LEAP-Asia-2018 Numerical Simulation Exercise – Phase I

Model Calibration report

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Table of Contents

Introduction

This report describes the process followed in the calibration of the selected constitutive model. The *model calibration report* covers the essential features of the constitutive model, the final model parameters, the calibration philosophy and the assumptions used in the calibration process. Finally, the report also presents a comparison between the predicted and experimental cyclic laboratory tests and liquefaction resistance curves.

The adopted constitutive model has been calibrated on the results of the provided cyclic torsional shear tests for D_r = 50% and 60% under an initial effective confining stress of 100 kPa.

Model Description

The constitutive model used in the simulation exercise is the PM4Sand model (Boulanger and Ziotopoulou 2015). The PM4Sand (version 3.1) model follows the basic framework of the stress-ratio controlled, critical state compatible, bounding surface plasticity model for sands presented by Dafalias and Manzari (2004), who extended the previous work by Manzari and Dafalias (1997) by adding a fabric-dilatancy related tensor quantity to account for the effect of fabric changes during loading. The fabric-dilatancy related tensor was used to macroscopically model the effect that microscopically-observed changes in sand fabric during plastic dilation have on the contractive response upon reversal of loading direction. The modifications were developed and implemented to improve the ability of the model to match existing engineering design relationships currently used to estimate liquefaction-induced ground deformations during earthquakes. These modifications are described in the manuals (version 1 in Boulanger 2010, version 2 in Boulanger and Ziotopoulou 2012, and version 3) and in the associated publications, as listed in the mentioned manuals.

The model is written in terms of effective stresses, with the conventional prime symbol dropped from the stress terms for convenience because all stresses are effective for the model. The stresses are represented by the tensor r, the principal effective stresses are σ_1, σ_2, and σ_3, the mean effective stress is p, the deviatoric stress tensor is s, and the deviatoric stress ratio tensor, r. The current implementation was further simplified by casting the various equations and relationships in terms of the in-plane stresses only. This limits the implementation to plane-strain (2D) applications, having the further advantage in its simplified implementation to improve the computational speed. The relationships between the various stress terms can be summarized as follows:

$$\boldsymbol{\sigma} = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{xy} & \sigma_{yy} \end{pmatrix} \tag{1}$$

$$p = \frac{\sigma_{xx} + \sigma_{yy}}{2} \tag{2}$$

$$\boldsymbol{s} = \boldsymbol{\sigma} - p\boldsymbol{I} = \begin{pmatrix} s_{xx} & s_{xy} \\ s_{xy} & s_{yy} \end{pmatrix} = \begin{pmatrix} \sigma_{xx} - p & \sigma_{xy} \\ \sigma_{xy} & \sigma_{yy} - p \end{pmatrix} \tag{3}$$

$$\boldsymbol{r} = \frac{\boldsymbol{s}}{p} = \begin{pmatrix} r_{xx} & r_{xy} \\ r_{xy} & r_{yy} \end{pmatrix} = \begin{pmatrix} \frac{\sigma_{xx} - p}{p} & \frac{\sigma_{xy}}{p} \\ \frac{\sigma_{xy}}{p} & \frac{\sigma_{yy} - p}{p} \end{pmatrix} \tag{4}$$

In eq. (3), $\boldsymbol{I}$ is the identity matrix. The deviatoric stress and deviatoric stress ratio tensors are symmetric with $r_{xx} = -r_{yy}$ and $s_{xx} = -s_{yy}$ (meaning a zero trace).

The strains are represented by a tensor, ε, expressed as the sum of the volumetric strain ε_v and of the deviatoric strain tensor, e. The volumetric strain is,

$$\varepsilon_v = \varepsilon_{xx} + \varepsilon_{yy} \tag{5}$$

and the deviatoric strain tensor is,

$$\boldsymbol{e} = \boldsymbol{\varepsilon} - \frac{\varepsilon_v}{3}\boldsymbol{I} = \begin{pmatrix} \varepsilon_{xx} - \frac{\varepsilon_v}{3} & \varepsilon_{xy} \\ \varepsilon_{xy} & \varepsilon_{yy} - \frac{\varepsilon_v}{3} \end{pmatrix} \tag{6}$$

In incremental form, the deviatoric and volumetric strain terms are decomposed into an elastic and a plastic part,

$$d\boldsymbol{e} = d\boldsymbol{e}^{el} + d\boldsymbol{e}^{pl} \tag{7}$$

$$d\varepsilon_v = d\varepsilon_v^{el} + d\varepsilon_v^{pl} \tag{8}$$

where:

$d\boldsymbol{e}^{el}$ = elastic deviatoric strain increment tensor

$d\boldsymbol{e}^{pl}$ = plastic deviatoric strain increment tensor

$d\varepsilon_v^{el}$ = elastic volumetric strain increment tensor

$d\varepsilon_v^{pl}$ = plastic volumetric strain increment tensor

This constitutive model follows the critical state theory and uses the relative state parameter index (ξ_R) as defined by Boulanger (2010) and shown in Figure 1. This relative parameter is defined by an empirical relationship for the critical state line:

$$\xi_R = D_{R,cs} - D_R \tag{9}$$

$$D_{R,cs} = \frac{R}{Q - \ln\left(100\frac{p}{p_A}\right)} \tag{10}$$

where $D_{R,cs}$ is the relative density at critical state for the current mean effective stress, instead, Q and R are two parameters that define the shape of critical curve.

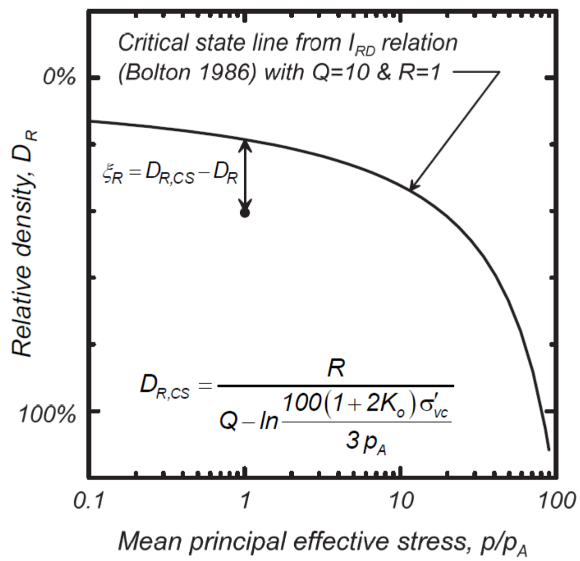

Figure 1: Relative state parameter index

Bounding, dilatancy and critical surfaces are incorporated in PM4Sand following the form of Dafalias and Manzari (2004).

The bounding (M^b) and dilatancy (M^d) ratios can be related to the critical stress (M) ratio:

$$M^b = M \cdot \exp\left(-n^b \xi_R\right) \tag{11}$$

$$M^d = M \cdot \exp\left(-n^d \xi_R\right) \tag{12}$$

where n^b and n^d are model parameters. The relationship for M is:

$$M = 2 \cdot \sin\left(\phi_{cv}\right) \tag{13}$$

where ϕ_{cv} is critical state friction angle.

As the soil is sheared toward critical state $\left(\xi_R = 0\right)$, the values of M_b and M_d will both approach the value of M. Thus, the bounding and dilatancy surfaces move together during shearing until they coincide with the critical state surface when the soil has reached critical state.

The few experimental data for loose-of-critical sands (having no peak) show that the maximum friction angles (presumably determined at the limit of strains possible within the laboratory tests) were only slightly smaller than the critical state values, such that extending the above relationships to loose-of-critical sands may tend to underestimate the peak friction angles (in this case theoretically coinciding with the critical state one). Consequently, in the present formulation the model allows n_b and n_d to be different for loose-of-critical and dense-of-critical states for the same sand.

A large portion of the post-liquefaction reconsolidation strains are due to the sedimentation effects which are not easily incorporated into either the elastic or plastic components of behaviour. For this reason, in the PM4Sand a post-shaking function was implemented. In a strongly pragmatic way, this function reduces volumetric and shear moduli, thus increasing reconsolidation strains to somehow simulate the sedimentation ones (not included in the model).

The post-shaking elastic moduli are determined by multiplying the conventional elastic moduli by a reduction factor F_{sed} as,

$$G_{post-shaking} = F_{sed} \cdot G \quad (14)$$

$$K_{post-shaking} = F_{sed} \cdot K \quad (15)$$

for more information on the F_{sed} it is possible refer to Boulanger and Ziotopoulou (2015).

The model require 27 input parameters, 3 of these are considered primary parameters while all the other parameters are suggested to be left with their default values. Table 1 reports the most important input parameters of the PM4Sand model, which were defined in the calibration process.

Table 1: Input parameters of the PM4Sand model

Dr	Initial relative density
G_0	shear modulus coefficient
hp_0	contraction rate parameter
p_A	atmospheric pressure
e_{max}	maximum void ratio
e_{min}	minimum void ratio
n_b	bounding surface parameter
n_d	dilatancy surface parameter
φ_{cv}	critical state friction angle
ν	Poisson's ratio
Q	critical state line parameter
R	critical state line parameter

Model Parameters

The model parameters obtained from the calibration process are listed in Table 2, which also include some parameters kept at their default value.

The model parameters are obtained by using the results of the provided cyclic torsional shear tests, as described in the next paragraph about the calibration procedure. It should also be noted that the selected model parameters from this report will be adopted for future simulations of the centrifuge model tests.

Table 2: Parameters of the PM4Sand model based on the cyclic torsional test data

Initial relative density / Model parameters	Dr = 50%	Dr = 60%
Dr	0.5	0.6
G_0	630	730
hp_0	0.08	0.05
p_A	101.3	101.3
e_{max}	0.78	0.78
e_{min}	0.51	0.51
n_b	0.5	0.5
n_d	0.3	0.1
φ_{cv}	32	32
ν	0.3	0.3
Q	10	10
R	1	1
PostShake	0	0

Calibration Method

The approach used in the calibration of the constitutive model parameters is hereafter explained.

The PM4Sand constitutive model is calibrated on the results of laboratory element tests. PM4Sand has 27 input parameters (6 primary and 21 secondary) but only three of them are required as independent inputs: the initial relative density (D_r), the shear modulus coefficient used to define the small strain shear modulus (Go) and the contraction rate parameter used for the calibration of the undrained shear strength (h_{p0}). Basically, these three parameters were calibrated against the experimental data. The initial relative density has been set equal the value of relative density used in the cyclic torsional tests, Dr=0.5 and 0.6.

The value of the shear modulus coefficient Go was determined as a function of the relative density using the follow relationship:

$$G_o = 167 \cdot \sqrt{46 \cdot Dr^2 + 2.5} \qquad (16)$$

The parameter h_{p0} scales the plastic contraction rate and is the primary parameter for the calibration of undrained cyclic strength. It is calibrated using an iterative process, in which undrained single-element simulations are conducted to match with the experimental liquefaction triggering curve by keeping the other parameters fixed.

With reference to the secondary parameters of the model, some with a clear physical meaning have been defined on the available experimental data, while the others have been left with their default values.

Shear strength parameters are computed from the monotonic triaxial test data, available on the NEES Hub (https://nees.org/dataviewer/view/1064:ds/1189).

Drained triaxial compression tests, carried out by Vasko (2015) on loose and dense specimens, were used to define the critical state line in the plane q : p' and the constant volume friction angle, ϕ'_c. As well known, the evaluation of critical state conditions in triaxial tests is a very complex issue, being such a test intrinsically affected by a number of experimental limitations (localization, bulging, shear stresses on the rough porous stones, difference between local and external displacements, etc.). One of the best ways to evaluate the final state is therefore the one that analyses dilatancy trend at the end of the tests. Based on all the elaborations of the available experimental data, and considering that the hypoplastic model assumes the critical state as an asymptotic state at infinite strains, in this case the best fit of this parameter is the following:

$$\phi_c = 32° \quad (17)$$

Minimum and maximum void ratios, emax and emin, have been defined as mean values of the experimental measurements carried out in the LEAP-UCD-2017 Simulation Exercise (Manzari et al. 2019).

To sum up, the model parameters for static loading conditions were defined on the physical properties and tests results provided for the considered sand.

Conversely, the model parameters for cyclic loading conditions were defined using experimental data of cyclic torsional tests (Dr = 50% and 60%).

The material parameters used to perform the simulations are those reported in Table 2 for each relative density. Every cyclic test is simulated imposing the prescribed CSR and computing the number of cycles, N_L, to induce liquefaction. Liquefaction condition has been defined according to the stress-based approach, i.e., r_u=95%, where r_u is the excess pore pressure ratio ($r_u = \Delta u/ p'_0$ ratio between the excess pore water pressure increment induced by cyclic loading and the initial effective confining pressure applied during the test, p'_0).

Liquefaction Strength Curves

The liquefaction strength curves, obtained from the simulated cyclic torsional tests, are hereafter plotted and compared with the experimental results (Figure 2). Table 3 reports the numerical values of the simulation results, i.e. the cyclic stress ratio, CSR, versus the number of cycles until excess pore pressure ratio, $r_u = \Delta u/p'_0$, achieved 95% for each simulated test.

It can be observed how the adopted calibration provides a good prediction of the experimental cyclic resistance curve for high/medium values of the cyclic resistance ratio (CRR), while underestimation of the experimental cyclic strength is observed for low values of CRR.

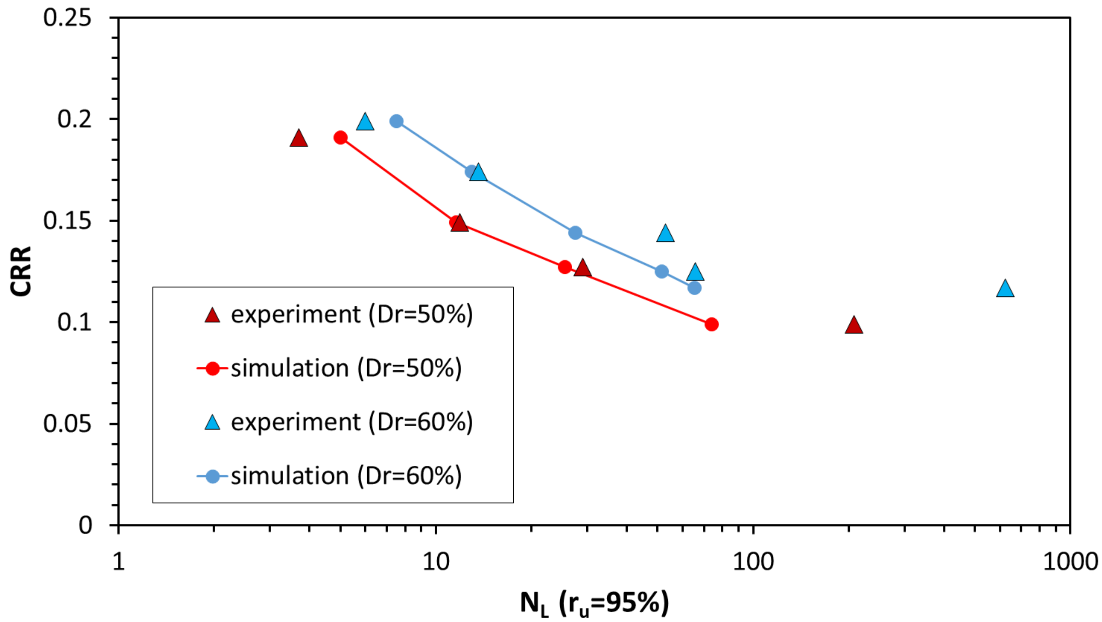

Figure 2: Liquefaction Strength Curves obtained from experimental and simulated cyclic torsional tests on Ottawa F65 Sand

Table 3: Predicted liquefaction strength curves from cyclic torsional test

Dr (%)	CSR	No. of cycles to 95% r_u
50	0.099	74
50	0.127	25.5
50	0.149	11.6
50	0.191	5
60	0.117	65.5
60	0.125	51.5
60	0.144	27.5
60	0.174	13
60	0.199	7.5

Simulation Results

In addition to the report on model calibration, the results of the simulation of the cyclic torsional tests previously mentioned are reported in separate files with the required format, i.e. *excel* files. The results of element test simulations and comparison with those of the provided cyclic torsional tests are also reported in Appendix A and B for Dr = 50 % and 60%, respectively.

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Boulanger, R.W. (2010). A sand plasticity model for earthquake engineering applications, Report No. UCD/CGM-10-01. Technical report, Center for Geotechnical Modeling, Department of Civil and Environmental Engineering, University of California.

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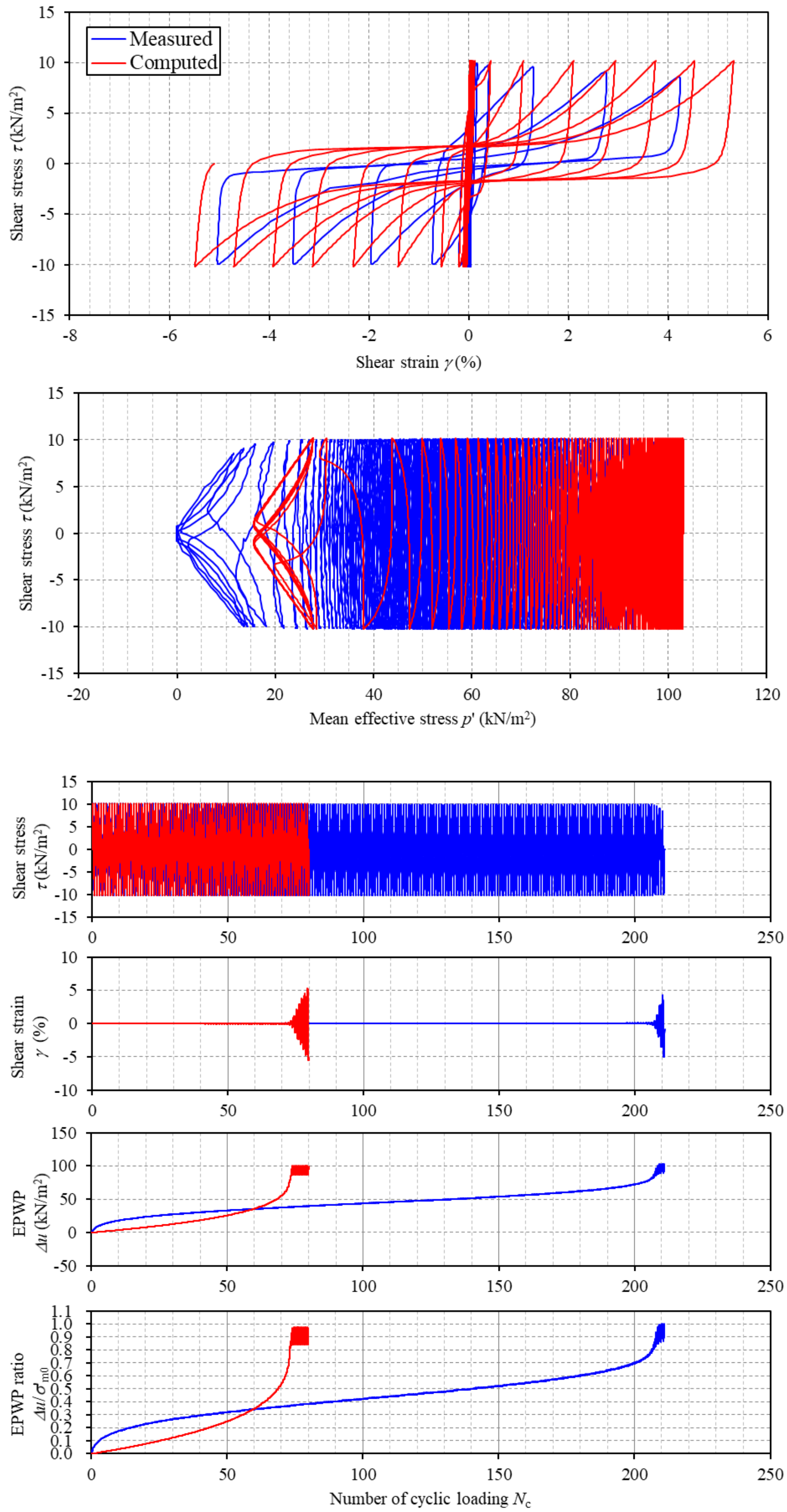
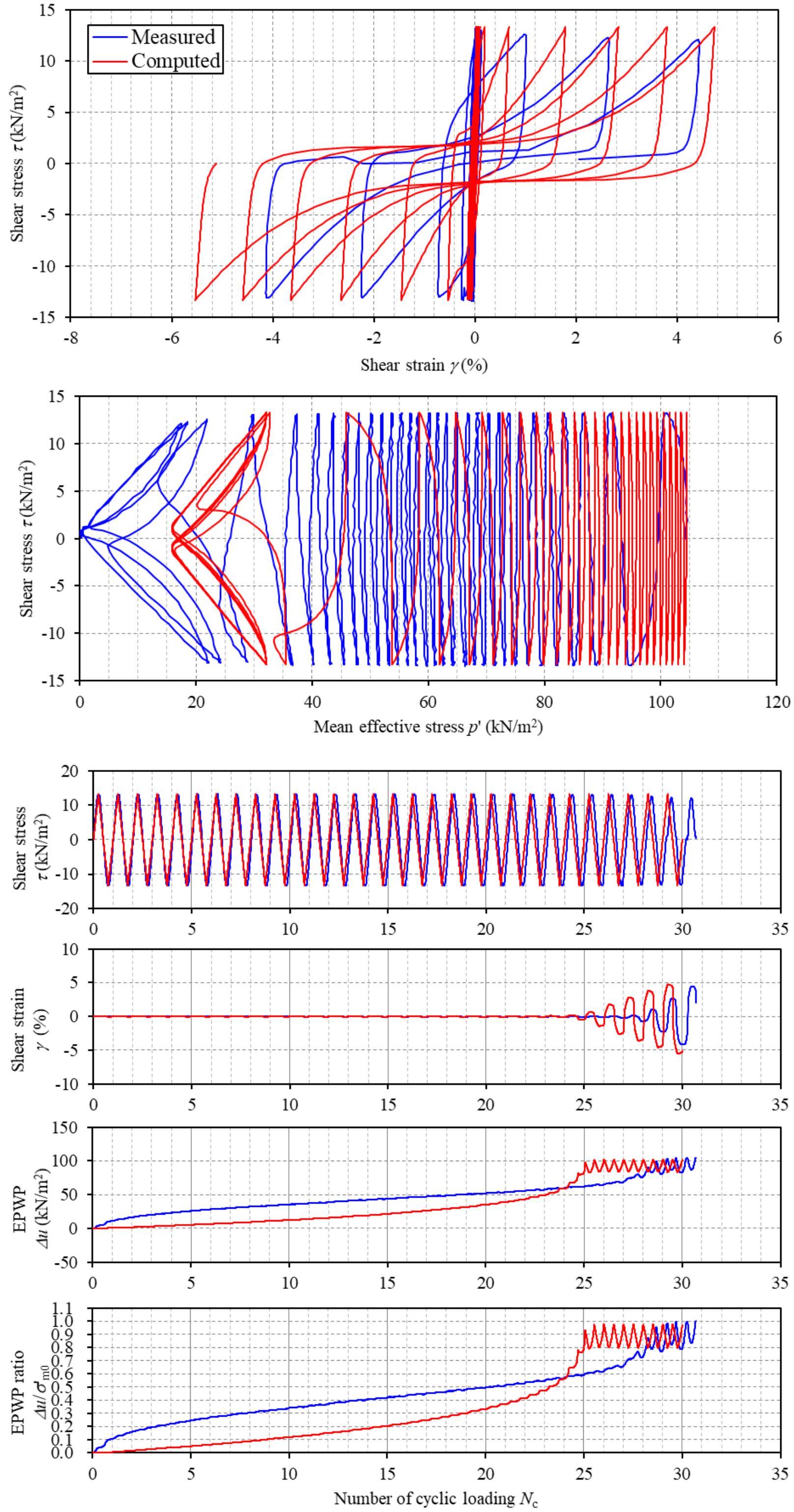
Appendix A: Simulation cyclic torsional tests Dr = 50%

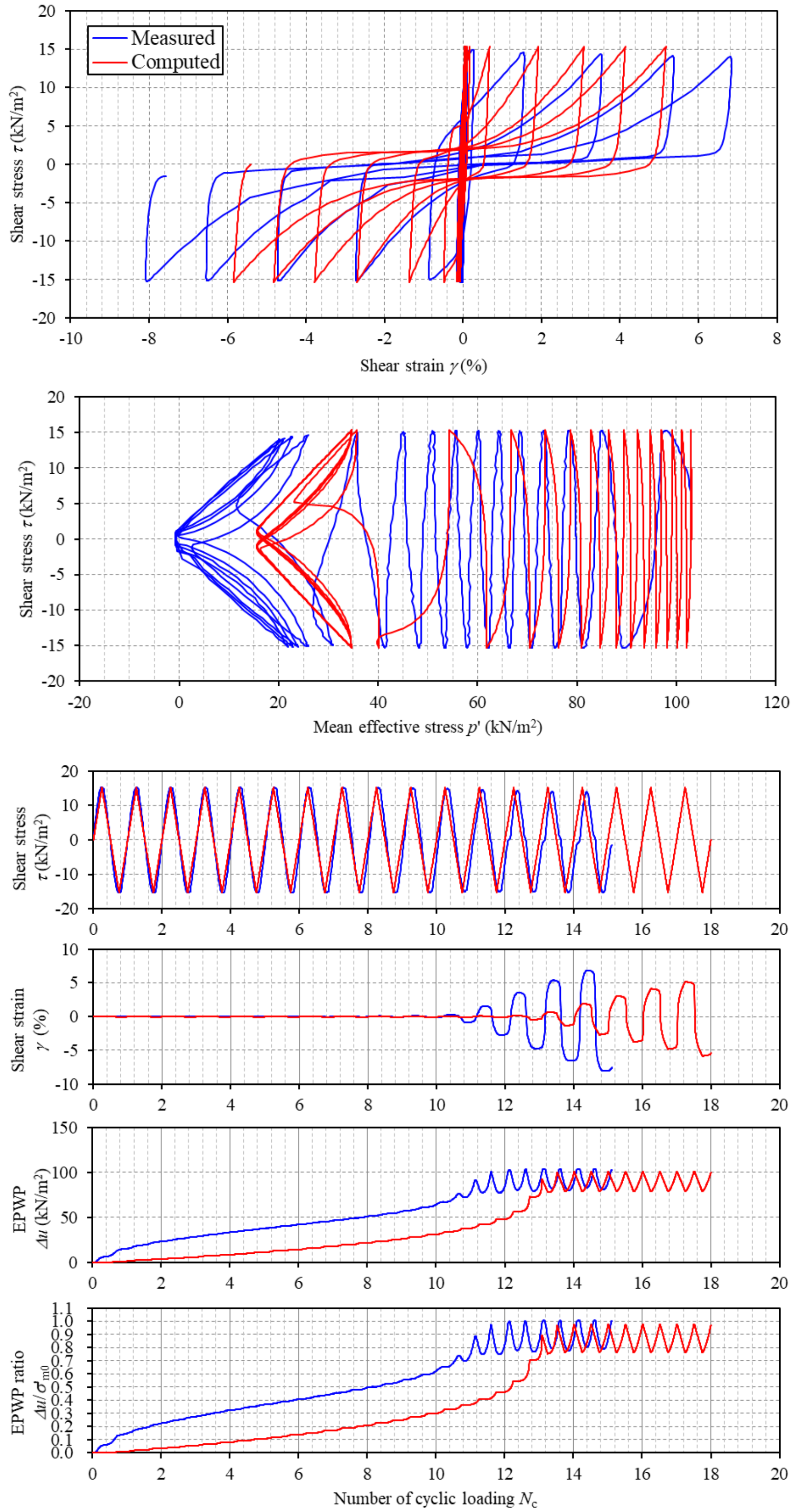
Test 1: CSR = 0.099; Number of cycles until r_u = 95% is achieved =74



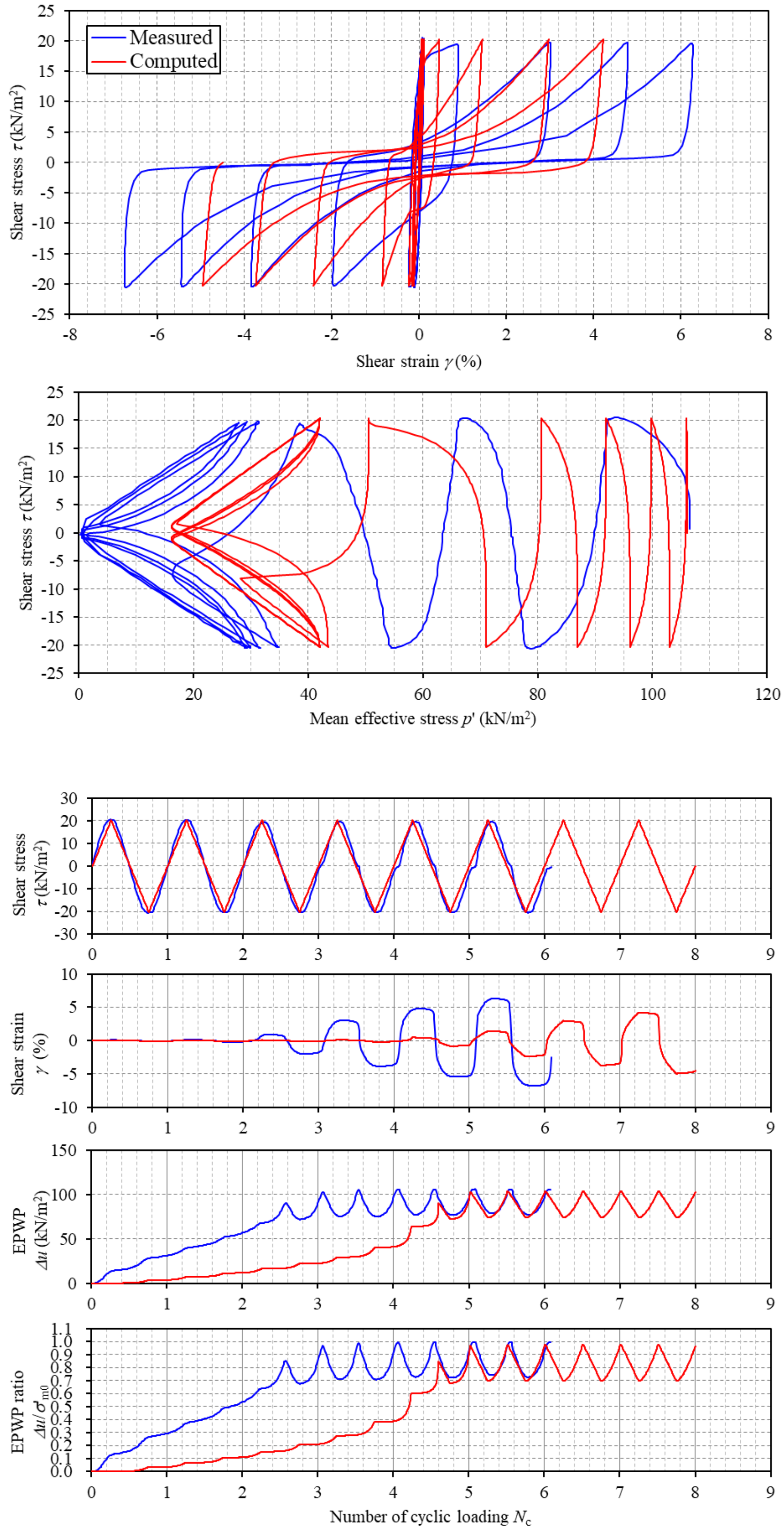
Test 2: CSR = 0.127; Number of cycles until r_u = 95% is achieved =25.5



Test 3: CSR = 0.149; Number of cycles until r_u = 95% is achieved =11.6

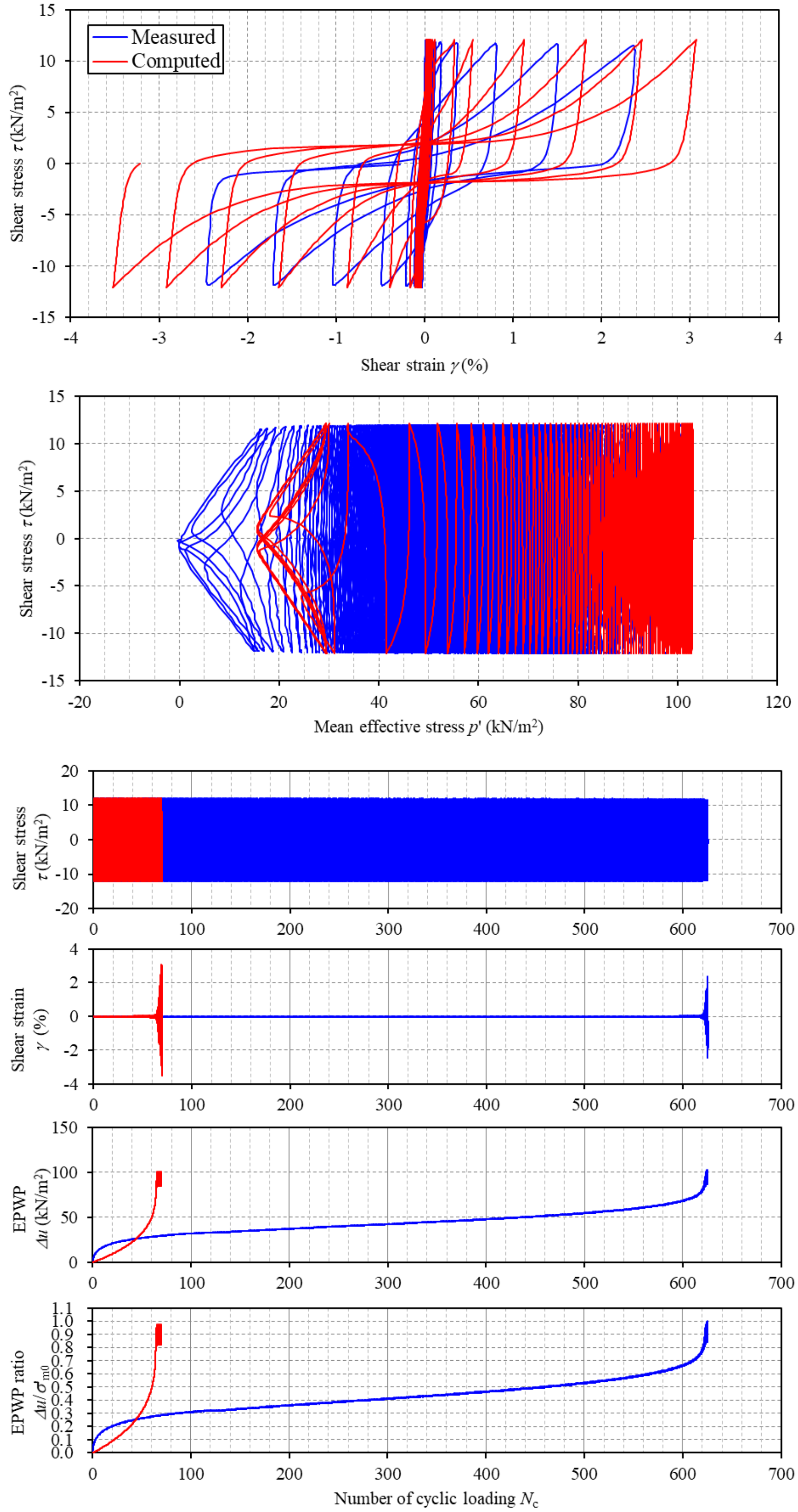


Test 4: CSR = 0.191; Number of cycles until r_u = 95% is achieved =5

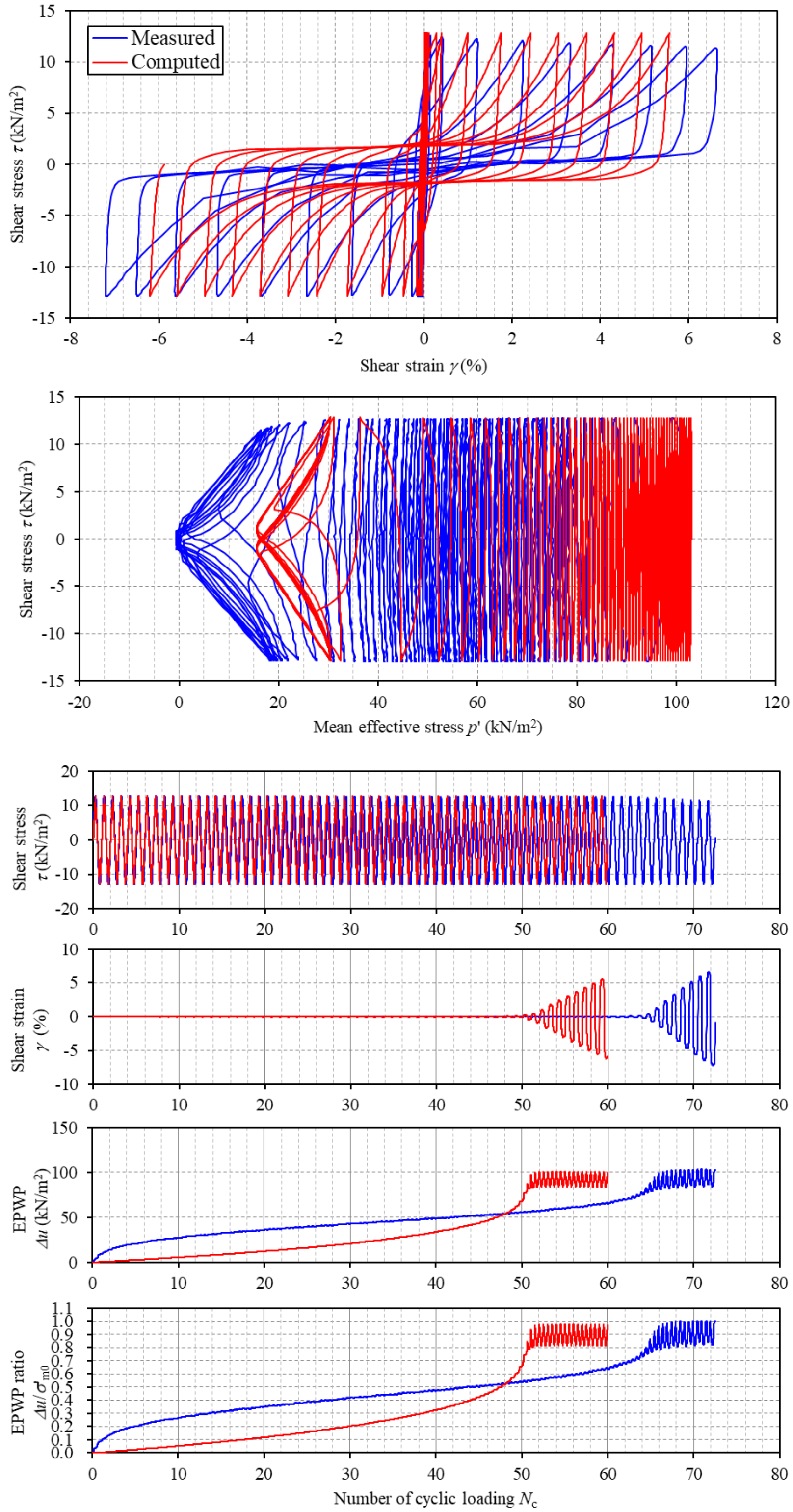


Appendix B: Simulation cyclic torsional tests Dr = 60%

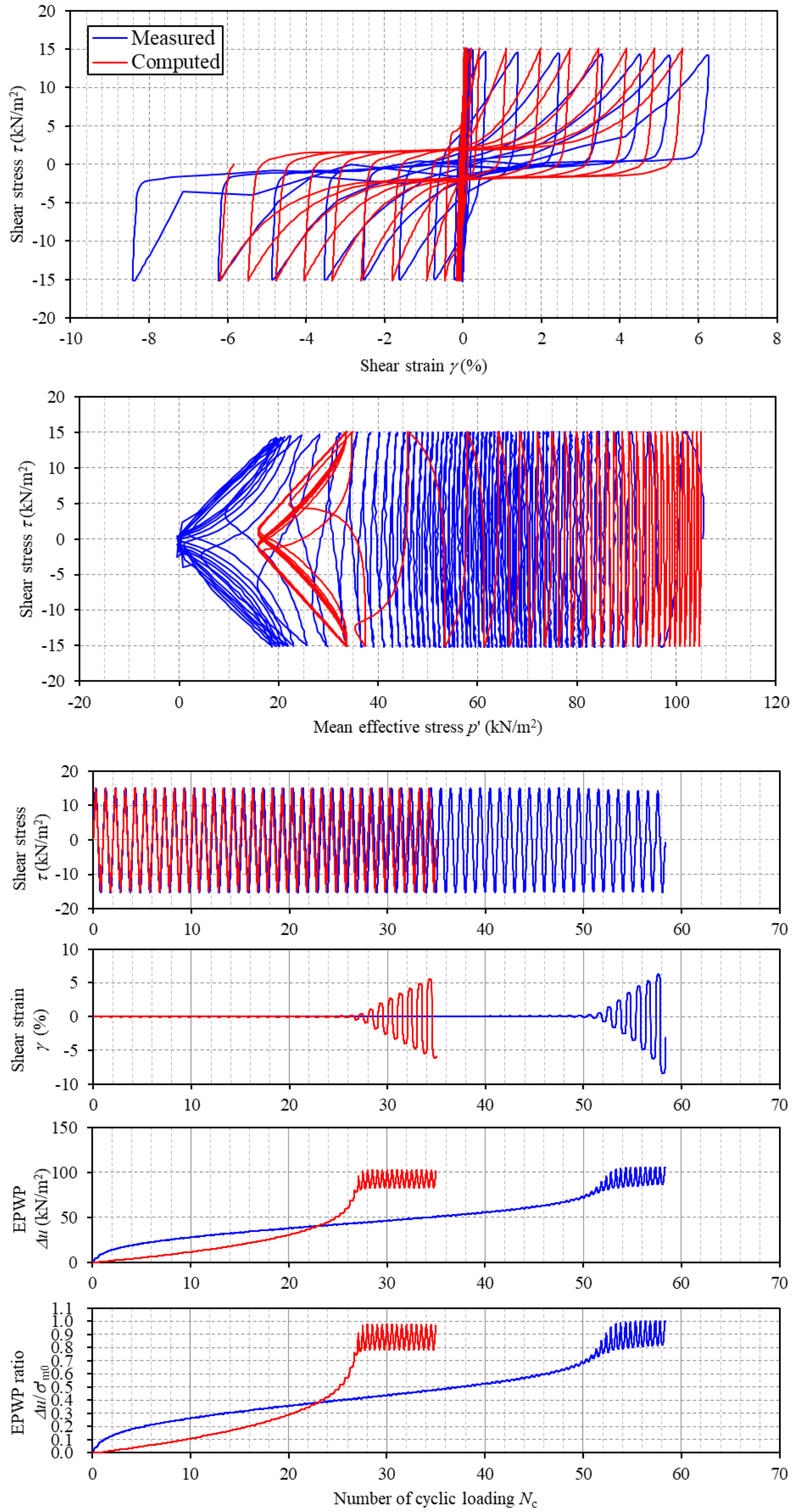
Test 1: CSR = 0.117; Number of cycles until r_u = 95% is achieved =65.5



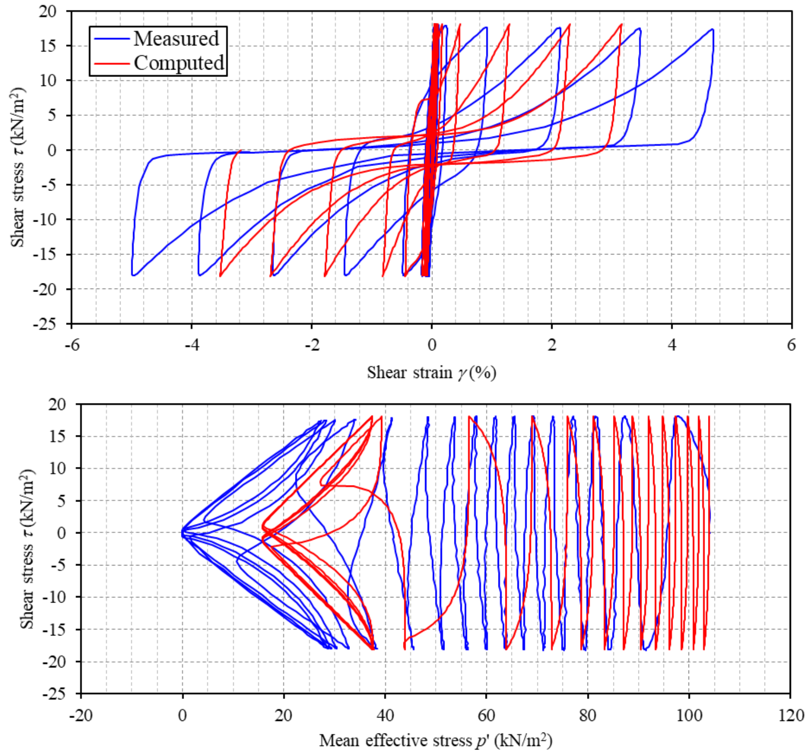
Test 2: CSR = 0.125; Number of cycles until r_u = 95% is achieved =51.5

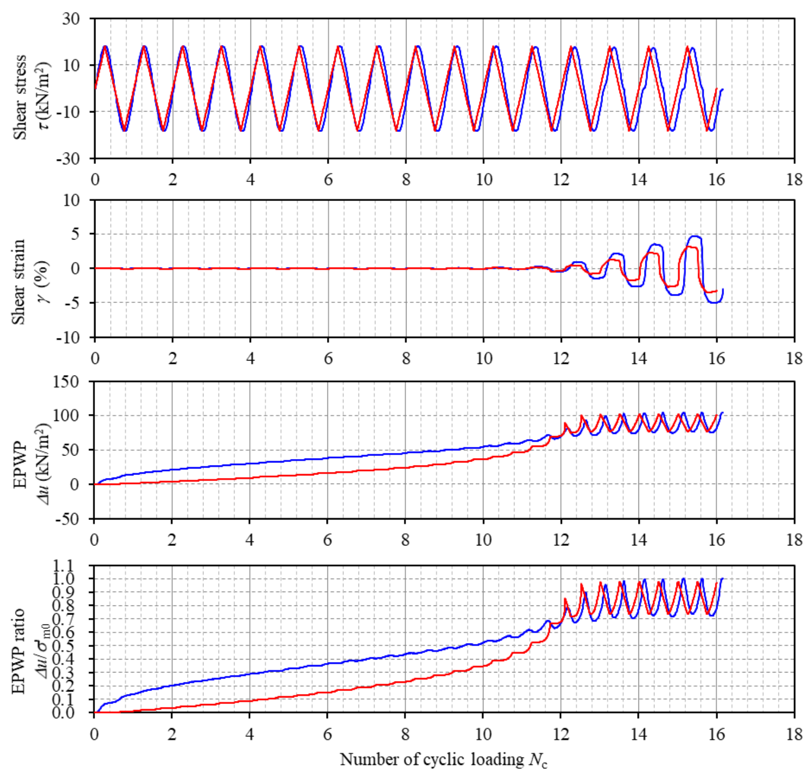


Test 3: CSR = 0.144; Number of cycles until r_u = 95% is achieved =27.5



Test 4: CSR = 0.174; Number of cycles until r_u = 95% is achieved =13





Test 5: CSR = 0.199; Number of cycles until r_u = 95% is achieved =7.5