The application of the Iwan soil model on a deep excavation

L’application du modèle de sol d’Iwan sur une excavation profonde

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ABSTRACT: Based on the Iwan model, numerical simulations of well documented construction of anchored diaphragm wall supporting the 20 m deep excavation in Berlin sand were carried out. The model incorporates the critical state concept by using two sets of elastic-plastic elements, one set for the volumetric response, and the other for shear. The parameters for the model were derived from laboratory and in-situ tests on Berlin sand, and from data for some well tested sands (Erksak, Toyoura, Portaway, Ticino, Ottawa). The results show that the model is capable of describing well the observed behavior of the diaphragm wall in all construction stages. These results are compared with published results obtained by the advanced MIT-S1 model.

RÉSUMÉ : Fondées sur le modèle d’Iwan, des simulations numériques de la construction bien documentée d'une paroi moulée ancrée, soutenant l'excavation de 20 m de profondeur dans le sable de Berlin, ont été effectuées. Le modèle incorpore les concepts de la mécanique des sols de l’état critique à l'aide de deux ensembles d’éléments élastoplastiques, un ensemble pour la réponse volumétrique, et l'autre pour le cisaillement. Les paramètres du modèle ont été obtenus à partir des essais en laboratoire et in situ sur le sable de Berlin, et en utilisant les données sur des sables bien testés (Erksak, Toyoura, Portaway, Tessin, Ottawa). Les résultats montrent que ce modèle est bien capable de retracer le comportement observé de la paroi moulée dans toutes les étapes de la construction. Ces résultats se comparent bien avec les résultats publiés obtenus en utilisant le modèle avancé MIT-S1.

KEYWORDS: constitutive models, sand behavior, Iwan system, diaphragm wall, finite element analysis, critical state.

1 INTRODUCTION

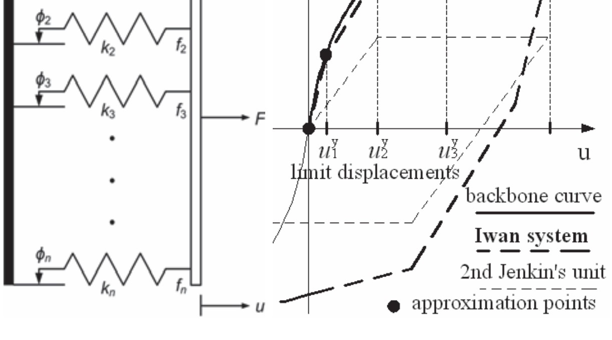
The parallel system of simple elastic-plastic elements, introduced by Iwan (1967) is very powerful tool for modeling the behavior of solid materials within the framework of continuum mechanics. The model is capable to trace almost any given stress-strain curve under steady straining and to account for unloading and reloading behavior without any extra rule. It also accounts for Masing’s rules for cycling loading (Masing, 1926) even for irregular cycles. Based on results of triaxial testing of sands, the model is developed into generalized 3D effective stress soil model for sand. The model is calibrated and verified on some well tested sands (Erksak, Toyoura, Portaway, Ticino, Ottawa) showing the great capabilities to predict the complex sand behavior in wide range of stress, strain and densities and for different drainage conditions by using a simple set of soil parameters (Sokolić, 2010).

In this paper the model is applied for simulating the performance of the support system for 20-m-mdeep excavation in Belin sand. The main goal was to validate the performance of the Iwan sand model used in complex numerical simulation, and to compare the results with published results obtained by using the advanced soil model MIT-S1 (Nikolinakou, 2011). The simple set of parameters for Berlin sand was derived by using the available results of laboratory and in-situ soil investigations together with interpretation of the results used in MIT-S1 numerical analysis.

2 IWAN SOIL MODEL

Iwan soil model consists of three characteristic units. The basic unit is Iwan three-dimensional spring-slider system that defines the development of elastic and plastic strains for any given 3D increment of strain. It is made of two separate Iwan systems (Figure 1) that distinguished shear from volumetric compression, which is often assumed in soil modeling (Colins et al. 2007). First Iwan system is used for modeling the shear behavior of sand in drained triaxial test (CID), while the second is used for the triaxial isotropic compression (ISO).

Second unit of the model is the set of material functions which describes the characteristic behavior of sand observed in triaxial testing. Material functions are used to define the shape of backbone curves under steady shearing and compression for different *‘state of sand’* (state of stress, strain and density). The backbone curves are used to calculate the strength and stiffness of each spring-slider element of 3D Iwan’s system, by using the pre-defined limit displacements of each element.



a) b)

Figure 1. One-dimensional Iwan distributed element model; a) parallel system of simple elastic-plastic elements; b) model response for primary loading and unloading

The unique shape of backbone curve is used for isotropic compression, while the shape of the shearing backbone curve depends on the *'state of sand'*.

The third unit of the model is the set of input parameters that consists of: material parameters (characteristic for each type of sand), parameters of initial conditions (initial void ratio e_0, over consolidation ratio *OCR* and K_0^{NC} coefficient for primary consolidation) and parameters of Iwan system (set of limit displacements for shearing and compression u_i^y).

Detailed description of the 1D Iwan system can be found in Iwan (1976) and Segelmen and Star (2008), and description of the generalized 3D Iwan sand model in Sokolić (2010). The model is developed within the critical state concept (Muir Wood, 1990). It accounts for following characteristics of real sand behavior:

- unique critical state line;
- single Mohr-Coulomb (MC) strength parameter for critical state (angle of internal friction for critical state);
- increase of peak strength for dense sand at low stress level
- MC failure criteria for general 3D stress space;
- high stiffness at small strains;
- stiffness reduction due to shearing;
- stress dependent dilatancy accounting for phase transformation line concept;
- limit compression line concept for isotropic compression
- development of hysteresis for unloading and reloading according to Massing rule

3 SOIL PROPERIES AND MODEL PARAMETERS

The soil profile at the site is characteristic for the geology of the central area of Berlin that consists of saturated deposits of quaternary age, reflecting three different glacial periods. Typical profile at the site includes 3-4 m of fill, overlaying three primary sandy till units: (1) S0, upper Holocene sand, approximately 6 m with lower 1-m-thick organic soil unit; (2) S1 glacial sands from the late Pleistocene period that are typically 10 m thick; and (3) S2 glacial sand from the early Pleistocene that are encountered approximately 22 m below the ground surface. The local groundwater table is located 2 m below the ground surface.

Berlin sand is poorly graded, fine-medium sand with rounded particles, which are associated with fluvio-glacial deposition. Mineral composition is mainly Quartz and Feldspar. The basic physical properties of Berlin sand are: $e_{\min} = 0.39$, $e_{\max} = 0.59$, $G_s = 2.65$, $d_{50} = 0.38$, $C_u = 3.0$; $C_z = 1.2$. When compared with other natural sands of similar particle size, shape and grading, it is apparent that Berlin sand exhibits very low formations void ratios and has a small range of formation conditions. Mechanical properties of Berlin sand were tested with detailed laboratory test program including a series of one-dimensional consolidation tests up to high confining stresses, and including drained and undrained triaxial tests for wide range of initial void ration ($e_0 = 0.43 - 0.60$) and consolidation pressure ($p' = 100$, 500 and 800 kPa). The in-situ properties of sand units were tested by heavy dynamic probing test (DPH) and cross-hole measurements of shear velocity propagation. In this study only a data available from published test results were used (Nikolinakou, 2011).

3.1 *Input parameters for Iwan sand model*

The priority in defining the input parameters for the Iwan sand model was the following:

a) *To take* material parameters directly from available published results of laboratory test or *to accept* the values adopted for MIT-S1 soil model, based on interpretation of soil investigations (Nikolinakou, 2011)
b) *To derive* the parameters to best fit the material functions used in MIT-S1 soil model (important for comparison of the numerical simulation results performed by MIT-S1 and IWAN sand model)
c) *To calibrate* the material parameters by performing the triaxial test simulations and compering the results to the available published test results
d) *To adopt* material parameters from Iwan sand model calibration performed on different types of sand (Sokolić, 2010)

Material parameters are defined for the set of material functions describing the behavior of real sand observed in triaxial tests (drained or undrained shearing and isotropic compression). All material functions are related to the *'state of sand'* which is defined by current void ratio *e*, current isotropic pressure *p'*, current critical void ratio $e_{cv}(p')$ and state index I_s, defined similarly to the standard density index:

$$I_s = (e_{cv} - e)/(e_{cv0} - e_{\min}) \qquad (1)$$

Minimum void ratio parameter is taken directly from laboratory test ($e_{\min} = 0.39$) while the in-situ profile of initial void ratio is accepted from MIT-S1 numerical model ($e_0^{S0} = 0.6$, $e_0^{S1} = 0.53$, $e_0^{S2} = 0.4$). The initial soil density is interpreted according to the DPH in situ measurements by using empirical correlations.

The initial K_0 values were not directly measured. In the MIT-S1 numerical analysis the values are interpreted according to DPH soil profile and taking in to account the geological deposition of sand layers. The following values are accepted: ($K_0^{S0} = 0.5$, $K_0^{S1} = 1.0$, $K_0^{S2} = 1.0$).

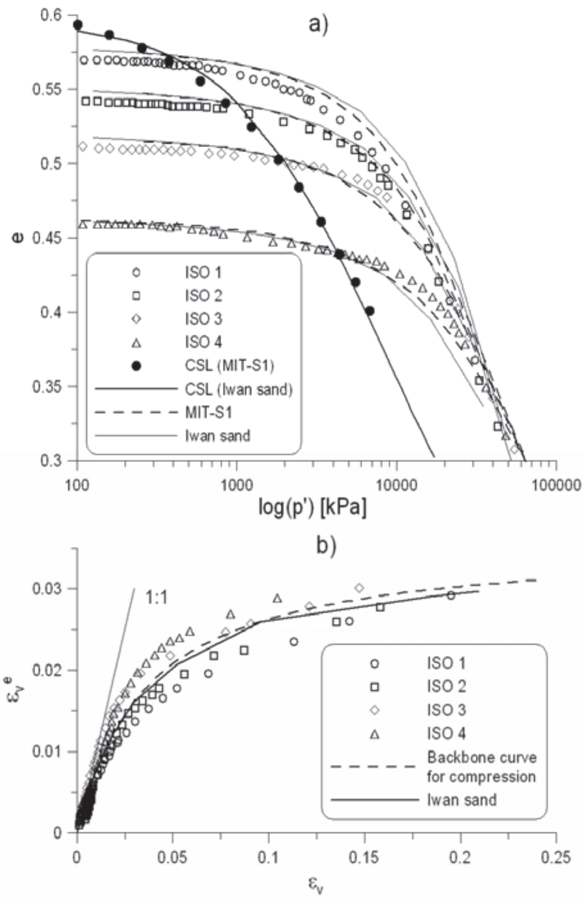


Figure 2. a) Critical state line (CSL) interpretation and comparison of predicted and 'measured' isotropic compression of Berlin sand; b) Backbone curve for isotropic compression of Berlin sand derived from odometer tests

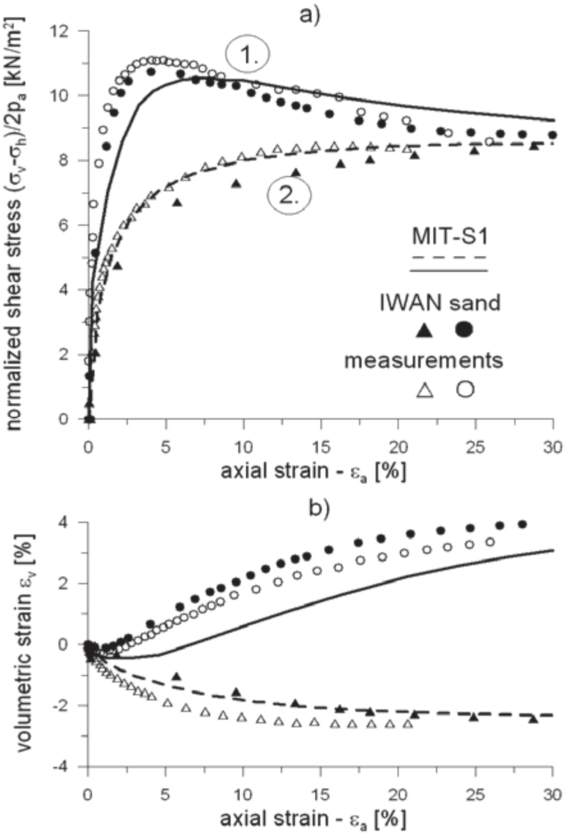


Figure 3. Comparison of predicted and measured results of CID triaxial test for danse and loose sample of Berlin sand

Table 1. Iwan sand model parameters. ($^{a)}$ material parameters for Berlin sand; $^{b)}$ initial state parameters; $^{c)}$ Iwan system parameters; * adopted from Iwan model calibration – Sokolić, 2010)

Parameter [unit]	*symbol*	*value*
$^{a)}$ Minimum void ratio	$e_{\min}$	0.389
$^{a)}$ Fiction angle for critical state [°]	φ_{cv}	31
$^{a)}$ Peak strength parameter	k_M	1.3
$^{a)}$ Initial shear stiffness parameter [kPa]	A	67.000
$^{a)}$ Power exponent for stiffness	m	0.33
$^{a)}$ Poisson's ratio	ν	0 *
$^{a)}$ Critical state line	Γ	2.35
	s_c	3544
	λ	0.385
$^{a)}$ Shear backbone curve	b	0.03 *
	a_1	0.16 *
	a_2	0.60 *
$^{a)}$ Dilatancy	d_1	2.0 *
	d_2	-0.5 *
$^{a)}$ Compression backbone curve	v	28
$^{b)}$ Initial void ratio	e_0	0.4 – 0.6
$^{b)}$ Over consolidation ratio	*OCR*	1.0
$^{b)}$ K_0 for normal consolidation	K_0^{NC}	0.5
$^{c)}$ Limit strains (20 elements) [%]	u_i^y	0.01 - 50

Critical state line (CSL) is defined by the following expression proposed by Sheng et. al. (2008):

$$e_{cv}=\Gamma/\left[(s_c+p')/p_{ref}\right]^{\lambda} \tag{2}$$

The parameters are derived to best fit the CSL line adopted for MIT-S1 soil model ($\Gamma = 2.35$, $s_c = 3544$, $\lambda = 0.385$; $p_{ref} = 100$ kPa). The value of CSL line for 'zero' isotropic pressure defines the material parameter $e_{cv0} = 0.60$ (Figure 2.a).

Shear strength is defined by following expressions (similar to concept proposed by Jeffries and Been 2006):

$$M_C = M_{cv} + k_M I_s \tag{3}$$

where M_C is the peak strength ratio for drained triaxial test ($M_c = q_p / p_p'$; q_p – peak deviator stress; p_p' – effective isotropic pressure at peak strength); M_{cv} is the strength ratio for critical state of sand ($M_{cv} = 6\sin(\varphi_{cv})/[3-\sin(\varphi_{cv})]$; $\varphi_{cv} = 31^o$ – friction angle for critical state taken from results of triaxial tests). Peak strength parameter $k_M = 1.3$ is calibrated by numerical simulations of CID test and by comparing the results to the available measurements (Figure 3.a).

Initial shear stiffness of the sand G_0 is defined by following expression (proposed by Pestana and Salvati 2006):

$$G_0 = A e^{-1.3}\left(p'/p_{ref}\right)^m \tag{4}$$

where $m = 0.33$ is power index accepted as proposed for MIT-S1 soil model, and $A = 67.000$ kPa is initial shear stiffness parameter derived to best fit the initial stiffness profile proposed for MIT-S1 numerical simulation.

Backbone curve for isotropic compression is defined by following expression (hyperbola):

$$\varepsilon_v^e = \varepsilon_v / \left(1+v\varepsilon_v\right) \tag{5}$$

where ε_v^e is elastic component of volumetric strain, ε_v is natural volumetric strain and $v = 28$ is material parameter for sand compression derived as best fit approximation of isotropic test results (Figure 2.b). The odometer tests performed on Berlin sand are interpreted as isotropic compression tests by using K_0 value according to Jaky's correlation $K_0 = 1-\sin\varphi = 0.5$.

All remaining material parameters are adopted from model calibration preformed on different types of sand (Erksak, Otawa, Ticino, Toyoura, Boštanja, Cambria). Parameters are used for backbone curve of triaxial shearing (double hyperbola function similar to stiffness reduction curve proposed by Fahey and Carter 1993) and stress dependent dilatancy function (integrated function as combination of expressions proposed by Li and Dafalias 2000, and Gutierrez 2003).

Input parameters for Iwan system are also adopted from model calibration (number of spring-slider elements $n_{Iw} = 20$; limit displacements for shearing and compression for each element spanning evenly the range of strains 0.01% to 50% in logarithmic scale).

4 NUMERICAL ANALYSIS

Numerical analysis of deep excavation are performed within the commercial finite-element program Plaxis 2D (Brinkgrawe, 2008). The geometry and boundary conditions of the model are adopted from the numerical analysis performed by the advanced model MIT-S1 (Nikolinakou, 2011). Two wall sections were analyzed (MQ3 and MQ5). Soil profile is modeled by three horizontal soil layers with underground water level 2 m below the surface level.

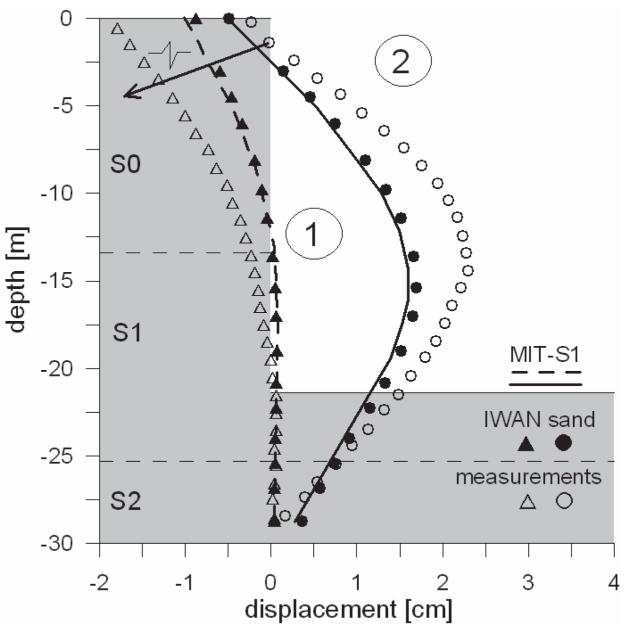


Figure 4. Comparison of measured and predicted displacement of diaphragm wall at MQ3 profile (excavation depth = 21.4 m; wall thickness = 1.5 m, height = 28.78 m; anchor free length = 34.5 m, fixed length = 8.0 m, dip angle = 35 °, prestress = 540 kN, spacing = 1.0 m); (1) – prestressing of geotechnical anchor; (2) – final excavation.

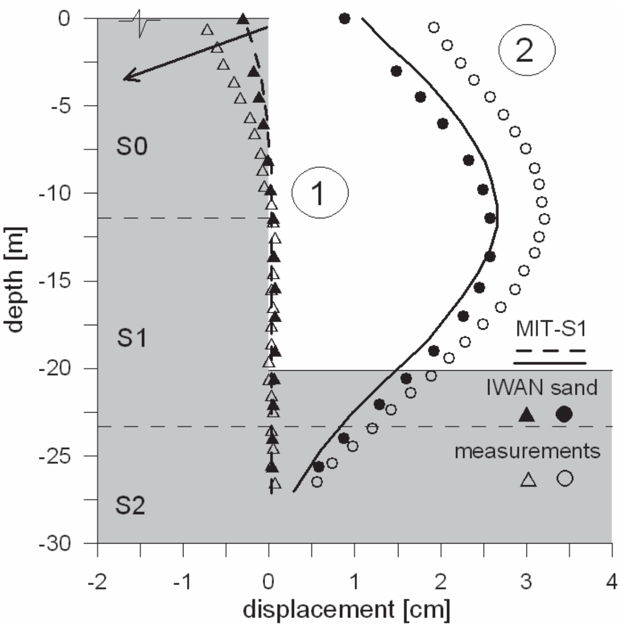


Figure 5. Comparison of measured and predicted displacement of diaphragm wall at MQ5 profile (excavation depth = 20.1 m; wall thickness = 1.2 m, height = 27.20 m; anchor free length = 26.5 m, fixed length = 8.0 m, dip angle = 25 °, prestress = 292 kN, spacing = 1.2 m);; (1) – prestressing of geotechnical anchor; (2) – final excavation

The retaining structure is modeled by using plate elements for diaphragm wall and using anchor / geotextile elements for geotechnical anchors. The analysis is performed in three characteristic phases: (0) – excavation to the anchor installation level; (1) – installation and pre stressing of the anchor; (2) – excavation to the final depth. Detailed information about structure elements, geometry of the excavation pit and material properties can be found in Nikolinakou (2011).

5 DISCUSSION AND CONCLUSION

A numerical simulation of isotropic compression of Berlin sand (Figure 2.a) shows the capability of the IWAN model to predict the volumetric strain development following the concept of limit compression line. IWAN model accurately predicts measured sand behavior, and overall behave similarly to the MIT-S1 soil model.

Numerical simulation of drained triaxial tests (Figure 3.a) shows the capability of the IWAN model to predict the real sand behavior of dense and loose samples. Comparing the results to the results gained by MIT-S1 soil model, the prediction of peak strength, stress reduction and dilatancy is more accurate.

Prediction of displacements for the deep excavation using IWAN model (Figure 4 and 5) are similar to predictions using MIT-S1 model. Minor deviation of results can be observed for the final excavation depth on MQ5 profile while all other simulations give almost same results. Comparing predictions to inclinometer measurements of wall displacements, the same trend can be observed. For the case of anchor prestressing wall displacements are toward the back soil, and attain typical shape of inward movement for the final excavation.

Observed results add to the confidence of using IWAN soil model in complex numerical simulation. The model predicts well real sand behavior for wide range of stress, strain and densities by using a single set of input parameters. Material parameters for the shear and dilatancy, calibrated to several sand types, may be used with confidence, while the basic parameters can be derived from basic laboratory and in situ tests.

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