The paper was published in the proceedings of the 10th European Conference on Numerical Methods in Geotechnical Engineering and was edited by Lidija Zdravkovic, Stavroula Kontoe, Aikaterini Tsiampousi and David Taborda. The conference was held from June 26th to June 28th 2023 at the Imperial College London, United Kingdom.

Proceedings 10th NUMGE 2023
10th European Conference on Numerical Methods in Geotechnical Engineering
Zdravkovic L, Kontoe S, Taborda DMG, Tsiampousi A (eds)

https://doi.org/10.53243/NUMGE2023-186

Evaluation of DeltaSand in numerical modelling of monotonic and cyclic element tests using experimental data of Toyoura sand

M. Fetrati[1], V. Galavi[2], M. Goodarzi[1], A. Ayub[1], S. Fazlighiyasabadi[1], S. Kreiter[1], T. Mörz[1]
[1] *MARUM–Center for Marine Environmental Sciences, University of Bremen, Bremen, Germany*
[2] *DIANA FEA BV, Delft, The Netherlands*

ABSTRACT: Due to the increase of complexity in offshore foundation design, advanced soil models are now more attractive to be adopted in design, in order to predict the mechanical behaviour of sand in different soil states for a wide range of stresses and strains. Before employing a constitutive model in boundary value problems, it is crucial to validate the model and calibrate its parameters at single point testing level. In this paper, the performance of DeltaSand - a new state-dependent double hardening constitutive model for sand - is evaluated. The assessment is based on available monotonic and cyclic triaxial laboratory tests as well as oedometer tests for Toyoura sand. The simulation results of Toyoura sand demonstrate that the DeltaSand model predicts the soil behaviour under both monotonic and cyclic loading with good accuracy by using only one set of parameters.

Keywords: Constitutive soil model; Element test simulation; Monotonic and cyclic tests; Elasto-plasticity; DeltaSand

1 INTRODUCTION

Foundations in offshore wind parks are subjected to monotonic and cyclic loading from the installation stage until the end of their lifetime. These cyclic loadings originate from an installation using a vibratory hammer, wind, sea waves, and loads due to the operation of the turbine. Therefore, an advanced constitutive model that predicts soil behaviour under cyclic loading conditions is of great importance. Various state-dependent advanced constitutive models have been introduced for cohesionless soils. Some examples are: hypoplastic model with intergranular strain (Fuentes & Triantafyllidis, 2015; Niemunis & Herle, 1997; von Wolffersdorff, 1996), Sanisand model (Dafalias & Manzari, 2004) and a new double hardening soil model, DeltaSand model (Galavi, 2021).

The hypoplastic model with intergranular strain is used widely and shows a good performance in numerical modelling (Mašın & Herle, 2005; Stutz & Wuttke, 2018). It is capable of reproducing the oedometer test results accurately, for both loose and dense sand during the initial loading phase (Machacek et al., 2021). However, this model underpredicts the reloading stiffness of soil which results in excessive irreversible deformations (ratcheting) as shown in the simulation of Karlsruhe sand under cyclic loading (Duque et al., 2022; Machacek et al., 2021; Wegener & Herle, 2014; Wichtmann et al., 2019). The Sanisand model performs poorly in all stages of the oedometer test including loading, unloading and reloading (Machacek et al., 2021; Wichtmann et al., 2019). The effect of ratcheting is a shortcoming of these models under cycling loading (Bode et al., 2020; Mašín, 2019).

DeltaSand shows a good performance in both monotonic and cyclic oedometer tests at different relative densities by means of a cap yield surface formulated based on a modified Bauer's equation to calculate the slope of normal compression of sands as a function of void ratio and stress (Galavi, 2021). The use of the cap yield surface also prevents ratcheting as it serves as a memory surface, which is lacking in both the hypoplastic and Sanisand models.

The material parameters of DeltaSand model consists of two parts, the basic parameters (monotonic) and the parameters needed for cyclic loading. The cyclic part of DeltaSand can be ignored in simulations with monotonic loading, e.g. conventional CPT. Fetrati et al. (2022) simulated a quasi-static CPT in Cuxhaven sand using DeltaSand and Hardening soil models, in which the cyclic part of DeltaSand was ignored, and only the monotonic experimental data were used to calibrate the soil model.

The benefits and drawbacks of complex constitutive models can be determined through validation procedures by element tests that include a wide range of loading conditions (Dafalias & Manzari, 2004; Machacek et al., 2021). Although Galavi (2021) validated the DeltaSand model using the conventional laboratory element tests of Karlsruhe sand, the performance of the model on other types of sands is necessary in order to use the model to capture the behaviour of sandy soils.

In the present study, the capability of the DeltaSand model (Galavi, 2021) to reproduce soil behaviour under monotonic and cyclic loading was investigated based on the available undrained/drained monotonic and cyclic laboratory tests of Toyoura sand.

The element test simulations were performed with PLAXIS "SoilTest" module (Plaxis, 2021). In the following, the methodology is first explained, and then the results of simulation are compared with available experimental data for Toyoura sand.

2 METHODOLOGY

2.1 Features of DeltaSand model

DeltaSand is a state-dependent elasto-pastic model based on a double hardening framework (Vermeer, 1978) in which mechanical properties are defined as a function of relative density and stress.

The yield function in the model is formed by three parts; the deviatoric, the volumetric and the tension-cut off. The model can take different deviatoric yield surfaces such as Matsuoka-Nakai or Mohr-Coulomb. In the current study, the Mohr-Coulomb yield surface was employed. An elliptical surface with isotropic expansion is considered to describe the volumetric yield surface (cap).

The hardening-softening rule of Wan and Guo (1998) is slightly modified by (Galavi, 2021) to define the position of the yield surface as a function of plastic deviatoric strain and relative density:

$$\sin \varphi'_{mob} = \sin \varphi'_i + \frac{\epsilon_q^p f_d^{(e)}}{A+\epsilon_q^p} (\sin \varphi'_{cv} - \sin \varphi'_i) \qquad (1)$$

where A is a plastic stiffness parameter, φ'_i is the effective friction angle at which mobilisation starts, φ'_{cv} is the friction angle at constant volume and $\epsilon^p{}_q$ is the plastic deviatoric strain. $f_d^{(e)}$ in Equation (1) is a void ratio function which connects hardening-softening rule to the current void ratio. This function is responsible for the evolution of sin (φ'_{mob}) into either hardening or softening trend, depending on the current void ratio.

In order to capture the soil deformation under cyclic loading, the isotropic hardening-softening rule equation is scaled as follows (2-4):

$$\sin \varphi'_{mob,kin} = \sin \varphi'_{i,kin} + \frac{C_{scale} \epsilon_q^{*p} f_d^{(e)}}{C_{scale} A + \epsilon_q^{*p}} \left(C_{sign} \sin \varphi'_p - \sin \varphi'_{i,kin} \right) \qquad (2)$$

Where

$$\sin \varphi'_p = \max (\sin \varphi'_{cv} , \sin \varphi'_{mob}) \qquad (3)$$

$$C_{scale} = C_{cyc} . e^{Dr} - \left(C_{cyc} . e^{Dr} - 1 \right) \frac{\epsilon_q^p}{A_{mat} + \epsilon_q^p} \qquad (4)$$

where φ'_{mob} is the mobilised friction angle, $\varphi'_{i,kin}$ is the friction angle at the loading reversal point, C_{sign} is 1 for loading and -1 for unloading conditions and C_{cyc} is a scaling parameter.

2.2 Parameter calibration

The input parameters of the model (Table 1) are calibrated using the published laboratory data of Toyoura sand (Pradhan et al., 1989; Sun et al., 2007; Verdugo & Ishihara, 1996; Yang & Sze, 2011).

A comprehensive sensitivity analysis has been done to identify a set of parameters for Toyoura sand to reproduce the soil behaviour in different types of element tests. The calibration has been performed manually using conventional trial and error parameter adjustment procedure. The oedometer parameter C_{oed}, hardness parameter, h_s, power stiffness parameter, n, and elastic parameter, f_G^{ref} are carefully calibrated by adjusting the $\epsilon_v - p$ curve. The $q - \epsilon_1$ curve of monotonic triaxial test were used to calibrate α, β and A_{mat}. Parameter α controls the peak friction angle, β governs volumetric changes in drained triaxial test and pore water pressure generated in undrained triaxial tests. A_{mat} is a plastic

Table 1. DeltaSand model parameters with laboratory tests used to determine corresponding parameters

f_G^{ref} [−]	n [−]	h_s [GPa]	C_{oed} [−]	α [−]	β [−]
Oedometer test	Oedometer test	Oedometer test	Oedometer test	Drained triaxial test	Undrained triaxial test
A_{mat} [−]	**G_{ratio}** [−]	**γ_r** [−]	**C_{cyc}** [−]	**f_{dens}** [−]	
Drained triaxial test	Undrained triaxial test	Undrained triaxial test	Cyclic triaxial test	Cyclic triaxial test	

stiffness parameter and captures the curvature of $q - \epsilon_1$. Cyclic parameters, C_{cyc} and f_{dens} control the required number of cycles to reach liquefaction in cyclic triaxial tests (Galavi, 2021). The parameters G_{ratio} and γ_r control the soil behaviour in small strain ranges. These two parameters should normally be obtained from the bender element test. In case of the absence of bender element test, these two parameters were determined by calibrating the initiation of the stress path in *q-p* space in undrained triaxial tests (Galavi, 2021).

3 RESULTS AND DISCUSSION

In this section, the calibration results of Toyoura sand, are presented. The oedometer tests, monotonic and cyclic triaxial tests were employed to obtain all the required parameters and to investigate the capability of DeltaSand.

3.1 Toyoura sand

The Japanese Toyoura sand was studied by different researchers (Pradhan et al., 1989; Sun et al., 2007; Verdugo & Ishihara, 1996). The two key characteristic parameters of this sand, e_{min} and e_{max}, was taken as 0.597 and 0.977, respectively. (Prearo, 2015; Verdugo & Ishihara, 1996). The set of parameters that was obtained in calibrating process for this sand is provided in Table 2.

Table 2. DeltaSand model parameters for Toyoura sand

f_G^{ref} [−]	n [−]	h_s [GPa]	C_{oed} [−]	α [−]	β [−]	A_{mat} [−]	e_{min} [−]
2200	0.51	1.25	0.85	1.6	0.9	0.013	0.597

e_{crit} [−]	e_{max} [−]	φ'_{cv} [°]	C_{cyc} [−]	f_{dens} [−]	G_{ratio} [−]	γ_r [−]
0.923	0.977	31	1.1	10000	7	0.00035

3.1.1 Isotropic compression tests

Pradhan et al. (1989) performed a series of isotropic compression tests in loose and dense states. These tests were used to obtain the parameters $h_s, n,$ and C_{oed}. As shown in Figure 1, DeltaSand solves ratcheting problem, and has a good prediction capability for both loose and dense sand.

3.1.2 Triaxial tests

Sun et al. (2007) conducted a series of drained triaxial tests on Toyoura sand with a void ratio of 0.68. Confining stresses of 0.2 MPa, 0.5 MPa and 1.0 MPa were chosen to be used for DeltaSand calibration. Values 0.923 for e_{cr} and 31° for φ'_{cv} were selected (Prearo, 2015; Verdugo & Ishihara, 1996).

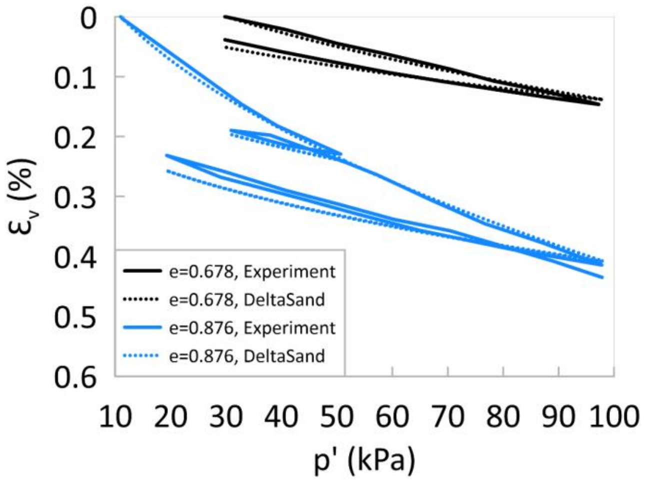

Figure 1. Isotropic compression tests for Toyoura sand

Figure 2(a) shows the $^{\sigma_{axial}}/_{\sigma_{radial}} - \varepsilon_1$ and $\varepsilon_v - \varepsilon_1$ curves in which DeltaSand underestimates the stress ratio for a confining stress of 0.2 MPa. Volumetric strains and soil stiffness are slightly overestimated.

The undrained triaxial tests for three void ratios with two confining stress are depicted in Figure 2(b). These experiments were done by Verdugo and Ishihara (1996) and were used for calibration. The stress path is well captured by DeltaSand, especially for medium-dense sand (*e*=0.735). The simulated $q - \varepsilon_1$ curves differ slightly from the experimental curves. The flow rule of DeltaSand is not stress dependent, and this might be an explanation for these discrepancies.

3.1.3 Cyclic Triaxial tests

Yang and Sze (2011) conducted a series of undrained cyclic triaxial tests. Two void ratios of 0.791 and 0.940 were chosen in this study to calibrate the cyclic part of DeltaSand. The results for the effective stress path and excess pore water pressure are presented in Figure 3. For the sand sample with void ratio of 0.791, the number of cycles to reach the zero mean effective stress is similar to the one reported in the experiment; this can be seen in Δp_w versus the number of cycles (Figure 3). DeltaSand soil model shows less loosening compared to the experiments (Figure 3(a)). For loose sand, symmetric and non-symmetric cyclic loading are used (Figures 3(b) and (c)). In both cases, samples failed suddenly in the experiments.

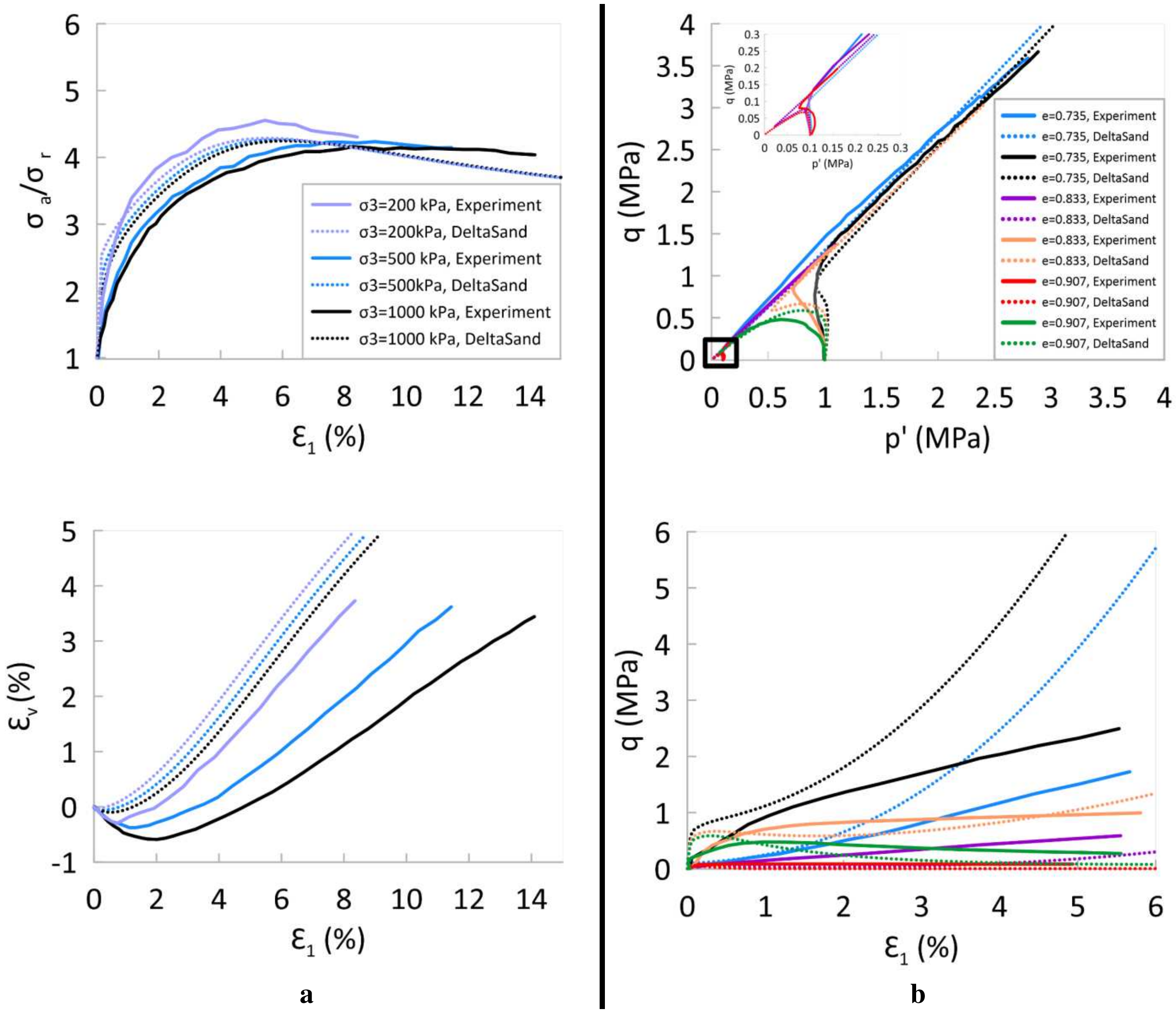

Figure 2. a) Drained triaxial tests with e=0.68, and b) undrained triaxial tests with two confining stresses of 0.1 and 1 MPa

4 CONCLUSION

In this study, the performance of the state-dependent soil model DeltaSand for Toyoura sand was evaluated through monotonic and cyclic tests. With one set of parameters, DeltaSand was able to accurately reproduce the sandy soil behaviour in various void ratios and stress states. However, the model showed some limitations as the volumetric strain was overestimated in drained triaxial tests on Toyoura sand. Despite this limitation, the results indicate that DeltaSand can be a useful tool in FEM-based geotechnical design for optimization of the design of offshore foundations and reducing project costs, as it can replicate both the monotonic and cyclic behaviour of the soil with good accuracy.

5 ACKNOWLEDGEMENTS

The authors acknowledge the support of the project “VCPTu2PDA”, FKZ: 03EE3025A by the Federal Ministry for Economic Affairs and Climate Action (BMWK). The support of RWE Renewables and COWI A/S as project partners is also greatly appreciated. Additionally, the authors would like to extend special thanks to Deltares for their contribution to developing the DeltaSand model.

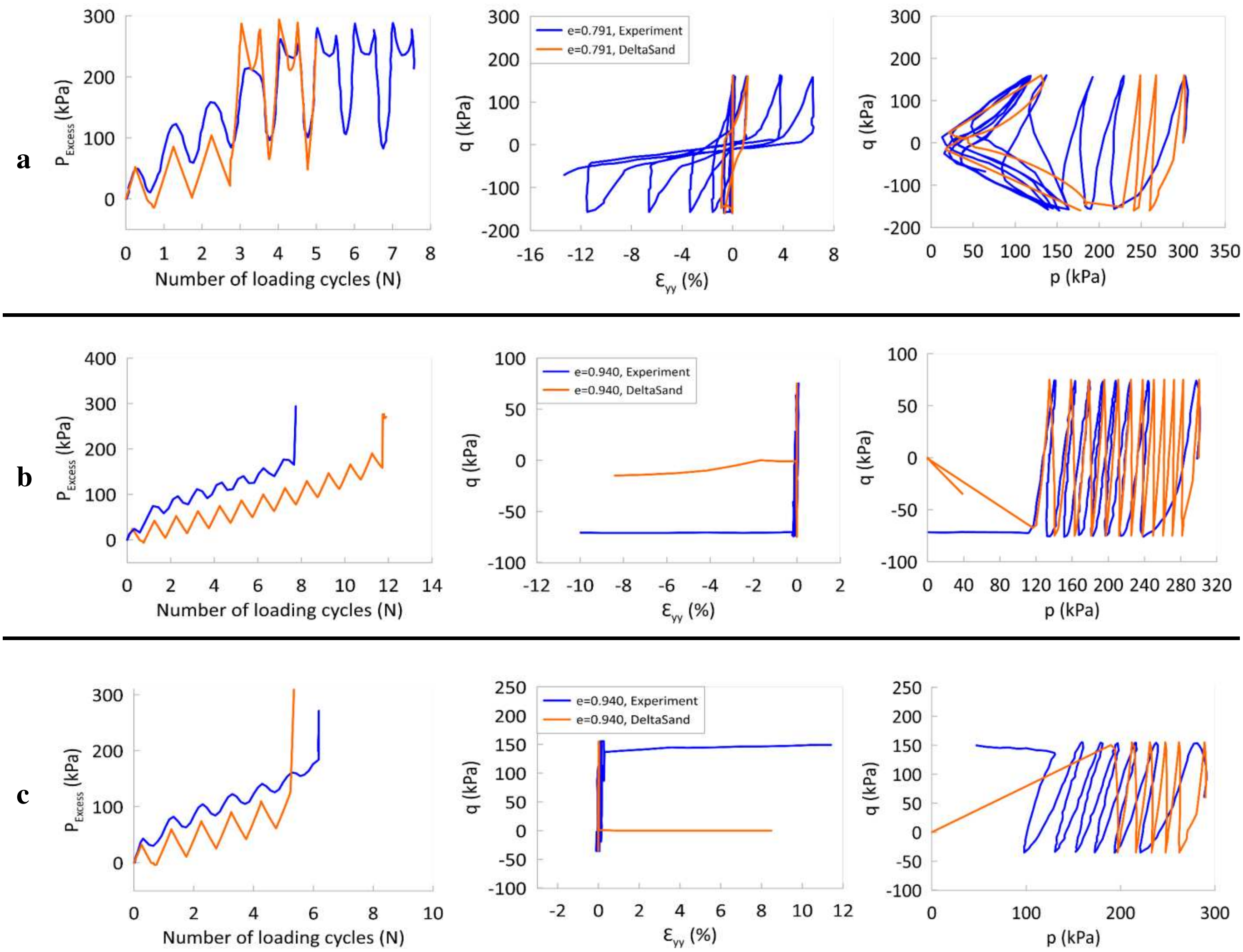

Figure 3. Undrained stress-controlled cyclic triaxial tests a) symmetrical loading on medium dense sand, b) symmetrical loading on loose sand, and c) non-symmetrical loading on loose sample

6 REFERENCES

Bode, M., Fellin, W., Mašín, D., Medicus, G., & Ostermann, A. (2020). An intergranular strain concept for material models formulated as rate equations. *International Journal for Numerical and Analytical Methods in Geomechanics*, *44*(7), 1003-1018.

Dafalias, Y. F., & Manzari, M. T. (2004). Simple plasticity sand model accounting for fabric change effects. *Journal of Engineering Mechanics*, *130*(6), 622-634. https://doi.org/10.1061/(Asce)0733-9399(2004)130:6(622)

Duque, J., Yang, M., Fuentes, W., Mašín, D., & Taiebat, M. (2022). Evaluation of four advanced plasticity and hypoplasticity models in simulating cyclic response of sands. Presentations and videos to 16th International Conference on Computational Plasticity (COMPLAS 2021).

Fetrati, M., Galavi, V., Goodarzi, M., Kreiter, S., & Mörz, T. (2022). Numerical simulation of CPT in sands using DeltaSand and Hardening Soil models. In *Cone Penetration Testing* (pp. 407-413).

Fuentes, W., & Triantafyllidis, T. (2015). ISA model: a constitutive model for soils with yield surface in the intergranular strain space. *International Journal for Numerical and Analytical Methods in Geomechanics*, *39*(11), 1235-1254.

Galavi, V. (2021). DeltaSand: A state dependent double hardening elasto-plastic model for sand: Formulation and validation. In *Computers and Geotechnics* (Vol. 129).

Machacek, J., Staubach, P., Tafili, M., Zachert, H., & Wichtmann, T. (2021). Investigation of three sophisticated constitutive soil models: From numerical formulations to element tests and the analysis of vibratory pile driving tests. *Computers and Geotechnics*, *138*. https://doi.org/https://doi.org/10.1016/j.compgeo.2021.104276

Mašín, D. (2019). Modelling of soil behaviour with hypoplasticity. *Springer Series in Geomechanics and Geoengineering, Ó Springer Nature Switzerland AG,* *https://doi.org/10.1007/978-3-030-03976-9*, *1007*, 978-973.

Mašın, D., & Herle, I. (2005). Numerical analyses of a tunnel in London clay using different constitutive models. Proceedings of the 5th international symposium TC28 geotechnical aspects of underground construction in soft ground, Amsterdam, The Netherlands,

Niemunis, A., & Herle, I. (1997). Hypoplastic model for cohesionless soils with elastic strain range. *Mechanics of Cohesive-Frictional Materials*, *2*(4), 279-299.

Plaxis. (2021). *Plaxis 2D Manual*. In Bentley Systems.

Pradhan, T. B., Tatsuoka, F., & Sato, Y. (1989). Experimental stress-dilatancy relations of sand subjected to cyclic loading. *Soils and Foundations*, *29*(1), 45-64.

Prearo, C. (2015). *Determination of cyclic resistance of clean sands from cone penetration test based on state parameters* University of Ferrara].

Stutz, H. H., & Wuttke, F. (2018). Hypoplastic modeling of soil-structure interfaces in offshore applications. *J. Zhejiang Univ. Sci. A*, *19*(8), 624-637.

Sun, D. A., Huang, W. X., Sheng, D. C., & Yamamoto, H. (2007). An Elastoplastic Model for Granular Materials Exhibiting Particle Crushing. *Key Engineering Materials*, *340-341*,1273-1278. https://doi.org/10.4028/www.scientific.net/KEM.340-341.1273

Verdugo, R., & Ishihara, K. (1996). THE STEADY STATE OF SANDY SOILS. *Soils and Foundations*.

Vermeer, P. A. (1978). A Double Hardening Model for Sand. *Géotechnique*,*28*,413-433. https://doi.org/10.1680/geot.1978.28.4.413

von Wolffersdorff, P.-A. (1996). A hypoplastic relation for granular materials with a predefined limit state surface. *Mechanics of Cohesive-Frictional Materials*, *1*, 251-271.

Wan, R. G., & Guo, P. J. (1998). A Simple Constitutive Model for Granular Soils- Modified Stress.pdf. In (Vol. 22, pp. 109-133).

Wegener, D., & Herle, I. (2014). Prediction of permanent soil deformations due to cyclic shearing with a hypoplastic constitutive model. In *Geotechnik* (Vol. 37, pp. 113-122).

Wichtmann, T., Fuentes, W., & Triantafyllidis, T. (2019). Inspection of three sophisticated constitutive models based on monotonic and cyclic tests on fine sand: Hypoplasticity vs. Sanisand vs. ISA. In *Soil Dynamics and Earthquake Engineering* (Vol. 124, pp. 172-183): Elsevier Ltd.

Yang, J., & Sze, H. Y. (2011). Cyclic behaviour and resistance of saturated sand under non-symmetrical loading conditions. *Géotechnique*, *61*(1), 59-73. https://doi.org/10.1680/geot.9.P.019