Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
© 2019 Associazione Geotecnica Italiana, Rome, Italy, ISBN 978-0-367-14328-2

A modified NorSand model for the prediction of static and cyclic behaviour of sands under simple shear loading

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ABSTRACT: The simple shear apparatus is a useful laboratory tool available to geotechnical engineers for seismic designs. Once simple shear test results can be predicted by a numerical model, engineers can use the modelling approach for the design of earth structures confidently. In this study, the NorSand soil model was modified to account for anisotropy effects on soil behaviour using the anisotropic critical state theory. Static and cyclic simple shear laboratory test results for Toyoura sand were compared to numerical behaviour predictions using the modified NorSand model. While static simple shear behaviour is well predicted by the modified model, cyclic behaviour comparisons are more nuanced. In the light of this study, the authors consider anisotropy to be a key component for better sand behaviour predictions under static and cyclic simple shear. However, the authors also consider the unloading phase of the cyclic loading deserves more attention to reach satisfactory behaviour predictions.

1 INTRODUCTION

The simple shear apparatus is by far the most widely used laboratory tool to assess the resistance of soils to loadings involving rotation of principal stress axes. Such rotation is an important part of the loading process occurring during cyclic loadings such as earthquakes and waves affecting offshore structures. Simple shear laboratory test results can be used to calibrate and verify the performance of numerical soil models used to predict soil behaviour under such loading condition.

The goal of this study is to compare the numerical prediction of the NorSand soil model to static and cyclic simple shear laboratory results found in the literature. A new version of the model incorporating anisotropy effects is proposed to enhance prediction performance.

Section 2 of this paper describes the newly formulated soil model, first by describing the basic NorSand model, followed by presenting the anisotropic critical state theory and finally by highlighting the modifications made to NorSand to accurately model soil anisotropy. Simulation results of static and cyclic simple shear tests are compared with laboratory data in Section 3. Finally, some discussion points are considered in Section 4.

2 SOIL MODEL DESCRIPTION

2.1 *NorSand*

NorSand is a critical state based soil model incorporating the state parameter ψ (Been & Jefferies 1985) as a basis for behaviour prediction. The model has been extensively used to successfully predict the behaviour of sands, loose and dense, under triaxial loading, both for drained and undrained conditions. In depth description of the model can be found in Jefferies & Been (2015).

To improve simulation results of cyclic simple shear tests, Jefferies et al. (2015) recently extended NorSand to incorporate the effect of principal stress rotation through Equation 1, where the variation of principal stress orientation ($\dot{\alpha}$) softens the yield surface. The plastic softening modulus Z is a new model parameter to be determined. Its function is to scale the effect that principal stress rotation has on the size of the yield surface. The calculated softening is scaled by the state parameter at image condition ψ_i. This addition serves the purpose of nullifying the effect of principal stress rotation when critical state is reached and, by definition, when the state parameter reaches a value of 0.

$$\left[\frac{\dot{\bar{\sigma}}_{mi}}{\bar{\sigma}_{mi}}\right]_{PSR} = \left[-Z\left(\frac{\bar{\sigma}_{mi}}{\bar{\sigma}_m} - \frac{1}{r}\right)\left|\frac{\dot{\alpha}}{\pi}\right| + \frac{1}{r}\right]|\psi_i| \tag{1}$$

where Z= plastic softening modulus; $\bar{\sigma}_m$= mean stress; $\bar{\sigma}_{mi}$= mean stress at image condition; r= NorSand's spacing ratio ($r = e = 2.72$); ψ_i= state parameter at image condition.

Cyclic simple shear modelling presented by Jefferies et al. (2015) showcased the appeal of their proposed approach. Basic features of soil behaviour under cyclic loading, such as pore water pressure buildup with each shearing cycle, were predicted by the model. However, results also highlighted deficiencies in correctly predicting deformations encountered during shearing, especially when dilation alternates with contraction after the phase transformation line is crossed.

2.2 *Anisotropic critical state theory*

The anisotropic critical state theory (Li & Dafalias 2012) is an elegant and simple way to incorporate anisotropic soil behaviour features into classical critical state soil mechanics. By adding a new anisotropy-dependent condition for critical state to occur, anisotropy influences soil behaviour through an apparent translation of the critical state line *CSL*, temporarily transforming into the dilatancy state line *DSL* (see Figure 1). State is consequently measured by the dilatancy state parameter ζ that represents the relative distance between the soil's void ratio e and the dilatancy state line, in a similar manner as the classical state parameter ψ is used. Within the anisotropic critical state theory, anisotropy evolves through shearing and depends on loading direction. Specifics of the anisotropic critical state theory are thoroughly described by Li & Dafalias (2012).

2.3 *Modified (anisotropic) NorSand*

To improve prediction capability of the NorSand soil model under simple shear loading, the authors modified NorSand to include the effect of anisotropy through the aforedescribed anisotropic critical state theory. Modifications mainly consisted of employing the dilatancy state parameter ζ in lieu of the usual state parameter ψ within the modelling procedure to account for the effect of anisotropy on soil behaviour. NorSand's principal stress rotation dependent softening

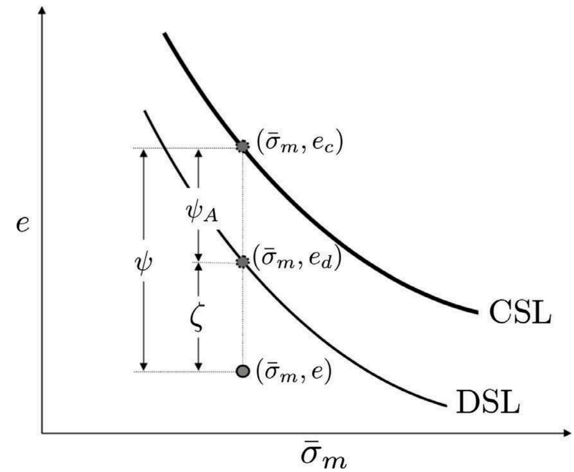

Figure 1. Anisotropic critical state theory (modified from Li & Dafalias 2012)

Table 1. NorSand model parameters and ACST parameters for Toyoura sand

NorSand parameters	Toyoura sand
Critical state line	
Γ	0.983
λ_e	0.019
Plasticity	
M_{tc}	1.28
χ_{tc}	4.4
N	0.41
H	305
Z	*variable*
Elasticity	
ν	0.2
$I_r = G/\bar{\sigma}_m$	$878\frac{(2.17-e)^2}{1+e}\left(\frac{\bar{\sigma}_m}{100}\right)^{-0.47}$

ACST parameters	Toyoura sand
c	5.7
e_A	0.10
F_0	0.45

law was also updated to remove its dependency on the state parameter, which proves itself incompatible with the basic premises of the anisotropic critical state theory (see Equation 2).

$$\left[\frac{\dot{\bar{\sigma}}_{mi}}{\bar{\sigma}_{mi}}\right]_{PSR} = \left[-Z\left(\frac{\bar{\sigma}_{mi}}{\bar{\sigma}_m} - \frac{1}{r}\right)\left|\frac{\dot{\alpha}}{\pi}\right| + \frac{1}{r}\right] \tag{2}$$

To verify the behaviour prediction potential of this modified anisotropic NorSand model, static and cyclic simple shear tests were modelled and compared with corresponding laboratory tests found in the literature. All laboratory tests used for comparison were carried out on Toyoura sand, a Japanese clean sand. Simulation parameters used for this study are indicated in Table 1. NorSand's parameters for Toyoura sand were taken from Ghafghazi & Shuttle (2008) while anisotropic critical state theory (ACST) parameters were taken from Gao et al. (2014). NorSand's plastic hardening parameter H was adjusted to a value of 305 to best fit laboratory behaviour. The model's plastic softening parameter Z was also adjusted for each modelling carried out to appropriately capture the rate of accumulation of pore pressure during principal stress rotation. Chosen values for the plastic softening parameter Z are indicated on each figure.

3 SIMULATION RESULTS

In this section, laboratory results are compared to numerical predictions using NorSand. Figures 2 through 4 follow the same layout: laboratory results are presented in parts A and B, anisotropic NorSand simulations in parts C and D, isotropic NorSand simulations in parts E and F. Stress paths are presented on the left side of each figure (parts A, C, E), while stress strain curves are presented on the right side (parts B, D, F). The static and cyclic simple shear laboratory results used for comparison are taken from Yoshimine et al. (1998) and Kiyota et al. (2008) respectively. Both series of tests were conducted using hollow cylinder torsional apparatuses.

3.1 *Static simple shear*

As can be seen on Figure 2, there is a wide range of behaviour observed in laboratory results (very contractive response for higher void ratios, very dilative response for lower void ratios). This is mostly well captured by the anisotropic NorSand model. Highly contractive behaviour is evident for higher void ratios. However, lower void ratios tend to yield more contractive predictions than what can be seen in laboratory results. On the opposite, the isotropic model fails to predict any contraction. Each modelled void ratio yields very strong dilation.

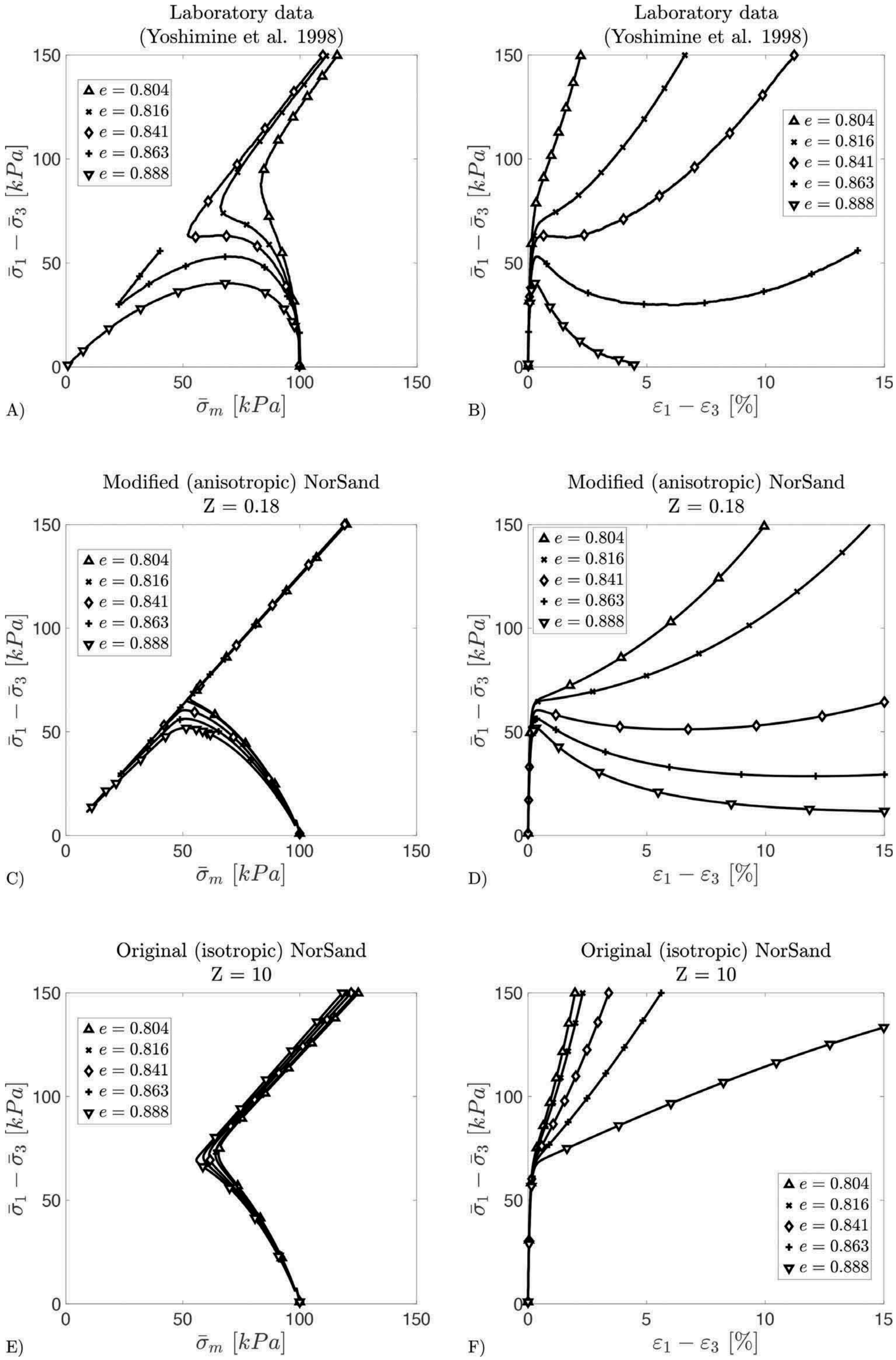

Figure 2. Static simple shear behaviour: comparison between laboratory results and numerical predictions

The width of modelled behaviour is also very narrow for the isotropic model, especially in terms of stress path, which is very far from what is evident from the laboratory results.

3.2 *Cyclic simple shear – loose sample*

The results shown in Figure 3 showcase the prediction performance of both NorSand models for the cyclic simple shearing of a loose Toyoura sand sample ($Dr = 25\%$, $e = 0.870$). Both versions of the model correctly accumulate pore water pressure within each shearing cycle through an appropriate scaling of the plastic softening parameter Z. However, once dilation eventually governs soil behaviour after the phase transformation line is crossed (after approximately 8.5 cycles), the isotropic NorSand model fails to produce significant shear deformations, contrary to what is observed in the laboratory test. The modified anisotropic NorSand model correctly predicts the large deformations associated with the alternation between dilatancy and contraction toward the end of the test.

3.3 *Cyclic simple shear – dense sample*

Numerical simulation results for a cyclic simple shear test on a medium dense Toyoura sand sample ($Dr = 50\%$, $e = 0.870$) are compared to laboratory results in Figure 4. Laboratory results show a classical example of cyclic mobility: an initially stiff response with accumulating pore water pressure within each shearing cycle, followed by a gradual accumulation of shear deformations once the effective mean stress has reduced sufficiently and dilatancy alternates with contraction to ultimately control soil behaviour. Both modelled NorSand responses correctly predict the accumulation of pore water pressure through shearing cycles but fail to capture the onset of large deformations toward the end of the test. Once a limiting effective mean stress value is reached (around approximately 26 kPa), unloading and reloading phases both remain elastic.

4 DISCUSSION

Results presented in the previous section highlight the potential of the anisotropic NorSand model, as well as some of the deficiencies it retained from the original isotropic version of the model. First, it is evident in Figure 2 that the inclusion of anisotropy into NorSand greatly enhances the model prediction potential for simple shear, especially if a wide range of void ratios is considered. The isotropic model's inability to predict any contractive behaviour in simple shear (even for large void ratios) is very misleading considering how contraction is an important part of the overall behaviour observed in the laboratory data.

The rate of accumulation of pore water pressure predicted by both models in Figures 3 and 4 is very similar and in line with what is observed in laboratory results of cyclic simple shear tests. However, an important discrepancy between the two models is evident in Figure 3 where the anisotropic model produces large deformations when dilation alternates with contraction, a behaviour feature completely missing from the isotropic model. This is achieved by the use of the dilatancy state parameter ζ in the anisotropic model instead of the classical state parameter ψ. As can be seen in Figure 5A, the dilatancy state parameter is positive (indicating a contractive behaviour) until the 7^{th} cycle, where it begins to alternate between positive and negative values (contraction alternating with dilation), generating large shear deformations. On the other hand, the state parameter remains negative during the whole loading sequence and large deformations are thus impossible to obtain with the isotropic model. Similarly, it can be seen on Figure 5B that both the dilatancy state parameter and the state parameter remain negative during the cyclic shearing of the medium dense sand, explaining why neither model was able to produce large deformations.

Both NorSand models used in this study use the same linear elastic formulation for elastic unloading and reloading (before the yield surface is touched). This translates into an absence of pore water pressure generation during unloading in cyclic simple shear tests, contrary to what is observed in laboratory results of Figures 3A and 4A. Other formulations might need

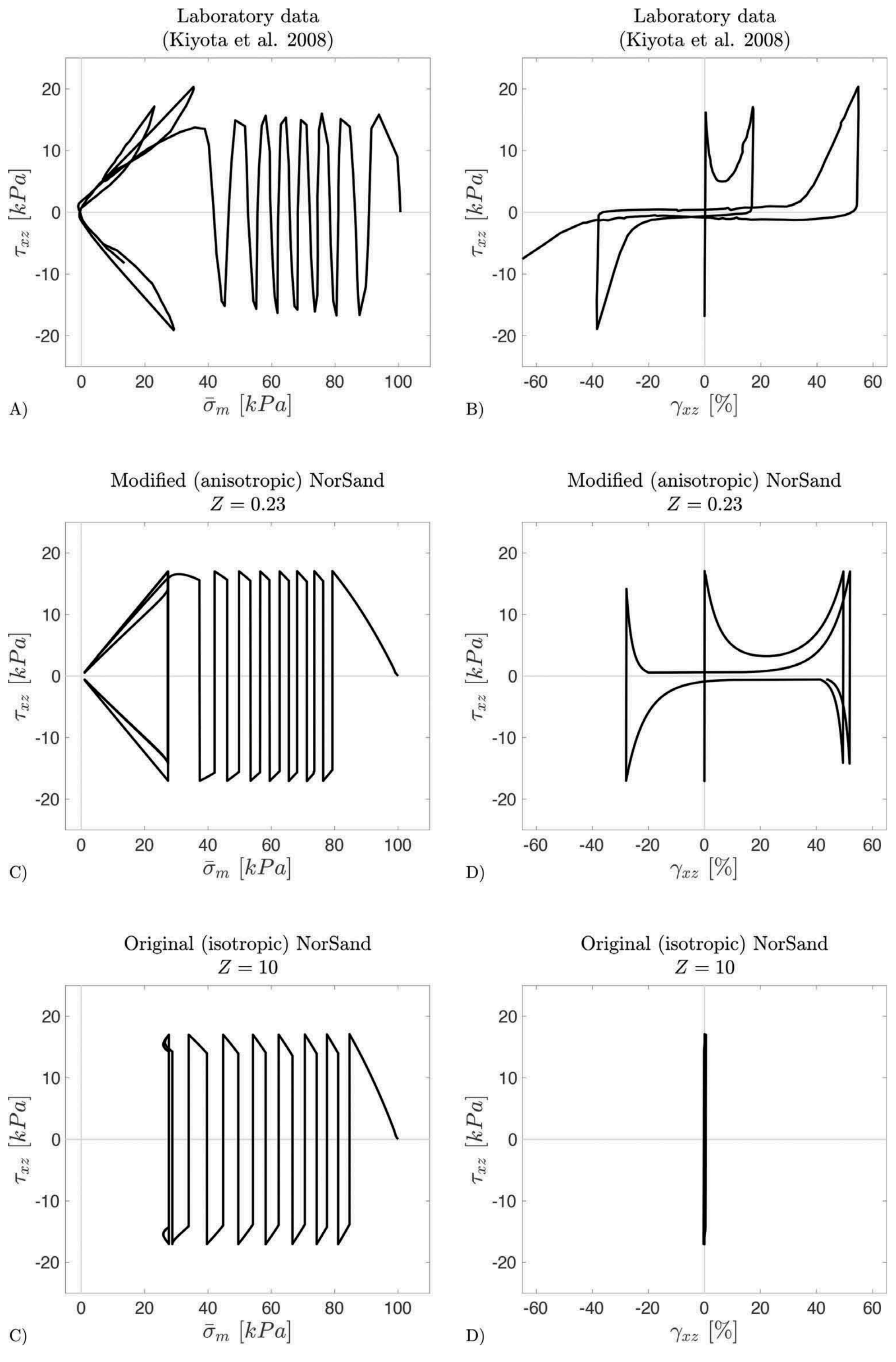

Figure 3. Cyclic simple shear behaviour: comparison between laboratory results and numerical predictions for a loose Toyoura sand sample ($Dr = 25\%$ or $e = 0.870$)

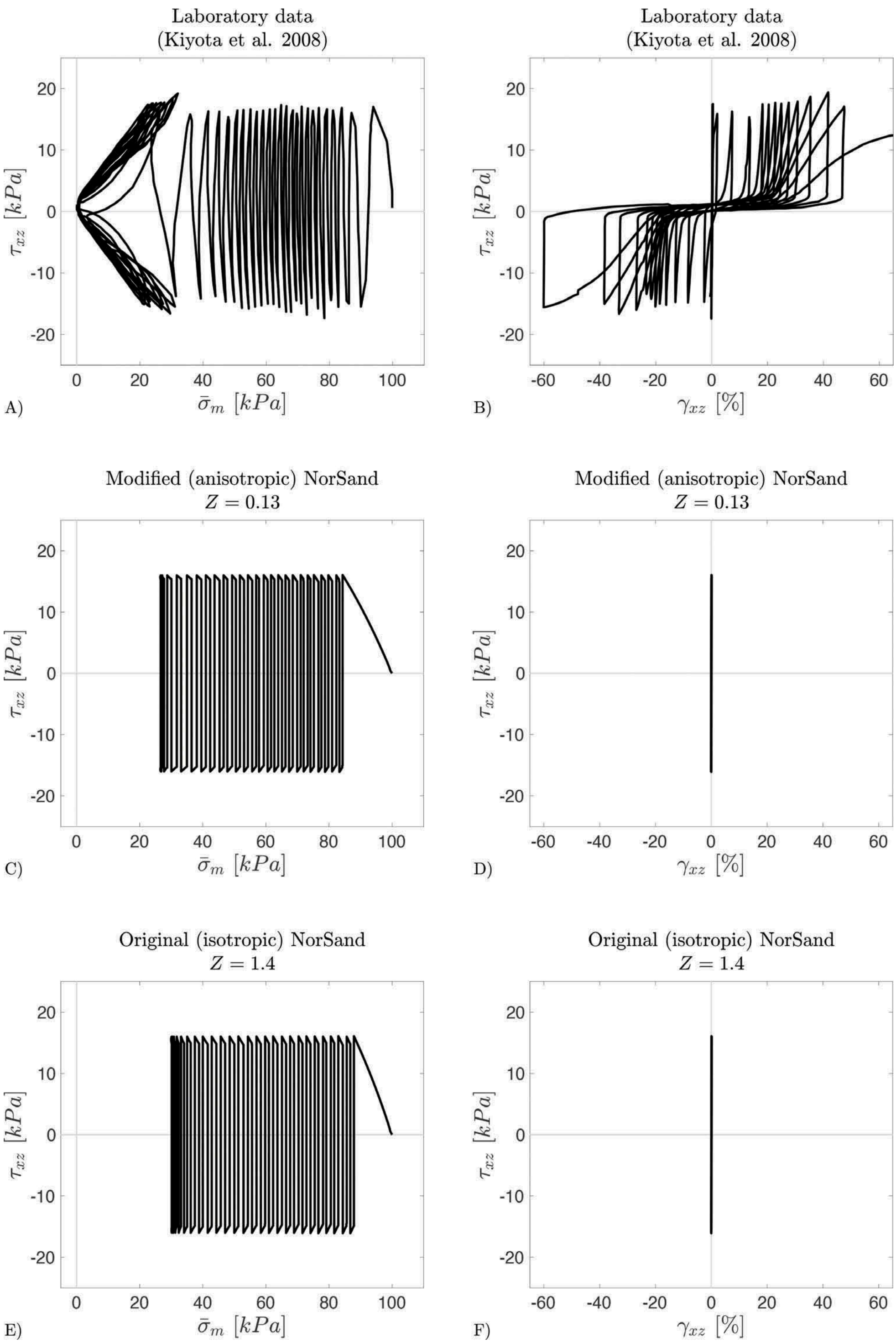

Figure 4. Cyclic simple shear behaviour: comparison between laboratory results and numerical predictions for a medium dense Toyoura sand sample ($Dr = 50\%$ or $e = 0.770$)

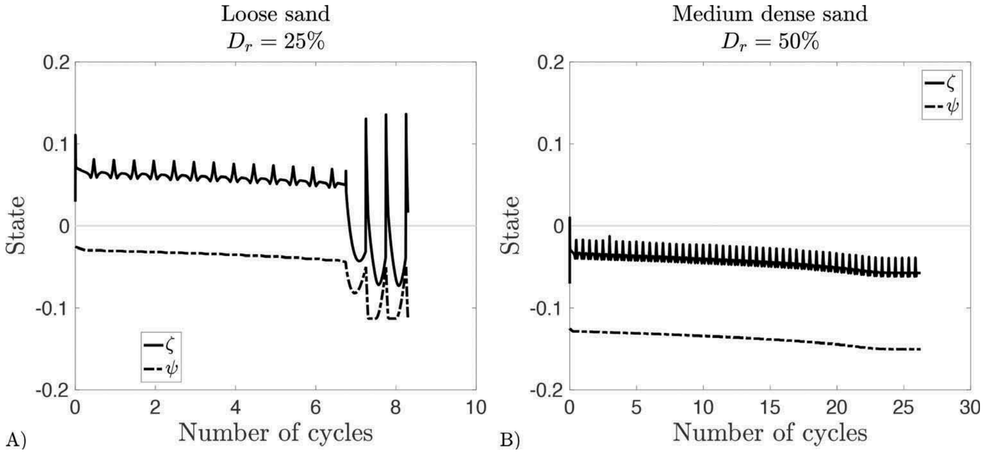

Figure 5. Evolution of the dilatancy state parameter ζ and the state parameter ψ through cycles of shearing

to be considered to fix this missing behaviour feature, which might be responsible for the inability of both models to appropriately predict large deformations associated with cyclic mobility in Figure 4.

5 CONCLUSION

In this study, numerical simulations of static and cyclic simple shear tests were compared to laboratory results for various testing conditions. It was found that greater prediction accuracy was achieved using the modified anisotropic NorSand model for the modelling of static simple shear for various void ratios, as well as for the cyclic simple shear test on loose Toyoura sand. However, predictions using the isotropic and anisotropic NorSand models yielded very similar (unsatisfactory) results for the simulation of a cyclic simple shear test on a medium dense sand.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support of the NSERC industrial research chair on the optimization of life cycle of rockfill dams and their industrial partners Hydro-Québec, SNC-Lavalin, Qualitas, WSP, Golder & Associates, Hatch, Conetec and Klohn Crippen Berger.

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