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Evaluation of properties of Solani sand for numerical analysis using UBC3D-PLM and experimental validation

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ABSTRACT: Liquefaction is a phenomenon induced in soil due to time dependent dynamic loading. Modelling liquefaction of soil numerically is a complicated task, as it involves generation of pore water pressure. Thus, evaluation of pore water pressure with accuracy is important. Methodology followed for evaluation of material model parameters as well as boundary conditions given for numerical evaluation governs the results to greater extent. PLAXIS has implemented UBC3D-PLM as a user defined material soil model, which is formulated specifically for liquefaction analysis and is efficient enough to model the onset of liquefaction and post liquefaction behavior as well. The present study talks about the key features of UBC3D-PLM and parameters governing them. The highlighted key features are namely, plastic potential function, soil densification rule, secondary yield surface, and post-liquefaction factor. The work illustrated here is divided in three parts. Firstly, evaluation of material model parameters using empirical relations, which requires constant volume friction angle as the input property measured from cyclic triaxial tests. This evaluation is done for Solani sand, which is locally available soil collected from the bed of Solani river near Roorkee, India. Secondly, evaluated parameters are validated in PLAXIS carrying out available test simulations. Lastly, the results obtained from numerical simulations using UBC3D-PLM are compared with those obtained on cyclic triaxial by conducting undrained cyclic triaxial tests, which covers the dynamic loading conditions.

1 INTRODUCTION

Liquefaction evaluation involves measurement of pore pressure generation, which governs the failure of soil. Researchers have made use of both experimental measurements and numerical evaluations individually to carry out liquefaction analysis. In recent studies, combine utilization of both the techniques have come into role effectively, such that shown by Beaty and Byrne (2011), Petalas et al. (2013), Rahman and Schreppers (2014). Makra (2013) in his master's thesis have talked about the applicability of UBC3D-PLM constitutive model in predicting the onset of liquefaction in embankments. Details about the critical parameters affecting the soil test results are also discussed, prior to comparison of experimental results on cyclic DSS (direct simple shear) with test results in PLAXIS. Galavi et al. (2013) have shown the capabilities of UBC3D-PLM in predicting mechanical behavior of liquefied soils, by considering a quay wall in Kobe region of Japan. Petalas et al. (2012) have validated the experimental results with the results obtained from test module of PLAXIS, under both monotonic (DSS & TxC) and cyclic (CDSS) loading condi-tions. Diaz-Segura (2015) have numerically calculated the onset of liquefaction from CRR parameter of (N1)60 using UBC3D-PLM, and have simultaneously compared the obtained CRR curve with CSR curve available in literature. Mercado (2016) in his Doctoral thesis have simulated the liquefaction induced damages of Port of California beach using UBC3D-PLM in 2D-PLAXIS. Kumari et al. (2018) have analyzed Embankment resting over liquefiable Nevada sand with and without stone columns and modelled liquefaction using Coupled Finite Element Analysis in PLAXIS. Bhatnagar et al. (2016) has validated liquefiable soil model using centrifuge test & has discussed the effect of remedial measures using UBC3D-PLM. From literature review, it can be observed that numerical modelling for liquefaction resistance is rarely reported for Indian soils. Modelling liquefaction, in PLAXIS using UBC3D-PLM and getting results as close to those obtained from experimental results is a major challenge. Work presented here is an attempt in this direction.

2 TOOLS

2.1 *Experimental*

For experimental measurement, Cyclic Triaxial is one the most versatile test apparatus that can be used for the study of liquefaction phenomenon as it has the advantage of control over drainage along with the feature of pore water pressure measurement, which is required to evaluate liquefaction potential of soil. Tests are conducted on required sample size, at desired relative density for particular confining pressure. Controlling the drainage conditions, stress or strain controlled tests are carried out following the available standard test methodology as per ASTM D 5311 or ASTM D 3999. Test apparatus is found capable under both monotonic and cyclic shear setup.

2.2 *Numerical*

For numerical evaluation, Computer Aided Engineering (CAE) is commonly used in modern design for various types of structures. PLAXIS is one such finite element program for 3D modelling of soil behavior. It has the advantage of fully automatic mesh generation, allowing use of 10-noded tetrahedron elements, based on graphical input of soil layers. UBC3D is a 3-D generalized formulation of the original 2-D UBCSAND model, utilized under UDM in PLAXIS and considered to be the most useful model to simulate the liquefaction behavior of soil. This model, based on elasto-plastic functions, utilizes isotropic and kinematic hardening rules for primary and secondary yield surfaces to properly account for accumulation of excess pore water pressure and effect of soil densification during cyclic loading.

3 METHODOLOGY

3.1 *Experimental measurement*

For experimental measurement, cyclic triaxial apparatus is used for liquefaction analysis using pore pressure measurement technique. For this purpose, a saturated cylindrical sample of 50 mm diameter and 100 mm length is prepared at 50% relative density using mould. Test set-up is pre-pared mounting the sample on 50 mm pedestal inside the triaxial cell, with load ram attached over its top by giving suction pressure of 10 kPa. Sample is subjected to initial cell pressure of 22 kPa followed by CO_2 and water flushing. Sample is then made saturated by giving consecutive cell pressure & back pressure increment of 35 kPa. After attaining a skempton's B-value of 95%, sample is considered to saturate by 100% and then it is subjected to consolidation for 1 hour under 100 kPa confining pressure. The completely saturated and consolidated soil specimen is then subjected to loading. For cyclic loading 1% shear strain is used with load period of 2000 milliseconds.

3.2 *Numerical evaluation*

For numerical evaluation, a 3D model of required geometry is constructed in three dimensional space as shown in Figure 1. Plaxis by default considers a geometry of 10-noded tetrahedral elements (meshed model shown in Figure 1). With the help of borehole option, one can construct a model of several layers. Presence of water table is also considered as a separate layer while creating borehole. UBC3d-PLM is selected as the material model for liquefaction analysis in material data set, which involves the pre-determination of parameters as

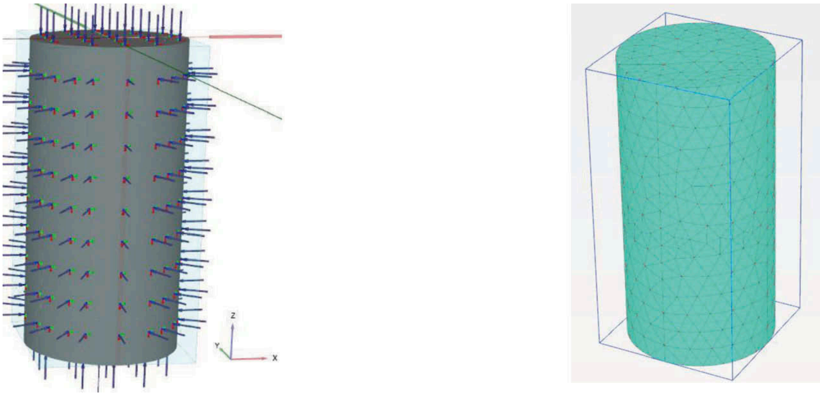


Figure 1. Cylindrical soil model prepared in PLAXIS with displacement and deformation boundary conditions and 10-noded tetrahedral element meshing

determined in section 3.2. Once the parameters are obtained and material is assigned to model, appropriate deformation and dynamic boundary conditions are selected for different soil surfaces of the model. Mesh is generated automatically, coarseness of the mesh can be decided as per the requirement. Coarse mesh leads to ease in calculation but deviates from accuracy, whereas finer mesh makes the calculations time consuming but more towards accuracy. Thereafter, analysis can be started, but prior to that nodes and stress points are selected to get the output curves for the desired response. Provision of staged construction in plaxis enables the user to analyze the model till the actual construction stage. Initial stage is by default given to calculate initial stresses, which acts as loading for further stages. In dynamic stage, we can give the input loading of desired amplitude and frequency. After the staged construction, model is ready to undergo calculations. Once the results gets converged for all the given loading steps, analysis is completed and desired response can be obtained in the output window.

3 MATERIAL USED

3.1 *Solani sand*

Field investigations were carried out using Standard Penetration Tests (SPT) and samples of sand were collected from Solani river bed, near Roorkee, which is an Indian city (185 kms north of New Delhi), lies in Seismic zone IV (IS 1893-2016). Laboratory tests were carried out on sand samples to evaluate index properties i.e grain size distribution, specific gravity, maximum and minimum void ratio, uniformity coefficient, coefficient of curvature, dry unit weight and relative density (Kirar, 2016).

Properties of Solani sand (sample shown in Figure 2), determined from basic laboratory testing are listed in Table 1. GSD shows 90% of the particles falls in fine sand range, thus as per (UCS) Unified Classification of Soil system, soil is classified as SP (poorly graded sand) type.

3.2 *Evaluation of properties*

Material properties to be used for numerical analysis are evaluated using available empirical relations (Mercado, 2016), as described in Table 2. These properties are used as input for test modules in Plaxis and analysis is executed.

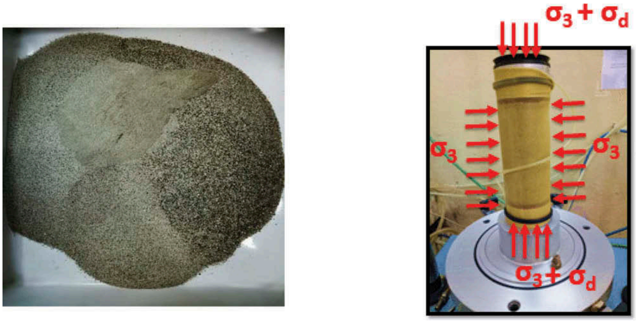


Figure 2. Cylindrical soil sample prepared from Solani sand for laboratory testing

Table 1. Index properties of Solani sand, Kirar (2016)

Particulars	Notation & Units	Values
Soil type		Solani Sand
Classification	SP	Poorly graded sand
Specific gravity		2.68
Uniformity coefficient	C_u	1.96
Coefficient of curvature	C_c	1.15
Grain size	D_{10} (mm)	0.12
	D_{30} (mm)	0.18
	D_{50} (mm)	0.210
	D_{60} (mm)	0.235
Minimum void ratio	emin	0.54
Maximum void ratio	emax	0.85

4 VALIDATION

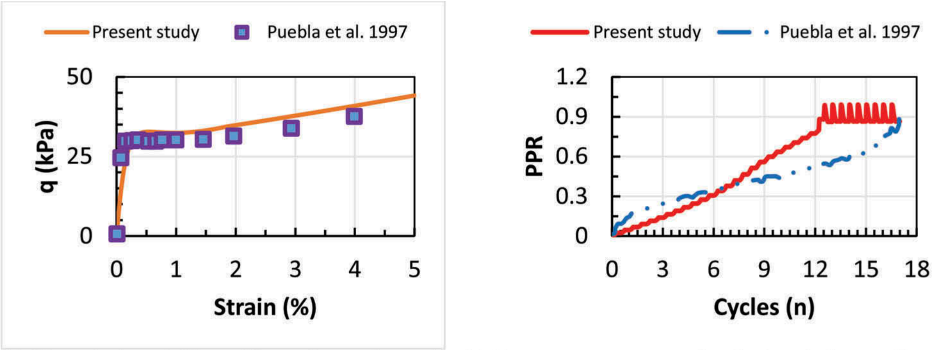
Petalas et al. (2013) have studied the mechanical behavior of some sands numerically under both monotonic and cyclic loading conditions. Evaluation of seismic liquefaction in sands is presented via constitutive model with it's three dimensional formulation. This model termed as UBC3D-PLM considering the effect of soil densification, models liquefaction under undrained cyclic loading. In the presented work, UBC3D-PLM is validated using triaxial compression tests and cyclic direct simple shear test. Results are compared with the measured experimental data. To carry out the numerical simulation, a cylindrical soil model is prepared in PLAXIS with appropriate displacement and deformation boundary conditions and 10-noded tetrahedral element meshing.

The behavior of loose Syncrude sand under monotonic loading is modelled using UBC3D-PLM, and numerical results are compared with experimental data as shown in Figure 3 (a), where the variation of deviatoric stress (q) with strain is shown. Puebla et al. (1997) had performed experiments triaxial compression test. For numerical analysis, maximum normal stress is given as 100 kPa for the duration kept as 1 day and shear strain taken as 6% for triaxial compression tests. Numerical evaluations proves to be in good agreement with experimental results.

The behavior of Fraser Delta sand under cyclic loading is modelled using UBC3D-PLM, and numerical results are compared with experimental data as shown in Figure 3 (b), where pore pressure ratio (PPR) with number of cycles are shown. Puebla et al. (1997) had performed experiments on cyclic direct simple shear (CDSS). For numerical analysis, initial vertical stress (σ_v) is given as 100 kPa. Number of steps per quarter cycle is kept 8 with duration per cycle as 1 day. All tests performed and thereby modelled were stress controlled and results

Table 2. Properties of Solani sand used for numerical analysis in PLAXIS

Property	Notation	Unit	Empirical Relations	Evaluation
Relative density	RD	%	Known	50
Initial void ratio	e_{init}		e_{max}-RD*(e_{max}-e_{min})	0.69
Unsaturated unit weight	γ_{unsat}	kN/m^3	(G*γ_w)/(1+e)	15.81
Saturated unit weight	γ_{sat}	kN/m^3	γ_{unsat} *(1+$\frac{eS}{G}$)	19.91
SPT N-value	$(N_1)_{60}$		RD^2*C_d	11.5
Elastic shear modulus number	K_G^e		$21.7*20*(N_1)_{60}{}^{0.333}$	978.82
Elastic bulk modulus number	K_B^e		K_G^e *0.7	685.17
Plastic shear modulus number	K_G^P		$K_G^e *(N_1)_{60}{}^2*0.003+100$	488.35
Elastic shear modulus index	m_e		Constant	0.5
Elastic bulk modulus index	n_e		Constant	0.5
Plastic shear modulus index	n_p		Constant	0.4
Constant volume friction angle	φ_{cv}	$^{\circ}$	Cyclic triaxial test	35
Peak friction angle	φ_p	$^{\circ}$	$\varphi_{cv}+\frac{(N_1)_{60}}{10}+\max.\,(0, \frac{(N_1)_{60}-15}{5})$	36.15
Cohesion	c		Nil	0
Tension cut-off	φ_t	kPa	Nil	0
Atmospheric pressure	P_A	kPa	Standard	100
Densification factor	f_{dense}		Constant	1
Post liquefaction factor	f_{post}		Constant	1
Reference Pressure	P_{ref}	kPa	Standard	100
Failure ratio	R_f		$1.1*(N_1)_{60}{}^{-0.15}$	0.76



(a) Numerical modelling of loose Syncrude sand under undrained triaxial compression

(b) Excess pore pressure developing during cyclic simple shearing on fraser sand

Figure 3. Comparison of results of numerical modelling conducted in available test modules of PLAXIS with the experimental results shown in literature{en}(a) Numerical modelling of loose Syncrude sand under undrained triaxial compression{en}(b) Excess pore pressure developing during cyclic simple shearing on fraser sand

are generated for Cyclic Stress Ratio (CSR) values 0.08, 0.1 and 0.12 with number of cycles kept as 17, 10 & 6 respectively. However, here the result only for CSR=0.08 is shown in Figure 3 (b). Numerical evaluations proves to be in good agreement with experimental results, though there is some deviation at higher number of cycles as can be seen in Figure 3 (b) for CSR=0.08. Evaluation for varying CSR values have shown that, with increasing resistance against liquefaction, number of cycles for initial liquefaction keeps reducing.

5 RESULTS AND DISCUSSIONS

Both experimental measurement and numerical analysis were carried out and results were obtained to make the necessary observation for the fulfillment of the objectives of present study.

5.1 *Experimental results*

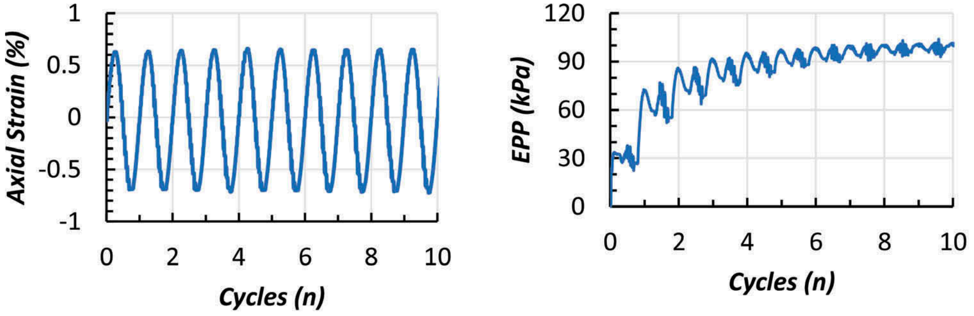
Cylindrical sample is subjected to sinusoidal cyclic loading of 0.67% axial strain as shown in Figure 4 (a). Due to continuous load cycles, deviatoric stresses gets reduced to zero and excess pore pressures (EPP) gets increasingly generated within the sample till it reaches a maximum value of initial confining pressure 100 kPa as shown in Figure 4 (b). It defines the state of initial liquefaction when pore pressures ratio becomes unity.

5.2 *Numerical results*

Cylindrical soil model is subjected to sinusoidal displacement loading of 0.67 mm as shown in Figure 5 (a). Due to continuous load cycles, deviatoric stresses reduces to zero and excess pore pressure is generated reaching a maximum value of initial effective confining pressure i.e 100 kPa as shown in Figure 5 (b). However, it can be observed that EPP reaches a value of 92 kPa within a fraction of cycle and then further increases slightly. Finally it crosses a value of 102 kPa after 3.4 cycles.

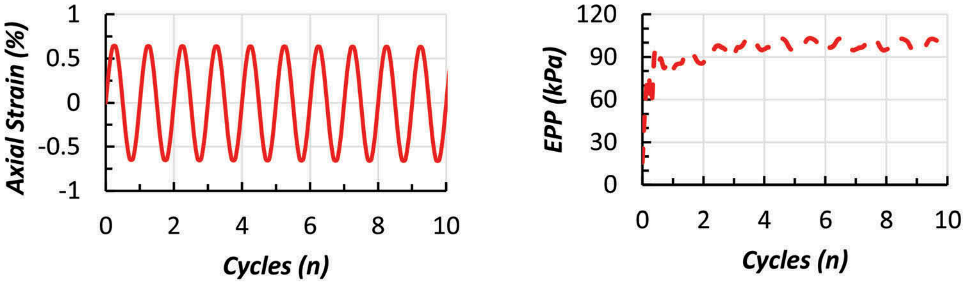
5.3 *Comparison*

When both experimental and numerical results are compared, it is observed that a maximum vertical displacement of 0.67 mm is caused in the sample both from experimental as well as numerical results as shown in Figure 6 (a). This was expected because the same input motion



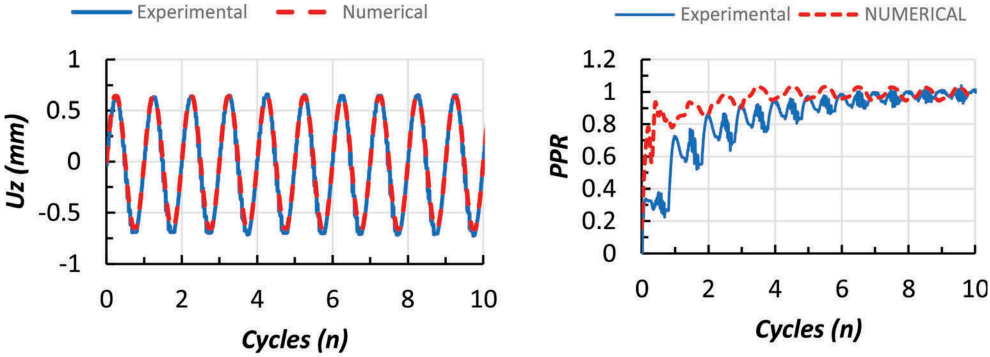
(a) Sinusoidal input motion (experimental) (b) Generated excess pore water pressure (experimental)

Figure 4. Results for cyclic undrained strain controlled test conducted on 50 mm diameter cylindrical soil sample subjected to 1% shear strain at 0.5 Hz frequency (a) Sinusoidal input motion (experimental) (b) Generated excess pore water pressure (experimental)



(a) Sinusoidal input motion (numerical) (b) Generated excess pore water pressure (numerical)

Figure 5. Results for analysis carried out on 50 mm diameter cylindrical soil model subjected to sinusoidal displacement loading of 0.67 mm at 0.5 Hz frequency (a) Sinusoidal input motion (numerical) (b) Generated excess pore water pressure (numerical)



(a) Vertical displacement after load application (b) Generated excess pore water pressure

Figure 6. Results for analysis carried out on 50 mm diameter cylindrical soil model subjected to sinusoidal displacement loading of 0.67 mm at 0.5 Hz frequency (a) Vertical displacement after load application (b) Generated excess pore water pressure

with amplitude of 0.67% axial strain is used for both experimental and numerical evaluation. The occurrence of initial liquefaction is shown at different cycles both experimentally and numerically, as can be seen in Figure 6 (b). It can be observed that initially there is much deviation in both values upto 2 cycles, after that values are getting closer and finally at 6 cycles both are in agreement. This can be due to difference in Skempton's B-value. Experimentally B-value achieved was 0.86, however this could not be ensured numerically and further investigation in this concern is going on.

6 CONCLUSION

The results of present numerical study are in good agreement with experimental data in literature. Experimental and numerical results, seems to show similar trend in terms of generated pore water pressures. Pore pressure values generated maximum upto a value of initial confining pressure applied, but numerically initial liquefaction occurs earlier than experimentally. This is probably because the initial condition of sample before application of load in experiment is difficult to be accurately simulated numerically. Further, there can be a bit difference in B-value of experimental and numerical results. This area needs to be further inspected and is a part of on-going study, that how sample conditions can be kept same both experimentally and numerically.

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