PLAXIS implementation of HYPOPLASTICITY

including standalone ABAQUS *umat* subroutines

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Chapter 1

INTRODUCTION

This page is a part of a research project www.soilmodels.info. The aim of this page is to provide user defined subroutine *umat* for the hypoplastic constitutive models, together with an interface for PLAXIS user defined subroutine *UsrMod*.

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Chapter 2

IMPLEMENTED MODELS - LITERATURE SOURCES

For details of material models available at this web site in the form of finite element implementation, the interested readers are referred to the journal publications. The following literature sources are relevant:

1. **Sand hypoplasticity model**:
   Model formulation is described in von Wolffersdorff (1996) [9]. For details of model calibration procedure, see Herle and Gudehus (1999) [2]. Small strain stiffness formulation (so-called intergranular strain concept) is described in Niemunis and Herle (1997) [8].

2. **Clay hypoplasticity model**:
   The implemented model has been published by Mašín (2013) [6]. This model is an anisotropic version of the general clay hypoplasticity model described thoroughly in Mašín [5]. Structure of the anisotropic stiffness matrix described in Mašín and Rott [7]. Structured-soil specific model features are described in Mašín (2007) [4]. The model can be used with the intergranular strain concept, its original formulation is in Niemunis and Herle (1997) [8], enhanced formulation implemented is in Mašín (2013) [6]. Most of the cited journal papers available here for free download in the form of PDF preprints.

Further details on calibration of material parameters of hypoplastic models can be found here.

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Nova, A. Niemunis, M. Pastor, C. Tamagnini, and G. Viggiani. The soilmodels.info project. International Journal for Numerical and Analytical Methods in Geomechanics, 32(12):1571-1572, 2008. [Letter PDF]

Chapter 3

TIME INTEGRATION

Constitutive models are integrated using explicit adaptive integration scheme with local substepping. The constitutive model forms an ordinary differential equation of the form

$$\frac{dy}{dt} = f(t, y)$$

The equation is for finite time step size Δt solved using the Runge-Kutta method. Solutions that correspond to the second- and third- order accuracy of Taylor series expansion are given by

$$y^{(2)}_{(t+\Delta t)} = y_{(t)} + k_2$$
$$y^{(3)}_{(t+\Delta t)} = y_{(t)} + \frac{1}{6}(k_1 + 4k_2 + k_3)$$

where

$$k_1 = \Delta t\ f\left(t, y_{(t)}\right)$$
$$k_2 = \Delta t\ f\left(t + \frac{\Delta t}{2}, y_{(t)} + \frac{k_1}{2}\right)$$
$$k_3 = \Delta t\ f\left(t + \Delta t, y_{(t)} - k_1 + 2k_2\right)$$

The accuracy of the solution is estimated following Fehlberg as the difference between the second- and third- order solutions. The time step size Δt is accepted, if

$$err = \left\| y^{(3)}_{(t+\Delta t)} - y^{(2)}_{(t+\Delta t)} \right\| < TOL$$

where TOL is a prescribed error tolerance. If the step-size Δt is accepted, $y^{(3)}_{(t+\Delta t)}$ is considered as a solution for the given time step and the new time step size Δt^n is estimated according to Hull

$$\Delta t^n = \min\left[4\Delta t, 0.9\Delta t\left(\frac{TOL}{err}\right)^{1/3}\right]$$

If the step-size Δt is not accepted, the step is re-computed with new time step size

$$\Delta t^n = \max\left[\frac{\Delta t}{4}, 0.9\Delta t\left(\frac{TOL}{err}\right)^{1/3}\right]$$

In the case the prescribed minimum time step size or the prescribed maximum number of time substeps is reached, the finite element program is asked to reject the current step and to decrease the size of the global time step.

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Chapter 4

INPUT OF PARAMETERS AND STATE VARIABLES IN PLAXIS

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4.1 Hypoplastic model for granular materials

Parameters are specified in the PLAXIS input in the following order:

- Parameter 1 – critical state friction angle φ_c
- Parameter 2 – p_t – shift of the mean stress due to cohesion. The effective stress $\boldsymbol{\sigma}$ used in the model formulation is replaced by $\boldsymbol{\sigma} - \mathbf{1}p_t$. Non-zero value of p_t is needed to overcome problems with stress-free state. If $p_t = 0$, it will be replaced by a default value of 1 kPa. Any other value can be input by user (for basic hypoplasticity, set p_t to very low number, e.g. $p_t = 1.e - 5$).
- Parameters 3-9 – parameters of the basic hypoplastic model for granular materials h_s, n, e_{d0}, e_{c0}, e_{i0}, α, β.
- Parameters 10-14 – the intergranular strain concept parameters (m_R, m_T, R, β_r, χ). If $m_R = 0$ the intergranular strain concept is switched off and the problem is simulated using the basic hypoplastic model.

- Parameter 15 – not used.
- Parameter 16 – initial void ratio corresponding to the zero mean stress e_0 or initial void ratio e. If $Par(16) < 10$, then e is calculated from the mean stress p and from $e_0 = Par(16)$ using Bauer [1] formula. If $Par(16) > 10$, then $e = Par(16) - 10$.
- Parameters 17-22 – initial values of the intergranular strain tensor $\boldsymbol{\delta}$ in Voigt notation (δ_{11}, δ_{22}, δ_{33}, $2\delta_{12}$, $2\delta_{13}$, $2\delta_{23}$).

State variables:
The routine uses 14 state variables:

- State v. 1-6 – intergranular strain tensor $\boldsymbol{\delta}$ in Voigt notation (δ_{11}, δ_{22}, δ_{33}, $2\delta_{12}$, $2\delta_{13}$, $2\delta_{23}$).
- State v. 7 – void ratio e.
- State v. 8 – not used.
- State v. 9 – Effective mean stress.
- State v. 10 – Number of evaluation of the constitutive model in one global time step (for postprocessing only).
- State v. 11 – Mobilised friction angle φ_{mob} in degrees (for postprocessing only).
- State v. 12 – Normalised length ρ of the intergranular strain tensor $\boldsymbol{\delta}$ (for postprocessing only).
- State v. 13 – Suggested size of the first time substep (for calculation controll).
- State v. 14 – free.

The hypoplastic model for granular materials is implemented via user defined subroutine usermod. To use the model in PLAXIS, copy the files UDSM_HPS.dll and UDSM_HPS64.dll into the PLAXIS installation directory. Then, select "user-defined model" from the Material model combo box in the General tab sheet (Fig. 4.1). (Fig. 4.1). After selecting the user-defined model, correct user-defined dynamic library (typically UDSM_HPS.dll) needs to be selected in the "Available DLL's" combo box under "Parameters" tab sheet. In the "Models in DLL" combo box, model with ID 1 (Hypoplas. - sand) must be selected. The parameters can then be input into the parameter table (Fig. 4.2).

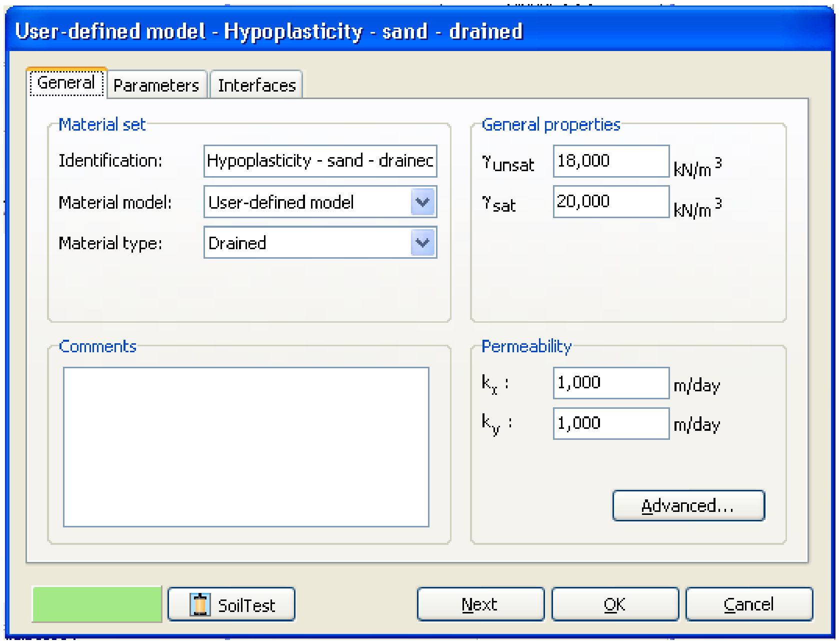

Figure 4.1: Selecting user defined model in the Material model combo box.

Parameters of the sand hypoplastic model for different soils have been evaluated by Herle and Gudehus [2]. They are given in Table 4.1. Parameters of the intergranular strain concept for granular materials are in Tab. 4.2.

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4.2 Hypoplastic model for clays

Parameters are specified in the PLAXIS input in the following order:

Parameters:

- Parameter 1 – critical state friction angle φ_c

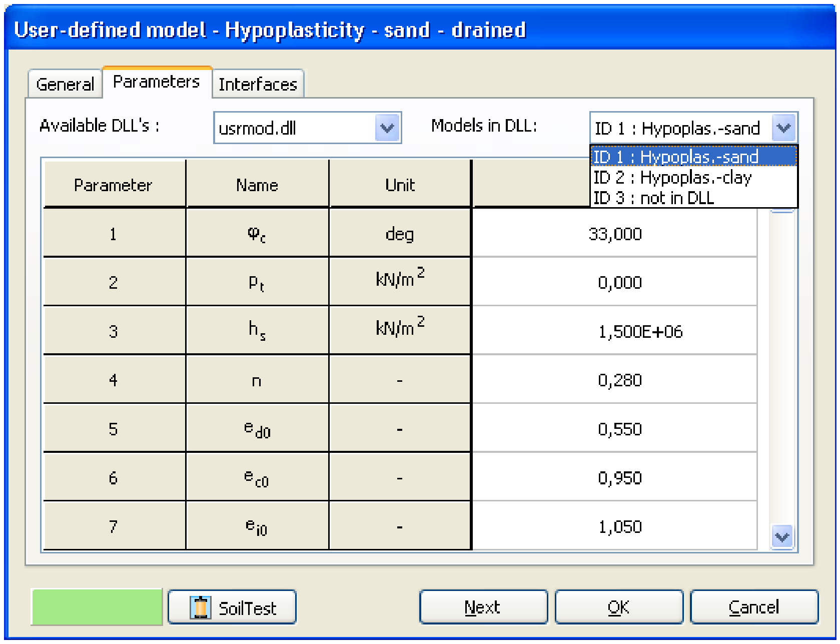

Figure 4.2: Selecting sand hypoplasticity model in the "Parameters" tab sheet.

- Parameter 2 – p_t – shift of the mean stress due to cohesion. The effective stress $\boldsymbol{\sigma}$ used in the model formulation is replaced by $\boldsymbol{\sigma} - \mathbf{1}p_t$. Non-zero value of p_t is needed to overcome problems with stress-free state. If $p_t = 0$, it will be replaced by a default value of 1 kPa. Any other value can be input by user (for basic hypoplasticity, set p_t to very low number, e.g. $p_t = 1.e - 5$).
- Parameters 3-5 – parameters of the basic hypoplastic model for clays λ^*, κ^*, N.
- Parameters 6 – Parameters of the basic hypoplastic model for clays ν_{pp} (in place of the parameter r of the Mašín (2005) [3] model, calibrated using the same procedure).
- Parameters 7 – α_G, ratio of horisontal and vertical shear moduli.
- Parameters 8-10 – parameters of the model for clays with meta-stable structure (k, A and s_f).
- Parameters 11-13 – Intergranular strain concept parameters R, β_r, χ.

	φ_c	h_s	n	e_{d0}	e_{c0}	e_{i0}	α	β
Hochstetten gravel	36°	32 $\times 10^6$ kPa	0.18	0.26	0.45	0.5	0.1	1.9
Hochstetten sand	33°	1.5 $\times 10^6$ kPa	0.28	0.55	0.95	1.05	0.25	1.5
Hostun sand	31°	1.0 $\times 10^6$ kPa	0.29	0.61	0.96	1.09	0.13	2
Karlsruhe sand	30°	5.8 $\times 10^6$ kPa	0.28	0.53	0.84	1	0.13	1
Lausitz sand	33°	1.6 $\times 10^6$ kPa	0.19	0.44	0.85	1	0.25	1
Toyoura sand	30°	2.6 $\times 10^6$ kPa	0.27	0.61	0.98	1.1	0.18	1.1

Table 4.1: *Typical parameters of the hypoplastic model for granular materials (Herle and Gudehus [2])*

	R	m_R	m_T	β_r	χ
Hochstetten sand	1.e-4	5.0	2.0	0.5	6

Table 4.2: *Parameters of the intergranular strain concept for sandy soils (Niemunis and Herle [8])*

- Parameters 14-15 – Very small strain shear stiffness parameters A_g and n_g. If $A_g = 0$ the intergranular strain concept is switched off and the problem is simulated using the basic hypoplastic model.
- Parameters 16 – Intergranular strain concept parameter m_{rat}.
- Parameter 17 – bulk modulus of water K_w for undrained analysis using the penalty approach with user-defined value of K_w. In drained analysis, consolidation analysis, and undrained analysis using PLAXIS option *undrained* K_w should be set to 0.
- Parameter 18 – Specifies vertical direction (set to 2 in PLAXIS2D, 3 in PLAXIS3D, 2 in SoilTest independently whether run from PX2D or PX3D).
- Parameter 19 – Parameter α_E (ratio of horizontal and vertical Young moduli). If set to zero, than calculated automatically from empirical formulation $\alpha_E = \alpha_G^{(1/0.8)}$.
- Parameter 20 – Parameter α_ν (ratio of horizontal and vertical Poisson ratios). If set to zero, than calculated automatically from empirical formulation $\alpha_\nu = \alpha_G$.

- Parameter 21 – Parameter α_f. Additional control of non-linearity inside state boundary surface. If set to zero, default value calculated from model parameters is used.
- Parameter 22 – initial void ratio e or overconsolidation ratio OCR. If $Par(19) < 10$, then $e = Par(19)$. If $Par(19) > 10$, then $OCR = Par(19) - 10$.
- Parameters 23-28 – initial values of the intergranular strain tensor $\boldsymbol{\delta}$ in Voigt notation (δ_{11}, δ_{22}, δ_{33}, $2\delta_{12}$, $2\delta_{13}$, $2\delta_{23}$).
- Parameter 29 – initial value of sensitivity (model for clays with meta-stable structure). If $s = 0$, the basic model is used.

State variables:
The routine uses 16 state variables:

- State v. 1-6 – intergranular strain tensor $\boldsymbol{\delta}$ in Voigt notation (δ_{11}, δ_{22}, δ_{33}, $2\delta_{12}$, $2\delta_{13}$, $2\delta_{23}$).
- State v. 7 – void ratio e.
- State v. 8 – Excess pore pressure u for undrained analysis using user-defined value of K_w. In undrained analysis using PLAXIS option *undrained* this variable is equal to 0 end excess pore pressure may be found in standard PLAXIS menu.
- State v. 9 – Effective mean stress.
- State v. 10 – Number of evaluation of the constitutive model in one global time step (for postprocessing only).
- State v. 11 – Mobilised friction angle φ_{mob} in degrees (for postprocessing only).
- State v. 12 – Normalised length ρ of the intergranular strain tensor $\boldsymbol{\delta}$ (for postprocessing only).
- State v. 13 – Suggested size of the first time substep (for calculation controll).
- State v. 14 – sensitivity s (for model with meta-stable structure).
- State v. 15 – overconsolidation ratio, defined as $OCR = p_e/p$.

- State v. 16 – 0 means model interation goes without problem. 1 means state boundary surface cut-off has been activated.

The hypoplastic model for granular materials is implemented via user defined subroutine usermod. To use the model in PLAXIS, copy the files UDSM_HPS.dll and UDSM_HPS64.dll into the PLAXIS installation directory. Then, select "user-defined model" from the Material model combo box in the General tab sheet (Fig. 4.1). After selecting the user-defined model, correct user-defined dynamic library (typically UDSM_HPS.dll) needs to be selected in the "Available DLL's" combo box under "Parameters" tab sheet. In the "Models in DLL" combo box, model with ID 2 (Hypoplas. - clay) must be selected. The parameters can then be input into the parameter table (Fig. 4.3).

Parameters of the clay hypoplastic model for different soils have been evaluated by Mašín and co-workers. They are given in Table 4.3. Parameters of the model for clays with meta-stable structure are in Tab. 4.4 and typical parameters of the intergranular strain concept for fine-grained soils are in Tab. 4.5.

	φ_c	λ^*	κ^*	N	ν_{pp}	α_G
Brno clay	22°	0.128	0.015	1.51	0.33	1.35
London clay	21.9°	0.095	0.015	1.19	0.1	2
Kaolin	27.5°	0.065	0.01	0.918	0.35	-
Dortmund clay	27.9°	0.057	0.008	0.749	0.38	-
Weald clay	24°	0.059	0.018	0.8	0.3	-
Koper silt	33°	0.103	0.015	1.31	0.28	-
Fujinomori clay	34°	0.045	0.011	0.887	0.36	-
Pisa clay	21.9°	0.14	0.01	1.56	0.31	-
Beaucaire clay	33°	0.06	0.01	0.85	0.21	-
Trmice clay	18.7°	0.09	0.01	1.09	0.09	-

Table 4.3: *Typical parameters of the hypoplastic model for clays.*

For estimation of α_G, see database from [7], here for free download in the form of PDF preprint.

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	k	A	s_f
Pisa clay	0.4	0.1	1
Bothkennar clay	0.35	0.5	1

Table 4.4: *Typical parameters of the model for clays with meta-stable structure (from [4])*

	R	β_r	χ	A_g	n_g	m_{rat}
London clay (data Gasparre)	5.e-5	0.08	0.9	270	1	0.5
Brno clay (nat.)	1e-4	0.2	0.8	5300	0.5	0.5

Table 4.5: *Typical parameters of the intergranular strain concept for clays*

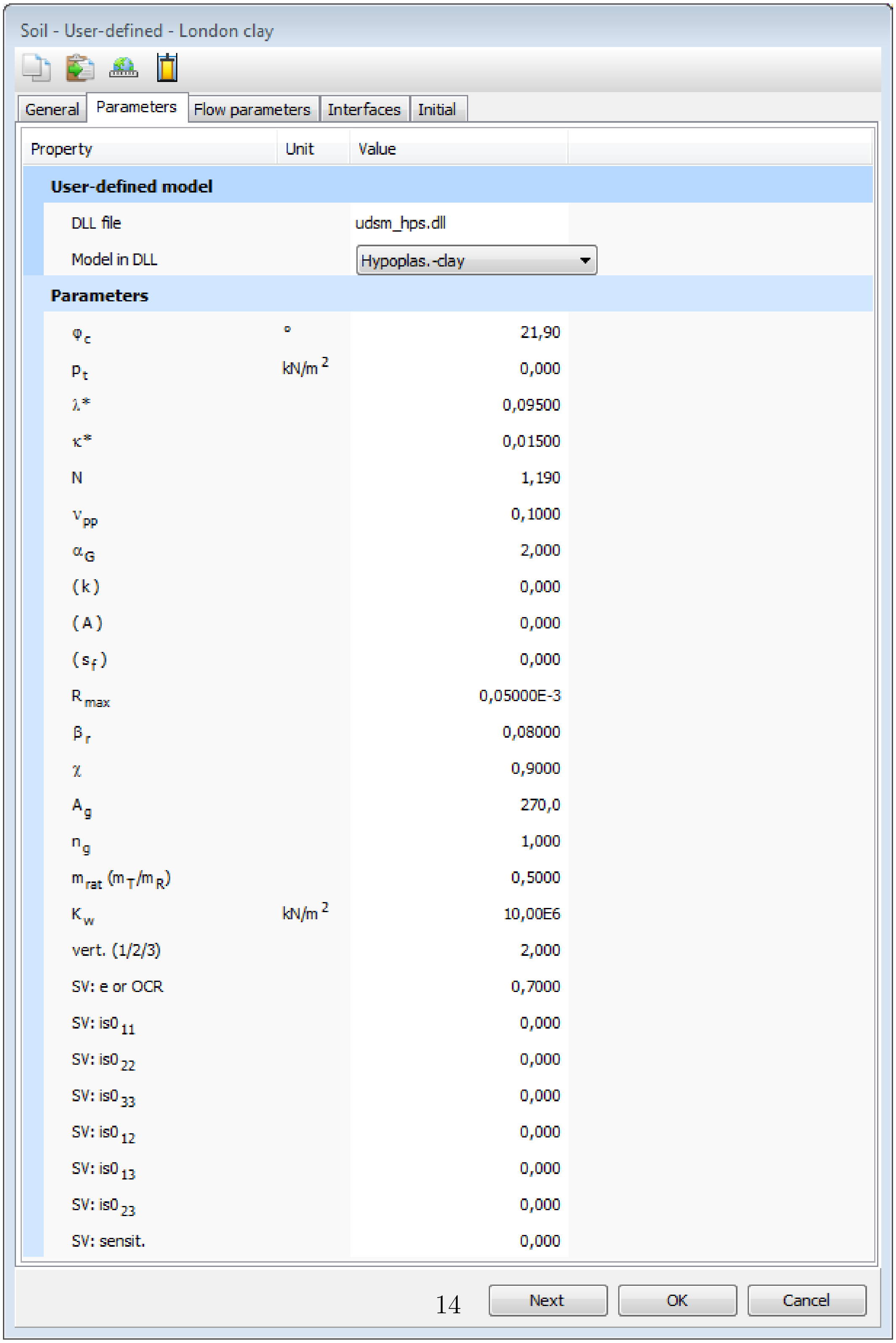

Figure 4.3: Selecting clay hypoplasticity model in the "Parameters" tab sheet.

Chapter 5

EXAMPLES

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5.1 Excavation in sand

The example of the excavation is taken over from PLAXIS manual; the problem is simulated with sand hypoplasticity model. Soil parameters of the sand correspond to the Hochstetten sand from Tab. 4.1; the intergranular strain parameters used are in Tab. 4.2. The sand is in a medium dense state with e_0=0.85.

Fig. 5.1 shows total displacements. Fig. 5.2 shows the normalised length of the intergranular strain tensor. The normalised length of the intergranular strain tensor varies between 0, which indicates the soil being inside the elastic range, and 1, corresponding to the state swept-out of the small-strain memory. In the case of the normalised length of the intergranular strain being equal to 1 the soil behaviour is governed by the basic hypoplastic model. Indeed, Fig. 5.2 shows that this is the case of an excavation, the soil below the bottom of the excavation and behind the wall is outside the small-strain-stiffness range. Fig. 5.3 shows mobilised friction angle, indicating emerging failure mechanism.

Input file for this example may be downloaded in Sec. 8.

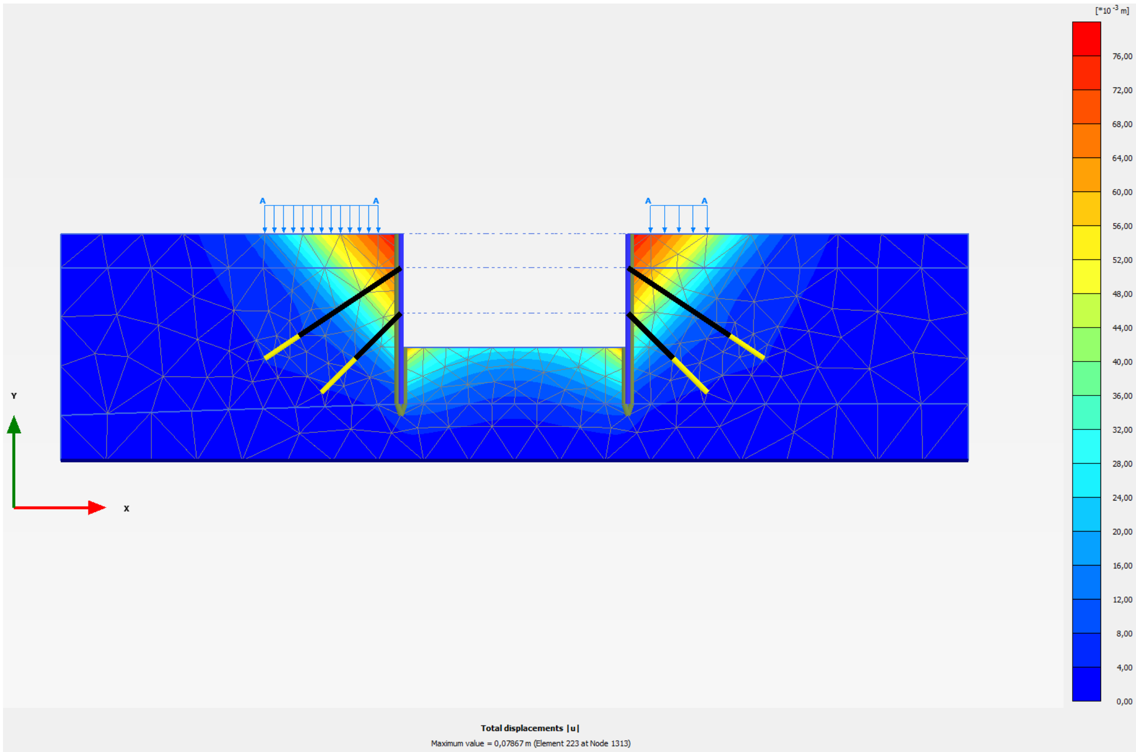

Figure 5.1: Excavation in sand - total displacement.

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5.2 NATM tunnel in clay

In this example, an NATM tunnel excavated in stiff clay is simulated. The clay is simulated with London clay parameters (Tab. 4.3 for parameters of the basic model; Tab 4.5. for the intergranular strain parameters), with the initial value of void ratio equal to 0.7.

Figure 5.4 shows the displacement field predicted by the anisotropic stiffness

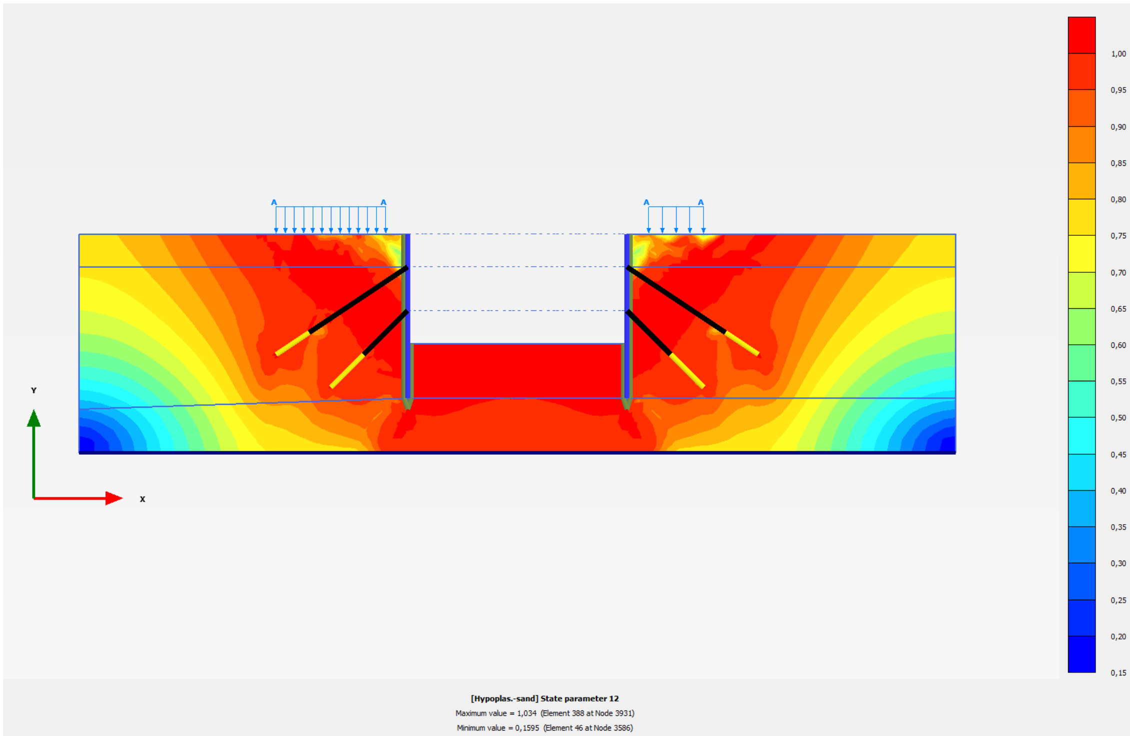

Figure 5.2: Excavation in sand - normalised length of the intergranular strain tensor.

model with $\alpha_G = 2$, whereas 5.5 shows the displacement field predicted by the model with $\alpha_G = 1$. Clearly, the anisotropic model predicts narrower and deeper surface settlement trough, which agrees better with monitored data. This is also clear from the settlement trough shown in Fig. 5.6. There, also predictions by the Mašín (2005) model [3] are included, which are close to the predictions by the isotropic model. Fig. 5.7 shows the normalised length of the intergranular strain tensor. The normalised length of the intergranular strain tensor in Fig. 5.7 demonstrates how the small-strain stiffness is activated in different parts of the modelled geometry.

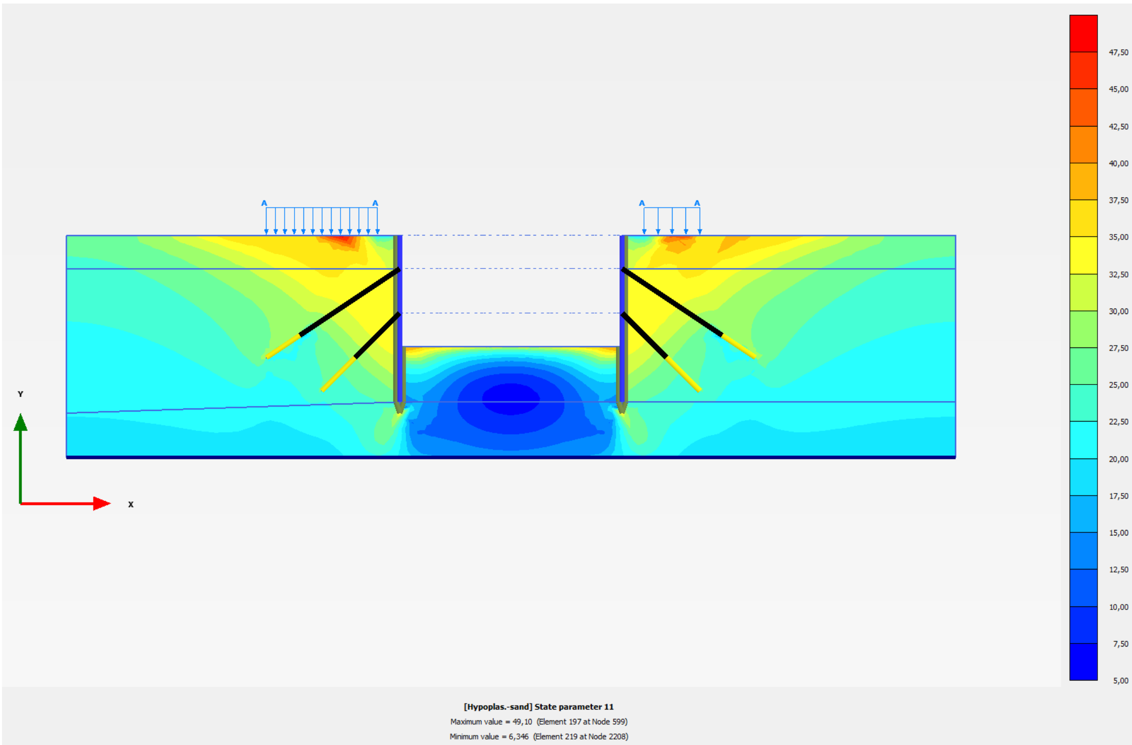

Figure 5.3: Excavation in sand - mobilised friction angle.

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5.3 Building subjected to an earthquake

This example demonstrates capabilities of a hypoplastic model in dynamic analysis of the earthquake impact on existing infrastructure. A real accelerogram of an earthquake recorded by USGS in 1989 is used for the analysis.

The building consists of 4 floors and a basement. It is 6 m wide and 25 m high. The subsoil consists of a sand with water level reaching the surface. The

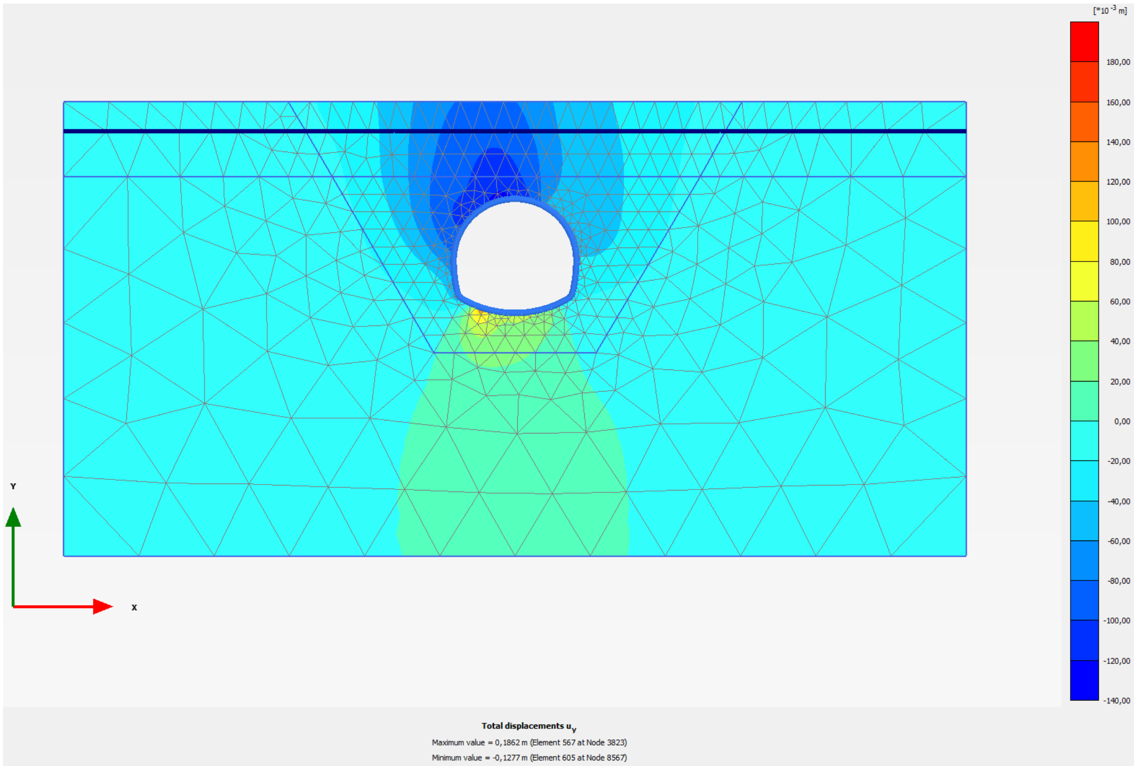

Figure 5.4: NATM tunnel construction - vertical displacement field predicted by the anisotropic model.

soil behaviour during the earthquake is considered as undrained. Two cases were simulated. In one case, the soil is in a loose state ($e_0 = e_{c0}$), in the second case the soil is in a dense state (e_0 is close to e_{d0}). Hypoplastic model parameters of the Hochstetten sand from Tab. 4.1 and the intergranular strain parameters from Tab. 4.2 are adopted.

Overall displacements of the top of the building are shown in Fig. 5.8. The soil response to the earthquake depends significantly on the soil state. The loose soil liquefies after 3-4 s of the earthquake, leading to the failure. The analysis cannot continue and fails. The displacements are much lower in the case of dense soil. Although some displacements occur also in this case, the soil retains some bearing capacity sufficient to overcome the failure.

Figure 5.9 shows total displacements after approx. 4 s of earthquake for the loose soil case, whereas Figure 5.10 shows the displacements at the same time (and in the

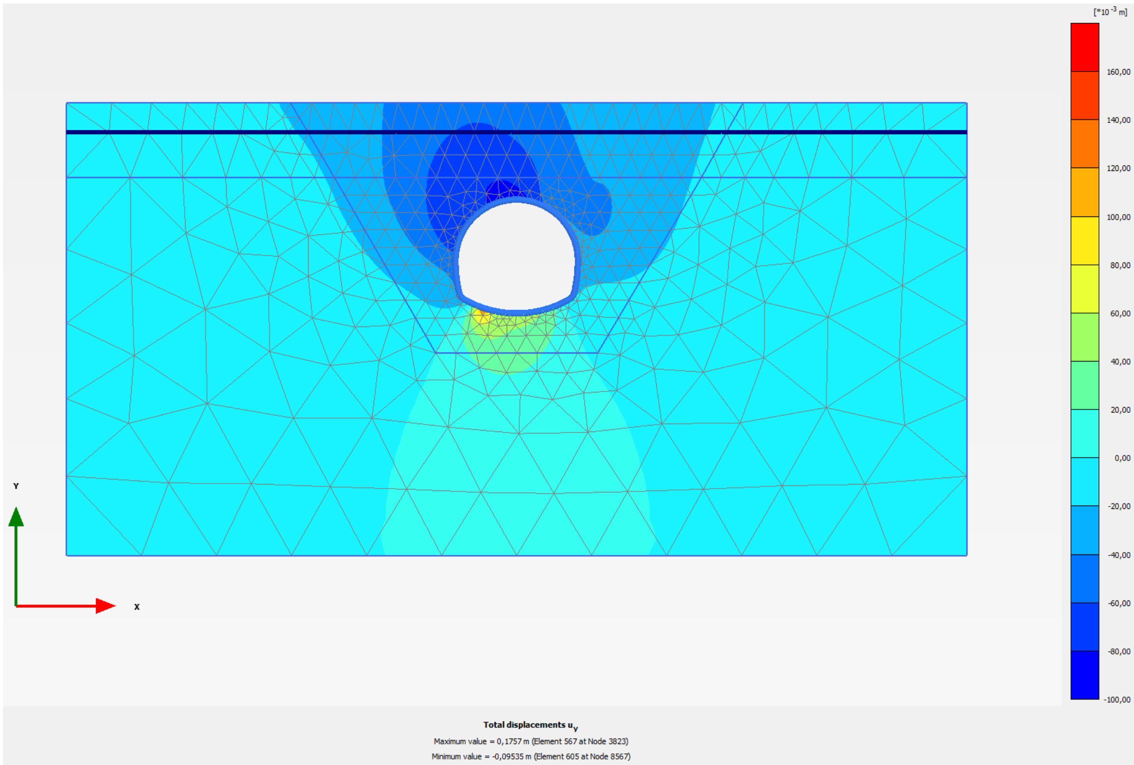

Figure 5.5: NATM tunnel construction - vertical displacement field predicted by the isotropic model.

same scale) for the dense soil. The figures indicate foundation failure for the loose soil case and relatively low displacements for the dense soil case.

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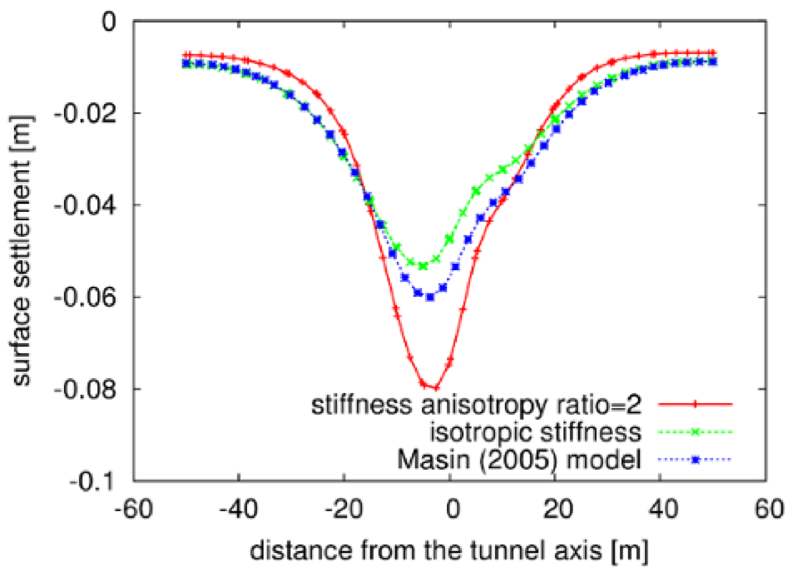

Figure 5.6: NATM tunnel construction - surface settlement troughs predicted by different models.

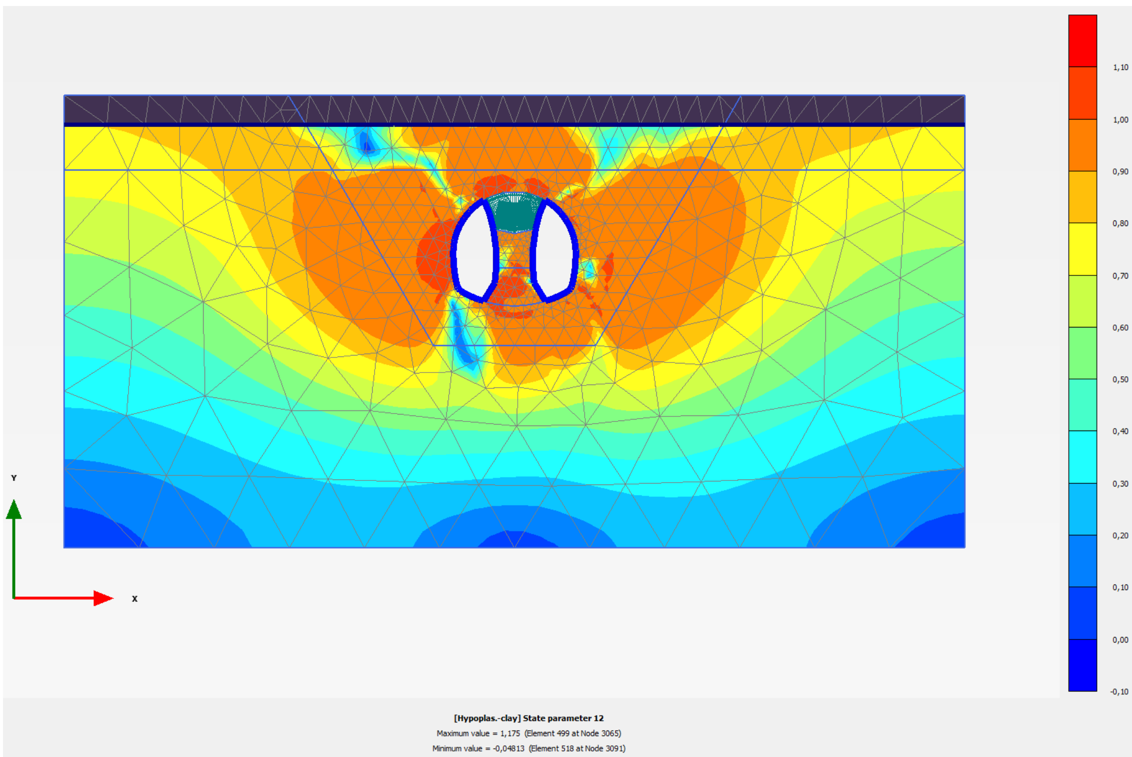

Figure 5.7: NATM tunnel construction - normalised length of the intergranular strain tensor.

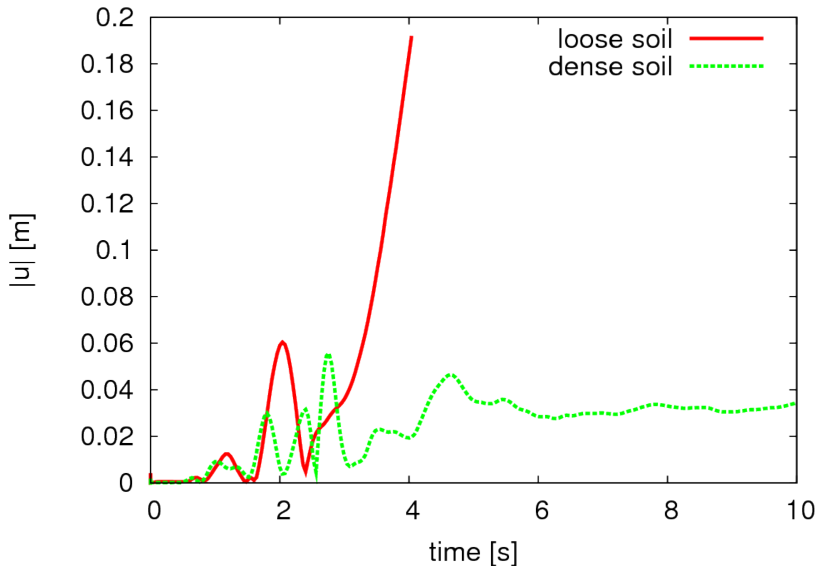

Figure 5.8: Displacement of the top of the building during the earthquake.

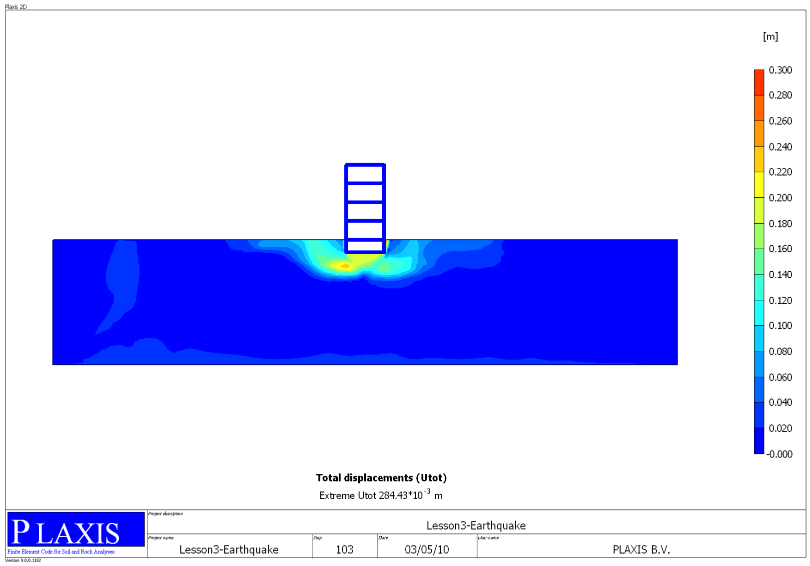

Figure 5.9: Total displacements after 4 s of earthquake - loose soil.

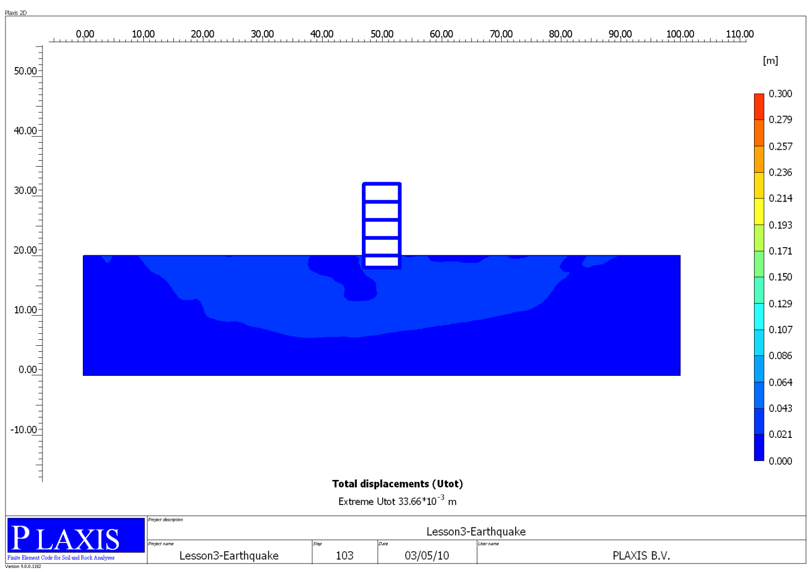

Figure 5.10: Total displacements after 4 s of earthquake - dense soil.

Chapter 6

TROUBLESHOOTING

Although the implementation has been tested to be accurate and robust, the hypoplastic models are highly non-linear which may cause problems during solving complex boundary value problems. When encountering problems, the following steps may help to improve the overall performance:

1. In the "Iterative procedure" settings under "Parameters" Tab sheet, set "Manual settings" and do not use the arc-length control.

2. Try to modify the iterative procedure by decreasing the "Desired minimum" and "Desired maximum" number of iterations (for example, 3 and 5 respectively).

3. The hypoplastic models are undefined in the tensile stress region, which can cause integration problems in the vicinity of the free surface and in the case of staged construction starting from the stress-free state. For this reason, artificial cohesion is introduced in the model implementation through the parameter p_t. The user can specify any p_t value; in the case p_t=0 kPa, the program replaces it by a default value p_t=1 kPa.

4. When used with interface elements, proper interface parameters must be input in the "Interface" Tab sheet under "Material models" window. Particularly, as some tensile stress is allowed for in the soil through the parameter p_t, the tensile stress should be allowed for also in the interface by increasing the cohesion value (e.g., 10 kPa). Convergence problems may also be caused by high interface stiffness. In the case PLAXIS keeps on iterating although the global error is below the tolerated value, or does not increase the step size although the

number of iterations is below the "desired minimum", problem is the most likely in interfaces.

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Chapter 7

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Chapter 8

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Chapter 9

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