear band developed within the specimen and further exacerbated the stress/strain non-uniformities. Figure (3-a) shows the stress-strain responses computed at three different locations within the soil specimen. The global stress-strain response computed by using the boundary forces and displacements is also shown for comparison.

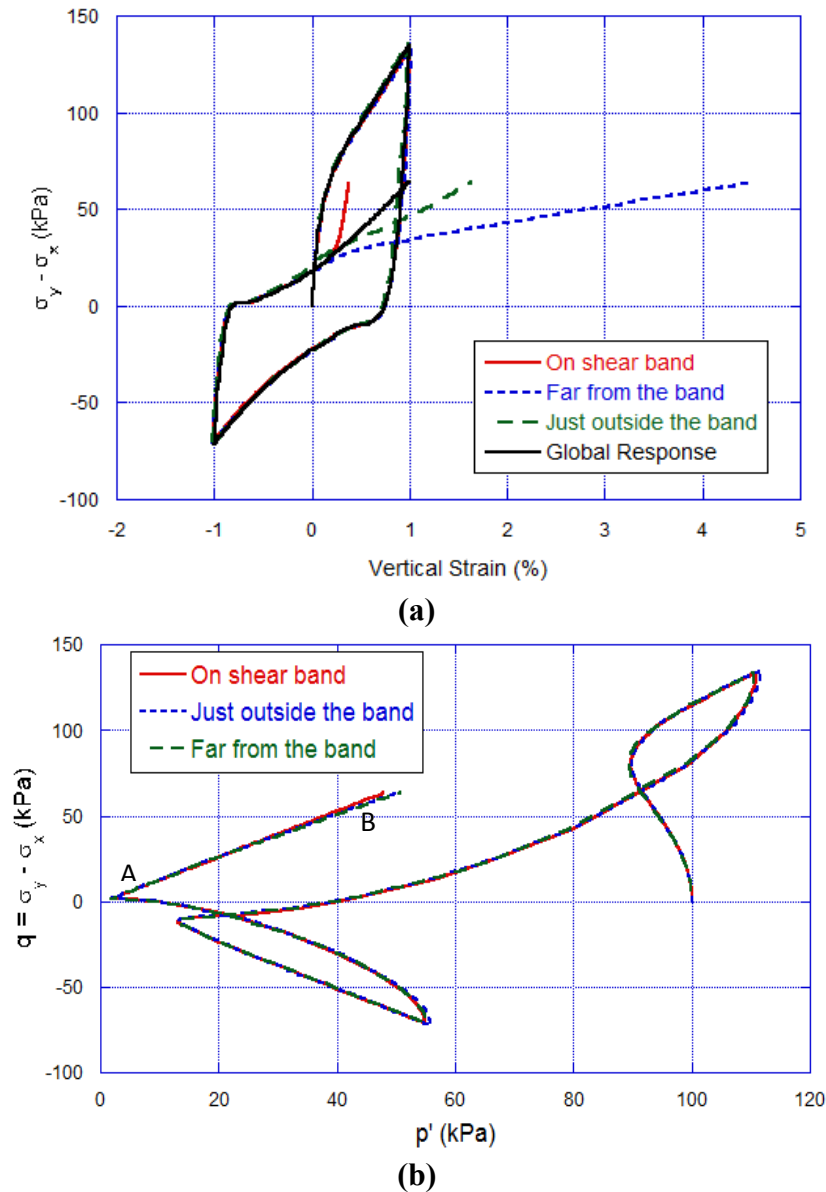


Figure 3. Comparison of the responses computed at three locations within the soil specimen with the global response obtained from boundary forces

It is observed that before the initiation of shear band, the computed global response correlate well with the stress-strain responses in all three locations. However, once the shear band develops the global response is no longer a true representation of what is taking place within the shear band.

It is noted that the pronounced multi-furcation of stress-strain curves once the shear band develops is less visible in the stress paths computed at the three different locations within the specimen (Figure 3-b).

Figure 4 shows the emergence and disappearance of fluid flow towards the dilating shear band during the last stage of reverse loading. Figure (4-a) shows the flow of pore fluid towards the shear band when the stress path reaches its last branch of reverse loading causing that involves dilation (point in Fig. 3-b). Figure 4-b shows that the fluid velocity diminishes as the soil tendency to dilate slows down (point B in Fig. 3-b).

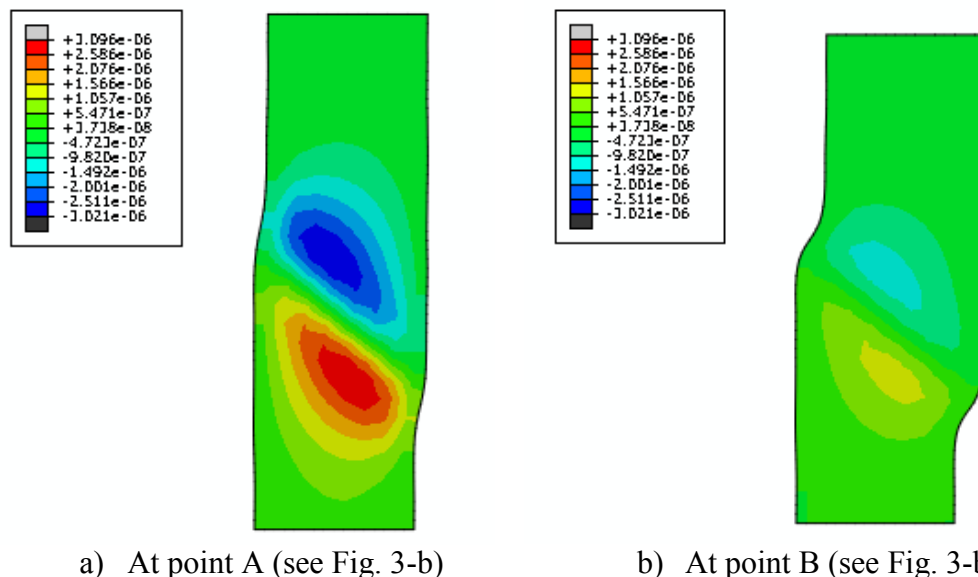


Figure 4. Contour plots of vertical velocity of pore fluid at two stages of the simulation

It is also noted that no visible pore fluid flow occurs within the soil specimen before the emergence of shear band.

The key question is whether such shear bands are commonly observed in cyclic testing of soils. Numerous numerical simulations on the same specimen but with smaller maximum shear strains show that while the initiation of shear band will be delayed in the tests with smaller maximum shear strains, majority of the specimens eventually develop shear bands and the overall responses measured from global boundary forces are no longer representative of the soil constitutive response.

CONCLUSION

Cyclic simple shear and biaxial tests are numerically simulated to investigate the effects of inherent heterogeneity and imperfections caused by boundary conditions on the global responses measured in the soil testing. The simulations show that while the global responses obtained from cyclic simple shear tests are not identical to the stress-strain response of the soil in the central portion of the specimen, they provide good approximations. Moreover, the simulations of cyclic biaxial tests show that before the initiation of a shear band, the global response of the soil very closely correspond to the soil stress-strain response.

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