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Evaluation of relative density effects on liquefiable sands using PM4Sand model

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ABSTRACT: When saturated soils are subjected to an earthquake, the excess pore pressures increase, and, in the case of sands, this may cause liquefaction. To simulate the behaviour of saturated sands under cyclic loading, the PM4Sand constitutive model (version 3.1) formulated by Boulanger & Ziotopoulou (2017), is used. The PM4Sand model represents an improvement of the elasto-plastic, stress ratio controlled, bounding surface plasticity model formulated by Dafalias & Manzari (2004). The model can realistically reproduce the pore pressure build-up, accumulation of strain as well as triggering of liquefaction. In this paper, the effect of different relative densities on liquefaction resistance is evaluated by comparing the results of a site response analysis performed on a soil column characterized by a saturated sand layer and subjected to given earthquake signals. The analyses are performed using the finite element code PLAXIS.

1 INTRODUCTION

In the past few years, the PM4Sand model (Boulanger & Ziotopoulou 2012, 2015, 2017) has gained much popularity as a practical constitutive model in numerical liquefaction analysis under seismic loading conditions. After the initial development of the model in a finite difference framework, the PM4Sand model has recently become available in the widely used geotechnical finite element software PLAXIS 2D (Vilhar et al. 2018). The aforementioned paper includes an initial validation of the model, whilst more validations and comparisons with the original and another implementation are part of ongoing research, which will be published in the near future.

The current paper focuses on the role that relative density in the PM4Sand model plays on the liquefaction potential. This is demonstrated on the basis of model simulations of cyclic direct simple-shear tests using a single stress point constitutive driver, as well as in finite element-based one-dimensional site response analyses.

Section 2 gives a brief description of the theoretical backgrounds of the PM4Sand model. Section 3 shows the influence of relative density in cyclic DSS tests, whereas Section 4 shows the corresponding influence in one-dimensional site response analysis. Finally, the conclusions of this research are written in Section 5.

2 PM4SAND: CONSTITUTIVE MODEL AND PARAMETERS

The PM4Sand model is an elasto-plastic, stress-ratio-controlled, critical state compatible, bounding surface plasticity model, based on the Dafalias-Manzari model (Manzari & Dafalias 1997, Dafalias & Manzari 2004) and later improved by Boulanger (2010) and Boulanger & Ziotopoulou (2012, 2013, 2015, 2017) at UC Davis (Ziotopoulou & Boulanger 2013, Ziotopoulou 2014).

The model has been implemented in finite element code PLAXIS by means of an implicit global time stepping scheme, with the advantage of a reduced computational time compared to the original explicit implementation, since larger load steps can be applied. Additionally, as a result, unconditional numerical stability and solution error control are guaranteed throughout the analysis.

The current implementation is characterized by a 2D modeling, to be consistent with the original formulation, meaning that it can be used only in plane strain analyses. For a detailed description of the formulation, the reader is referred to Boulanger & Ziotopoulou (2017), while the implementation and validation in PLAXIS has been presented in Vilhar et al. (2018).

The model is characterized by four surfaces: the yield, bounding, dilation and critical state surface. The current state is defined by the relative state parameter index ξ_R, i.e. the difference between the current relative density D_R and its value at critical state $D_{R,CS}$. This parameter changes during the simulation, meaning that the soil properties evolve, due to changes in the mean effective stress and/or void ratio, as well as the position of the bounding and dilation surfaces (Ziotopoulou 2018), that can rotate and finally coincide at critical state.

Another important characteristic of the model is the capability to account for fabric changes.

The PM4Sand model is characterized by 3 primary parameters, that need to be calibrated based on the soil characteristics, and 20 secondary parameters, that are automatically evaluated based on index properties or set to default values as they normally do not need to be modified. In PLAXIS only 10 most applicable secondary parameters are adjustable by the user. Usually the variation of these parameters is used in the calibration process in practice (e.g. Ziotopoulou et al. 2018).

The primary parameters are: the relative density D_R, the shear modulus coefficient G_0 and the contraction rate parameter h_{p0}. The input value of D_R is considered an "apparent relative density" obtained from field tests rather than a strict measure of relative density following conventional laboratory tests and can be adjusted to improve the calibration (Boulanger & Ziotopoulou 2015).

The shear modulus coefficient allows to model the stress and fabric dependent elastic shear modulus. When G is known (e.g. based on the shear wave velocity and the soil density), G_0 can be calculated based on the following formula:

$$G = G_0 p_A \left(\frac{p'}{p_A}\right)^{1/2} \tag{1}$$

where p_A is the atmospheric pressure and p' is the mean effective stress.

Alternatively, a simplified expression to calculate G_0 has been given by Boulanger & Ziotopoulou (2015) for typical densities and stress levels:

$$G_0 = 167\sqrt{(N_1)_{60} + 2.5} \tag{2}$$

where the normalized SPT blow counts $(N_1)_{60}$ can be derived from the following expression (Idriss & Boulanger 2008):

$$D_R = \sqrt{\frac{(N_1)_{60}}{46}} \tag{3}$$

Finally, h_{p0} is the parameter that represents the contraction rate and needs to be chosen to match the model response to specific cyclic resistance ratios *CRR*. Idriss & Boulanger (2008) have collected many cases to determine a liquefaction triggering correlation. An SPT-based estimate of CRR for an earthquake of M=7.5 and 1 atm effective overburden stress is assumed to be approximately equal to the CRR value at 15 uniform loading cycles causing a peak single amplitude shear strain of 3% in DSS loading.

Default values are assigned to the secondary parameters. The reference pressure p_a is considered equal to 101.3 kPa, while the maximum void ratio e_{max} is equal to 0.8. A value of 0.5 is assigned to both the minimum void ratio e_{min} and the bounding ratio coefficient n_b, while the dilatancy ratio coefficient n_d is equal to 0.1. The friction angle is set to 33 degrees and a Poisson's ratio of 0.3 is assumed. The parameters Q and R from Bolton's dilatancy relationship are taken equal to 10 and 1.5, respectively (Bolton 1986).

3 THE EFFECT OF THE RELATIVE DENSITY IN CYCLIC DSS TESTS

The relative density is one of the primary parameters of the PM4Sand model and it can be used also to determine the shear modulus coefficient. The effect of different relative densities is here investigated through a series of undrained stress-controlled cyclic DSS tests performed

Table 1. PM4Sand primary parameters, their corresponding values and cyclic resistance ratios corresponding to different relative densities.

D_R	$(N_1)_{60}$	G_0	$CRR_{M=7.5,\ 1atm}$	h_{p0}
0.35	6	476	0.090	0.53
0.55	14	677	0.147	0.40
0.75	26	890	0.312	0.64

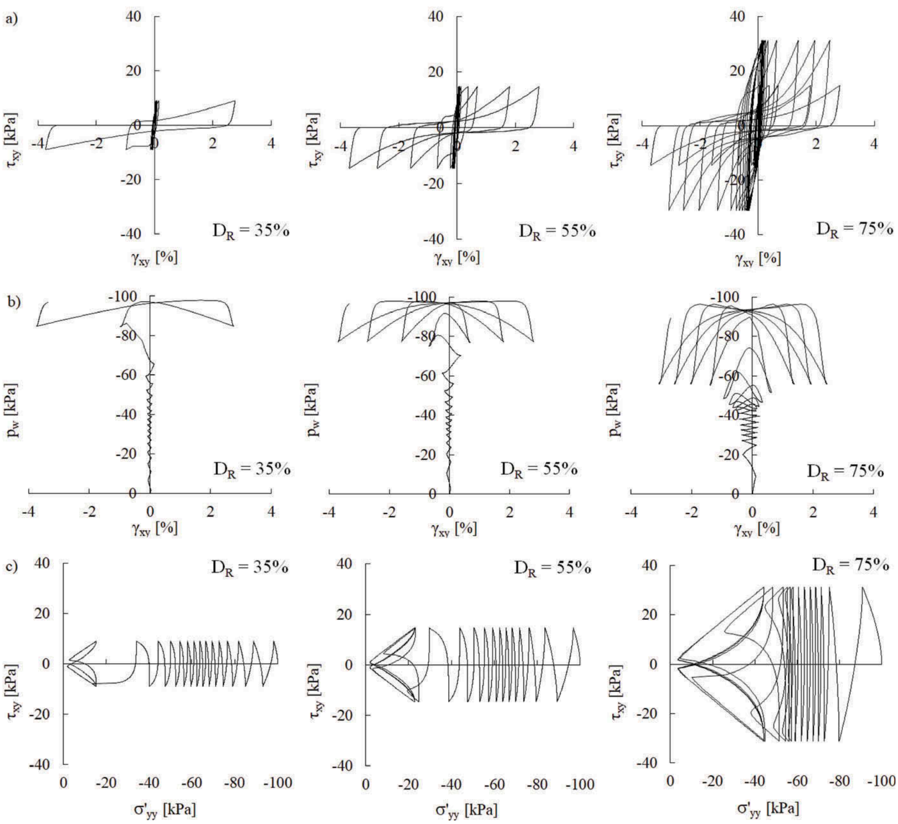

Figure 1. Results from cyclic DSS test for 3 different relative densities. Shear stress vs. shear strain (a), pore pressure vs. shear strain (b), shear stress vs. vertical effective stress (c).

with the SoilTest facility in PLAXIS (i.e. a single stress point constitutive driver that can be used to simulate soil lab tests considering homogeneous stress/strain conditions).

The tests are performed considering an anisotropic consolidation with K_0 equal to 0.5 and an initial vertical stress equal to 100 kPa. The shear stress amplitude is different for the different data sets (different relative densities) and has been chosen equal to the value that triggers liquefaction at 3% shear strain when applying 15 uniform cycles.

The model parameters and the corresponding cyclic resistance ratios for each case are shown in Table 1, while the results of cyclic DSS tests are shown in Figure 1.

The results show that 15 cycles of loading were needed to produce 3 % single amplitude shear strain. The ability of PM4Sand model to accumulate shear strain without locking into repeatable stress-strain loops is clearly visible. Moreover, the typical transition from the repeating stiffer loops that gradually accumulate the pore-pressure to final few loops with parts of significant reduction of stiffness, strain accumulation and approaching zero effective vertical stress is shown. During the final loops, the stress state moves up and down along the failure envelope, generating the known butterfly shape. The increasing cyclic resistance ratio with increasing relative density corresponds to the expected material behaviour of sands.

4 THE EFFECT OF THE RELATIVE DENSITY IN A ONE-DIMENSIONAL SITE RESPONSE ANALYSIS

To evaluate the effect of different relative densities of a soil subjected to different earthquake signals, a one-dimensional site response analysis is performed in PLAXIS.

Table 2. Material properties of the rock-like formationmodelled with a linear elasticmodel.

Unit weight kN/m^3	Shear wave velocity, v_s m/s	Shear modulus, G kPa	Poisson's ratio, ν -
19.44	159	50098	0.3

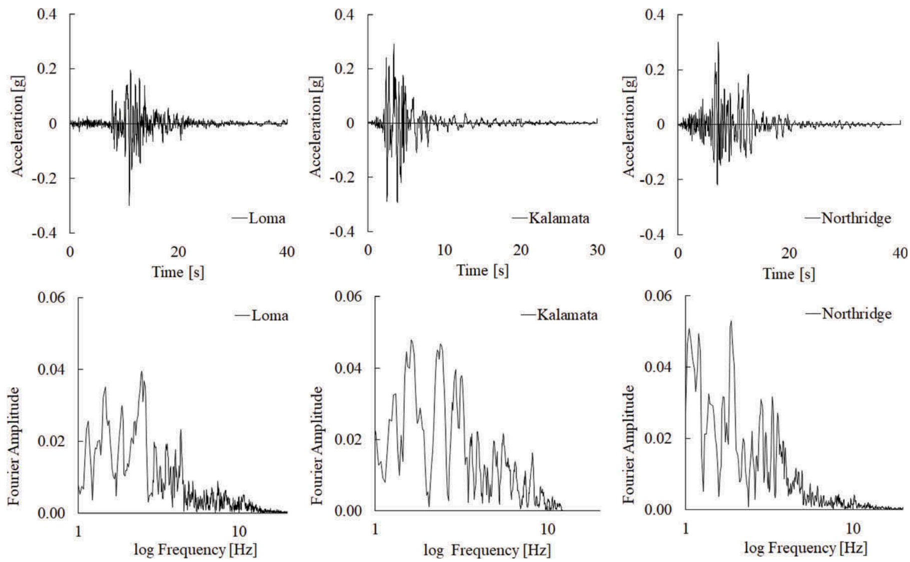

Figure 2. Time history accelerations scaled at 0.3g and Fourier Amplitude spectra of Loma Prieta (left), Kalamata (center) and Northridge (right) earthquake.

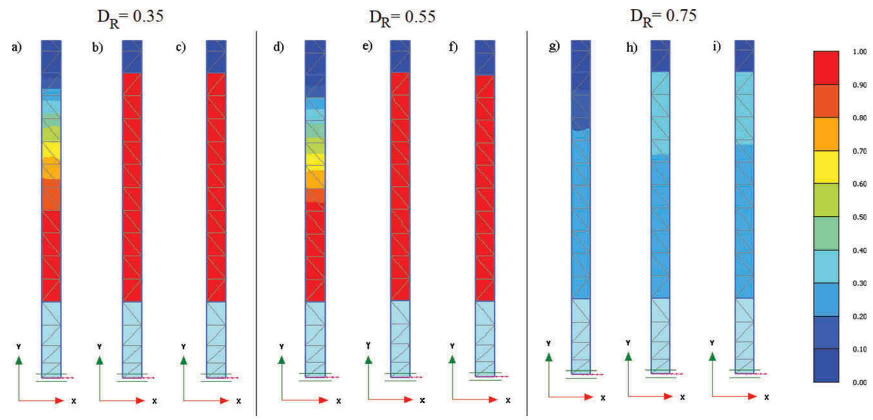

Figure 3. Maximum pore pressure ratio contours for Loma Prieta earthquake (a, d, g), Kalamata earthquake (b, e, h) and Northridge earthquake (c, f, i) for different relative densities.

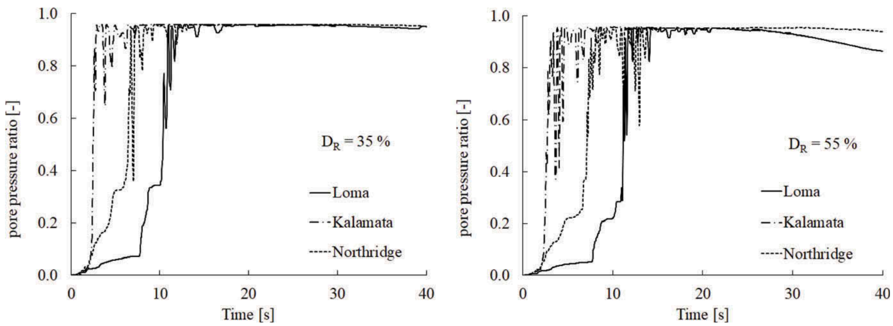

Figure 4. Comparison of the pore pressure ratio evolution for loose (left) and medium loose (right) sand, for different earthquake recordings.

The model consists of an arbitrarily thin soil column with tied degrees of freedom as lateral boundary condition and with the water table at a depth of 2 m. The sand layer is located below a 2 m thick dry crust, modelled as a non-porous material to ensure that no excess pore pressures are generated in the layer above the water table, and over a 1 m thick rock-like formation, modelled with a linear elastic model. The thickness of the sand layer is 3 m. The material properties of the rock-like formation are the same for all cases and shown in Table 2.

The material properties of the sand layer and the dry crust are the same as the ones specified in Table 1, considering a unit weight of soil of 15.4 kN/m^3 and 18 kN/m^3 for the dry crust and the sand layer, respectively. Rayleigh damping coefficients different than zero are specified to account for damping also at very small strains. The chosen values are 0.1047 and 0.00053 for α_R and β_R, respectively. A small permeability coefficient equal to 0.00001 m/s is specified to allow for vertical consolidation of excess pore pressures in the sand layers (except for the top layer) during the dynamic calculation.

The soil column is subjected to three different outcrop motions, scaled at the same maximum acceleration of 0.3g but with different frequency content and duration. The three signals are the Loma Prieta, Kalamata and Northridge earthquake recordings, and they are applied at the base of the model in combination with a compliant base boundary condition (Galavi et al. 2013). The time history accelerations and Fourier Amplitude spectra are shown in Figure 2.

The contours corresponding to the maximum pore pressure ratio, r_u, show that liquefaction has occurred in the case of all the three earthquake signals for the loose and medium loose

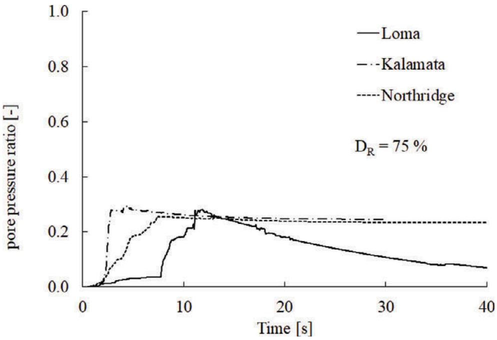

Figure 5. Pore pressure ratio evolution for dense sand, for different earthquake recordings.

sand layers (D_R equal to 0.35 and 0.55, respectively), while the maximum pore pressure ratio reached in the case of the dense sand is quite low, indicating that the sand layer does not liquefy (Figure 3). Liquefaction occurs at different times, depending on the earthquake characteristics, but the time seems to be independent from the relative density, as shown in Figure 4 for the loose and medium loose sand in a selected stress point. In the case of the dense sand (Figure 5), the pore pressure ratio increases with time until a maximum of roughly 0.3. It can be noticed that this value decreases in the case of the Loma Prieta earthquake, due to a partial dissipation of the excess pore pressures.

5 CONCLUSIONS

This paper presents the results of the influence of relative density on the effects of cyclic loading using the PM4Sand model in PLAXIS. The model is used both for the simulation of laboratory tests based on a single stress point and for the simulation of a one-dimensional site response analysis in PLAXIS 2D.

The results of cyclic DSS tests show that the model is capable of accumulating shear strains and excess pore pressures while the effective vertical stress tends to zero, leading to liquefaction after 15 stress-controlled loading cycles. The different relative densities are characterized by a different cyclic resistance ratio, i.e. it increases with increasing relative density, as expected.

The one-dimensional site response analysis is performed modelling a soil column with tied degrees of freedom for the lateral boundaries in PLAXIS. Three different earthquake recordings, scaled at the same peak acceleration but with different frequency content and duration, are applied at the base of the rock-like formation, through a compliant base. The results show that the loose and medium loose sand liquefy in the case of all three selected earthquakes. The evolution of the pore pressure ratio shows that the onset of liquefaction occurs at different times based on the characteristics of the earthquake, but it seems to be independent from the relative density of the saturated sand. Where the loose and medium dense sands liquefy, the dense sand does not liquefy: after an initial increase of the pore pressure ratio, the excess pore pressures are partially dissipated.

The results show that the PM4Sand model implemented in PLAXIS can reproduce the behaviour of sands characterized by different relative densities and subjected to cyclic loading.

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