Research Article

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Excavations in the vicinity of the antiflood embankments – calculating issues

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Abstract: According to Polish law, it is prohibited to perform excavations or locate buildings closer than 50 m from the embankment. In order to obtain exemption from this ban, filtration and stability analysis of the embankment and excavation in the flood conditions have to be performed. This paper presents results of the numerical investigations on interactions between excavations and embankment. Complex nature of the problem is presented. Methodology of numerical simulations and real case examples are described.

Keywords: excavation; stability; embankment; flood; filtration.

1 Introduction

According to Polish law (Water Law Act, July 20, 2017), it is prohibited to perform excavations or locate buildings closer than 50 m from the embankment. In order to obtain exemption from this ban (given by Polish State Water Holding), filtration and stability analysis of the embankment and excavation in the flood conditions have to be performed. Such an analysis should contain stability (slope stability and uplift possibility) and filtration calculations of the embankment and excavations in three variants:

- Before excavation (existing state of the embankment)
- During excavation (with open excavation)
- Final state (after finishing of the investment)

Presentation of the methodology of performing such calculations with the use of Finite Element Method (FEM) system ZSoil v. 18 is a main topic of this article. Real case examples (from the author engineering practice) are presented, and complex nature of the subject is underlined.

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It is worth noting that for mountain and submountain rivers embankment, it is necessary to perform filtration and stability calculations in the transient flow conditions – because water levels changes during flood are very rapid and faster than soil reaction.

2 Possible interactions between excavation and embankment

Excavation and embankment should not be treated separately. If the excavation is located “close” to the embankment, some interactions could occur. Of course, if the excavation is located “far” from embankment, there would be no interaction. It is not possible to judge “a priori” if an excavation is “close” or “far” from the embankment – it depends on excavation dimensions, soil conditions, and time of the flood.

From slope stability point of view, such interaction could occur even not during the flood (Fig. 1). If the excavation is performed “close” to the embankment, one higher slope forms from slopes of the embankment and excavation.

Another source of the possible interaction is an influence of the excavation located “close” to the embankment on filtration phenomena during the flood. Some leakage to the excavation could happen. Also the risk of the uplift of the impermeable layer could rise, when such layer (or soil layer above it) is thinned due to excavation (Fig. 2). If the excavation is supported, additional water pressure on the support structure could occur. Also seepage line could move upward (Fig. 3).

3 Methodology of numerical simulations

In the presented approach, combined problems of excavation, transient flow, and stability are investigated. Thus, methodology has to respect both rules of numerical

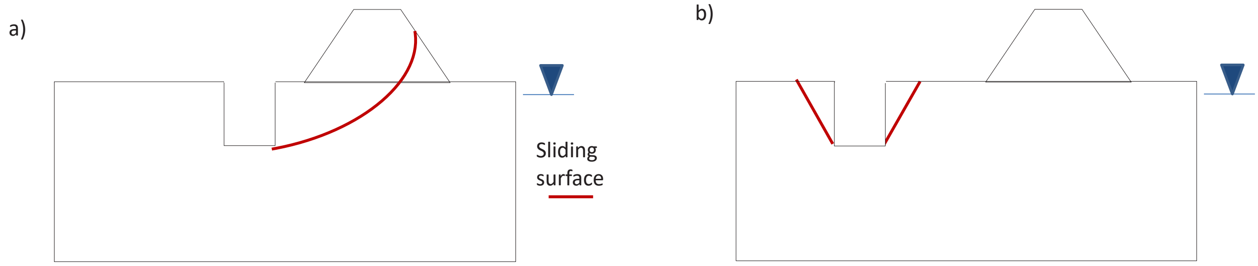


Figure 1: Interaction between embankment and excavation from the slope stability point of view: (a) excavation "close" to the embankment – interaction possible even not during the flood and (b) excavation "far" from the embankment – no interaction.

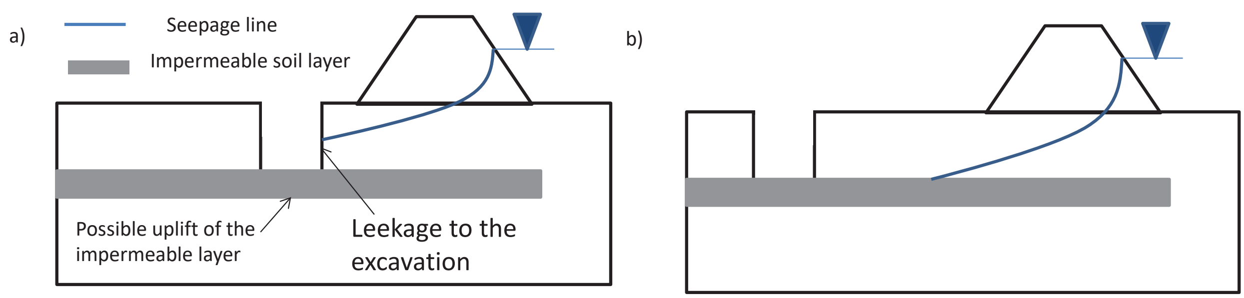


Figure 2: Interaction between embankment and excavation during the flood: (a) excavation "close" to the embankment – leakage to the excavation and uplift of the impermeable layer possible and (b) excavation "far" from the embankment – no interaction.

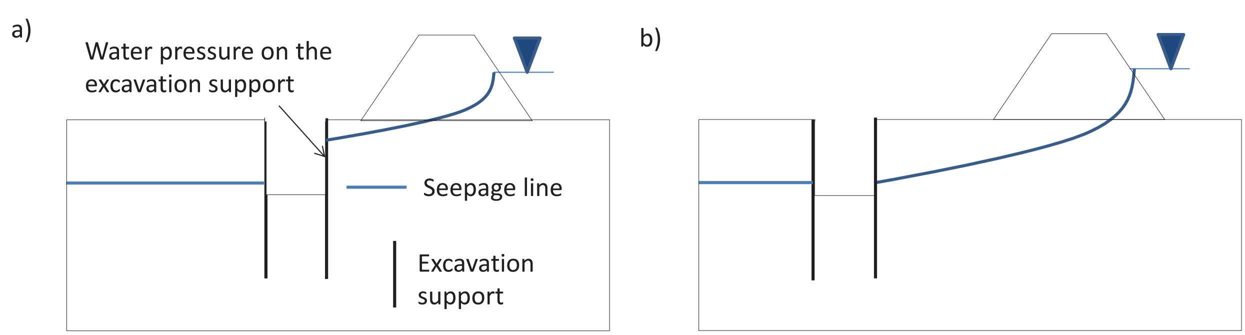


Figure 3: Interaction between embankment and excavation during the flood: (a) excavation "close" to the embankment – water pressure on excavation support, seepage line moves upward and (b) excavation "far" from the embankment – no interaction.

modeling of excavation and antiflood embankments. 2D model (2d flow and plain strain) is used.

Whole excavation process (especially in more complicated cases, with support construction) should be modeled first. "In situ" state is modeled, and then partial unloading method is used (detailed description is given by Grodecki, 2007; and Urbański and Grodecki, 2010) to model progressive excavation. Contact elements are used between soil continuum and structural elements (e.g., sheet pile walls) in order to allow discontinuous displacement field.

Then, simulation of the flood is performed. One should note that flood could appear on every stage of the excavation. So for complicated support constructions, few flow analyses should be performed. It is necessary especially when static scheme of the excavation support changes during excavation. Influence of moment (on excavation stage scheme) when flood appear is discussed later in this paper. Model of transient flow with description of partial saturation zone by van Genuchten (1980) is used. Coulomb–Mohr model with cut-off condition (no tension) is used for soil. Obtained results consist of time–

space distribution of pore pressures and fluid velocities, stability factor, and corresponding failure mechanism on every important moment during flood and internal forces in the structural elements (e.g., sheet pile walls used to support excavation). From obtained fluid velocities field, time history of the leakage (flow) could be derived. Pore pressures under the impermeable soil layer could be used to check uplift possibility.

Detailed description of the used approach after Urbański and Grodecki (2000) and Urbański, Grodecki, and Kot (2016) is given below.

Modified Darcy's law with permeability reduced in the partial saturation zone (p>0, 0<S<1, after van Genuchten (1980) is used:

$$\mathbf{q} = -k \cdot k_r(S(p))\mathbf{grad}(-p/\gamma_w + z), \quad k_r(S) = \frac{(S-S_r)^3}{(1-S_r)^3} \quad (1)$$

where k is the Darcy coefficient for saturated soil, S is the saturation ratio (0≤S≤1), $z\Xi y$ is the gravity potential, γ is the water-specific weight, and S_r is the residual saturation.

Saturation is related to the pressure via formula:

$$S = S(p) = \begin{cases} 1 & \text{for} \quad p \le 0 \\ S_r + \dfrac{1-S_r}{\left[1+(\alpha p/\gamma)^2\right]^{0.5}} & \text{for} \quad p > 0 \end{cases} \quad (2)$$

Flow model is completed by continuity equation of Richards:

$$S\dot{\varepsilon}_v + div\mathbf{q} = n\left[\frac{S}{\beta} - \frac{dS}{dp}\right]\dot{p} \quad (3)$$

where β is the fluid bulk modulus, n (0<n<1) is the porosity (being additional characteristic of the soil), and $\dot{\varepsilon}_v$ is volumetric strain ratio.

Obtained pore pressure distribution is automatically included in static analysis, via effective stresses hypothesis.

Stability analysis is performed with the use of the c-ϕ reduction method. More detailed description may be found in ZSoil documentation (Zimmermann et al. 2005) or in works by Griffiths and Lane (1999) and Matsui and San (1992). Obtained SF values are compared with required minimal value of 1.50 of Polish legal regulations. Stability could be analyzed in any time during the flood, but typically three moments are crucial: before the flood, at the end of the culmination phase, and during descending phase.

4 Real – case examples

Presented examples (from the author engineering practice) cover two typical problems:

- Example 1 – shallow excavation (2 m deep, 2 m wide, located 2 m from the embankment)
- Example 2 – deep excavation (6.5 m deep, located 9 m from the embankment, for 2-storey underground car park)

Both excavations are located near the Vistula River embankments. Flood wave based on catastrophic flood from 2010 year is used in simulations (Fig. 4). Initial groundwater table is horizontal at 216 m a.s.l. Hydraulic contact between permeable soils (sands and gravels) in subsoil is assumed. In both cases, obtained results (visible influence of the excavation on embankment stability in Example 1 and influence of the flood on bending moment in the diaphragm wall in Example 2) prove that excavations are located "close" from the embankment.

4.1 Shallow excavation

Numerical model of the embankment in the existing state is presented in Fig. 5 a and material parameters are given in Table 1.

Clay (in embankment) and silty clay (in subsoil) are low permeable soils, and clay (in deep subsoil) is almost impermeable. Sand and gravel are components of very permeable subsoil. Silty clay with I_L = 0.60 is a weak layer, which had significant influence on stability of the structure with open excavation.

In the existing state (without an excavation), no influence of the flood on stability of the embankment is observed, and Stability Factor SF = 2.08 is achieved on

Table 1: Most important material parameters used in analysis of shallow excavation.

	γ [kN/m³]	c[kPa]	ϕ[°]	k [m/d]
Clay (I_L = 0.30, embankment)	20.0	11.9	12.4	0.0086
Silty clay (I_L = 0.20)	21.0	17.0	14.8	0.0086
Silty clay (I_L = 0.35)	20.0	9.5	10.8	0.0086
Silty clay (I_L = 0.60)	19.0	6.9	8.4	0.0086
Sand (I_D = 0.45)	18.5	0	32.7	15
Gravel (I_D = 0.45)	18.5	0	38.1	86.4
Clay (I_l = 0.30)	21.5	50	10.0	8.64×10^{-6}

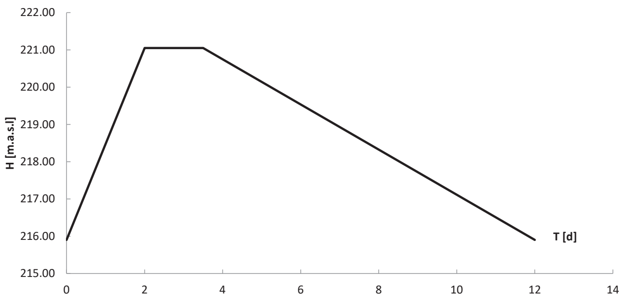


Figure 4: Flood wave used in real – case examples.

every stage of the flood. Obtained stability loss mechanism is presented in Fig. 6. Risk of the uplift is checked; maximal pressure under the clay layer of the subsoil is 59.4 kPa and is much lower than vertical stress (84 kPa), so uplift will not happen.

Numerical model of the embankment with open, not supported excavation is presented in Fig. 5 b. Performed numerical simulations shows strong negative influence of the excavation on stability of the structure, and SF drops down from 2.08 in the existing state to 1.44 before the flood and 1.22 during culmination of the flood (failure

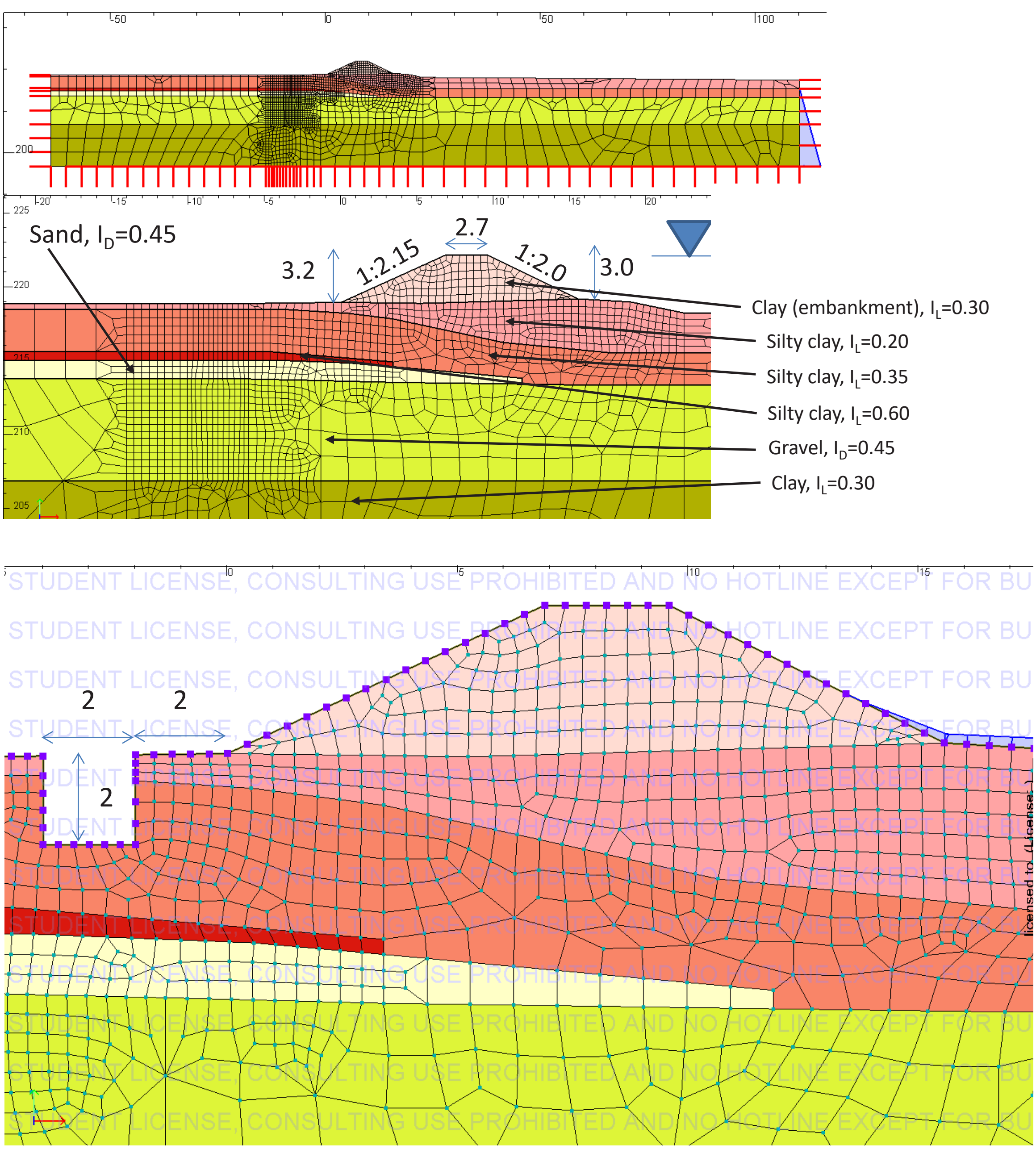


Figure 5: Numerical model of the embankment (a) with shallow excavation existing state and (b) with open excavation.

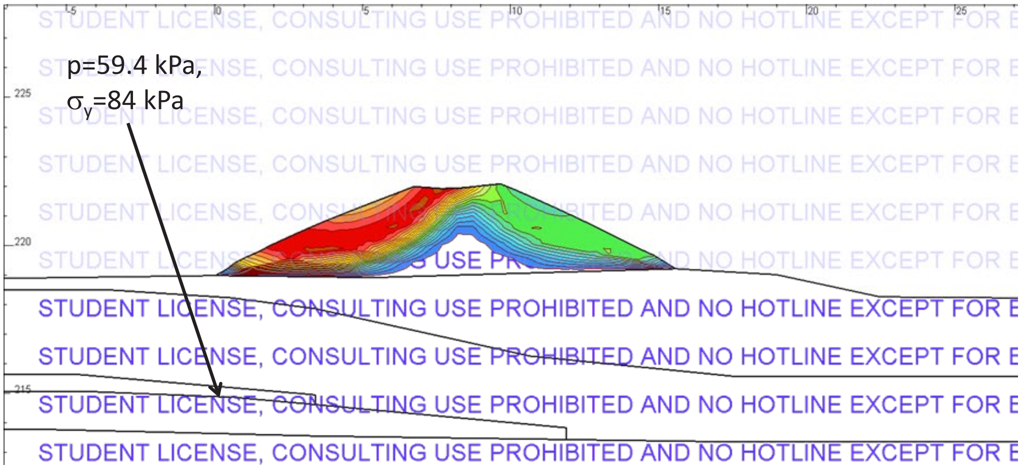


Figure 6: Failure mode in the existing state of the embankment.

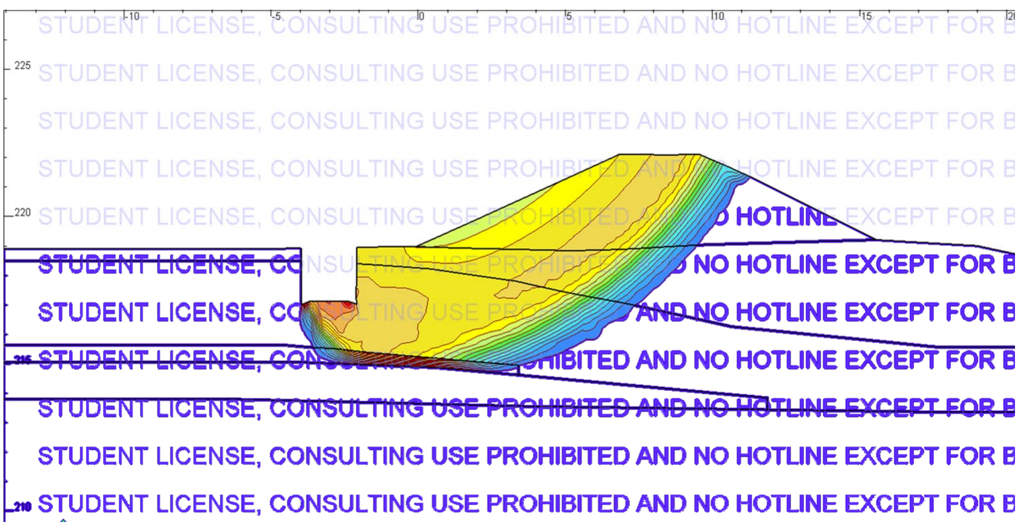


Figure 7: Failure mechanism of the embankment with shallow excavation, the same in all phases of the flood.

mechanism is presented in Fig. 7). Even worse, just after culmination of the flood, uplift of the excavation bottom occurs (Fig. 8).

Then, the so-called system excavation support (steel walls with struts at the top and bottom of the excavation) was designed as a remedy to an insufficient stability of the excavation and embankment. Performed calculations show that obtained stability factors are satisfactory (1.88 before the flood, 1.62 during the culmination of the flood) but destruction by uplift still happen for T = 5.1 d, identically like for unsupported excavation case. So such variant was rejected. Failure mechanism for all phases of the flood is presented in Fig. 9.

Finally, protection of the excavation by sheet pile walls with struts at the top embedded into deep almost impermeable clay layer was proposed. For such variant, identical stability calculations results like for existing (without excavation) embankment were received (the influence of the excavation on embankment stability vanished, in every phase of the flood). Obtained envelopes of the bending moment in the sheet pile walls (with SF = 1.25, EC-7 approach) are presented in Fig. 10.

4.2 Deep excavation

Numerical model of the embankment with finished excavation state is presented in Fig. 11 and material parameters are given in Table 2. A 6.5-m deep excavation was protected with 0.60-m-thick reinforced concrete diaphragm wall, with two struts and baseplate. Situation was highly complicated, because of the two concrete

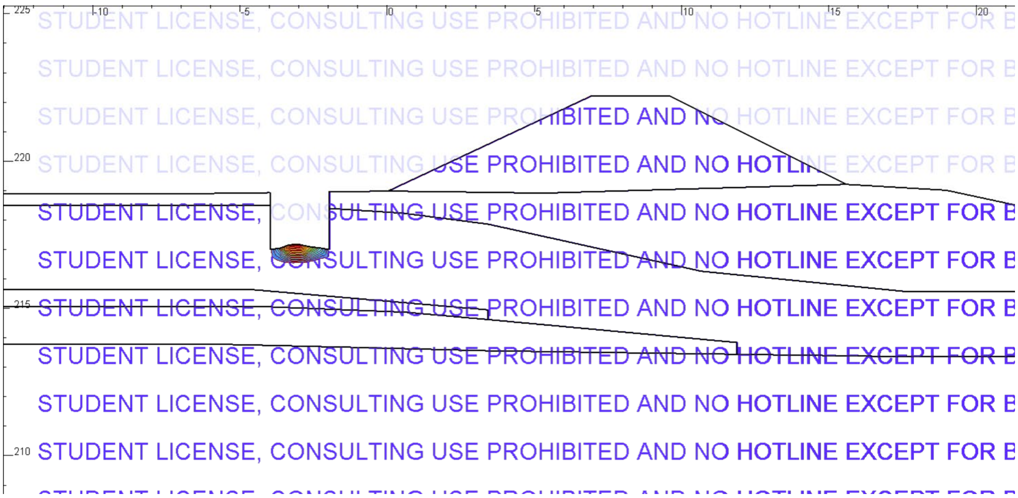


Figure 8: Failure by uplift of the excavation bottom, just after culmination of the flood (T = 5.1 d).

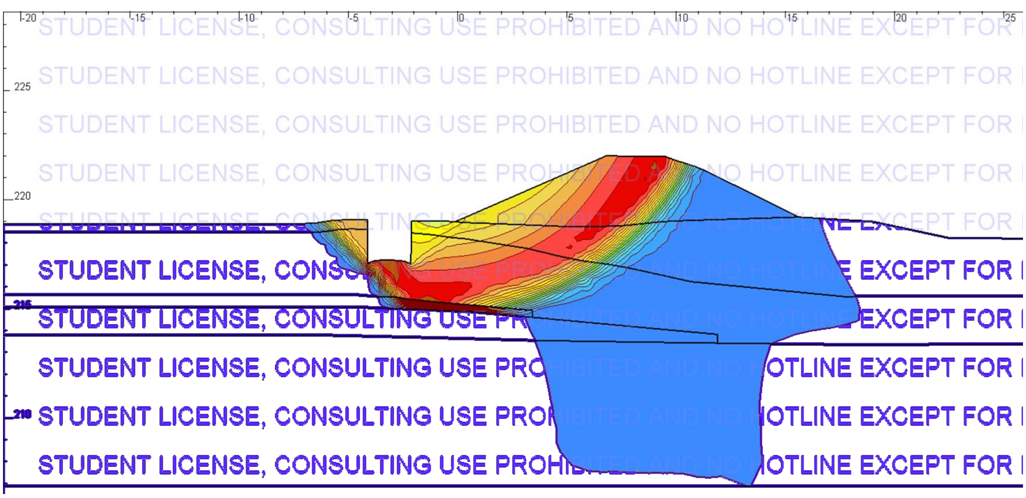


Figure 9: Failure mechanism of the embankment with shallow excavation with "system excavation support," the same in all phases of the flood.

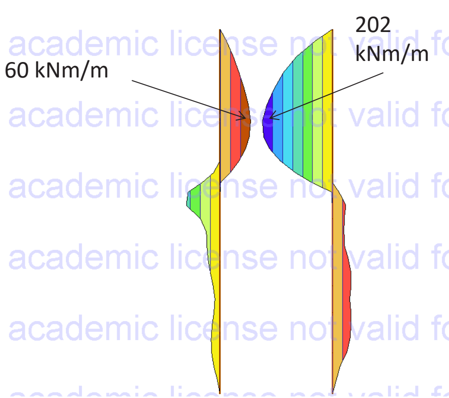


Figure 10: Bending moment envelopes, shallow excavation protected by sheet pile walls with strut at the top, SF = 1.25 (EC-7 approach).

retaining walls which exists in the embankment (lower one acting as a foundation of the waterside boulevard and higher one as an antiflood structure).

Artificial embankments and silty clay (I_L = 0.10) are low permeable soils, and clay (in deep subsoil) is almost impermeable. Sand and gravel are components of very permeable subsoil.

Full process of the excavation was modeled. Influence of the flood was analyzed in two crucial steeps of the excavation: after reaching of the maximal depth but before installing of the baseplate and for final state (with baseplate installed). Pore pressure distribution during culmination of the flood (Fig. 12) is almost identical in both cases.

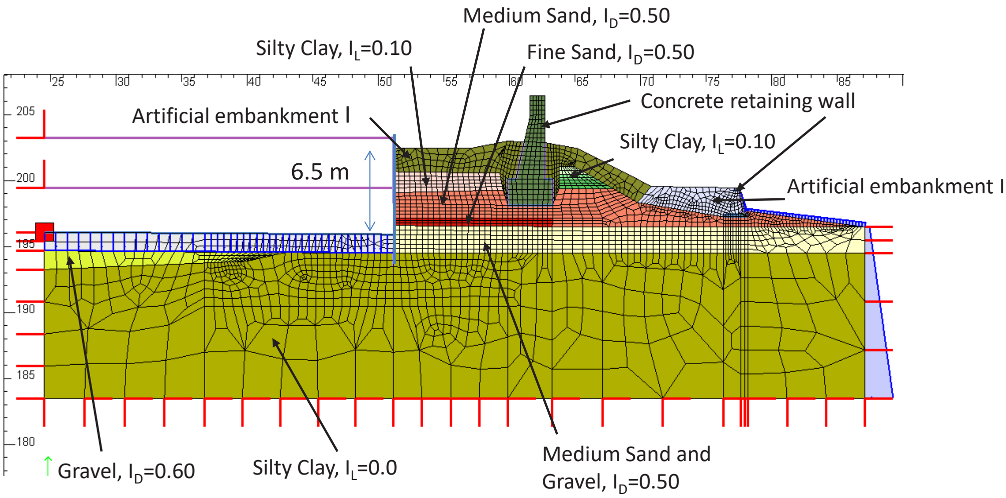


Figure 11: Numerical model of the deep excavation near the embankment – finished excavation.

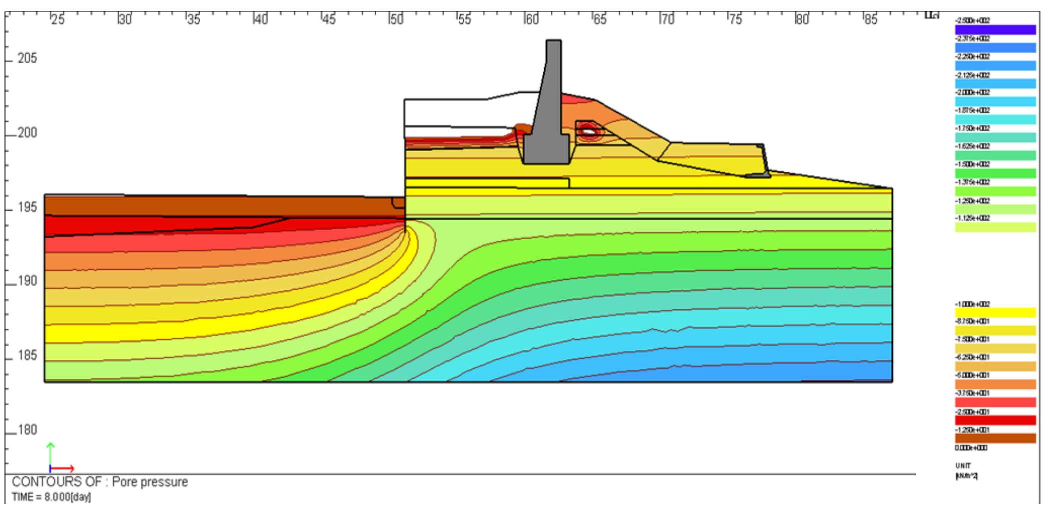


Figure 12: Pore pressure distribution, culmination of the flood, maximal depth of the excavation, no baseplate installed.

Table 2: Most important material parameters used in analysis of deep excavation.

	g [kN/m³]	c[kPa]	f[°]	k [m/d]
Artificial embankment I	21.2	12.8	24.6	0.0285
Artificial embankment II	21.2	11.2	17.4	0.0527
Concrete	24.0	–	–	Impermeable
Silty clay, I_L = 0.10	19.8	14.0	9.5	0.00203
Medium sand, I_D = 0.50	18.5	0	33.0	9.5
Fine sand, I_D = 0.50	17.5	0	30.5	3.5
Medium sand and gravel, I_D = 0.50	20.2	0	33.0	12.0
Gravel, I_D = 0.60	20.7	0	39	15.0
Clay, I_L = 0.0	20.4	60	13	0.000864

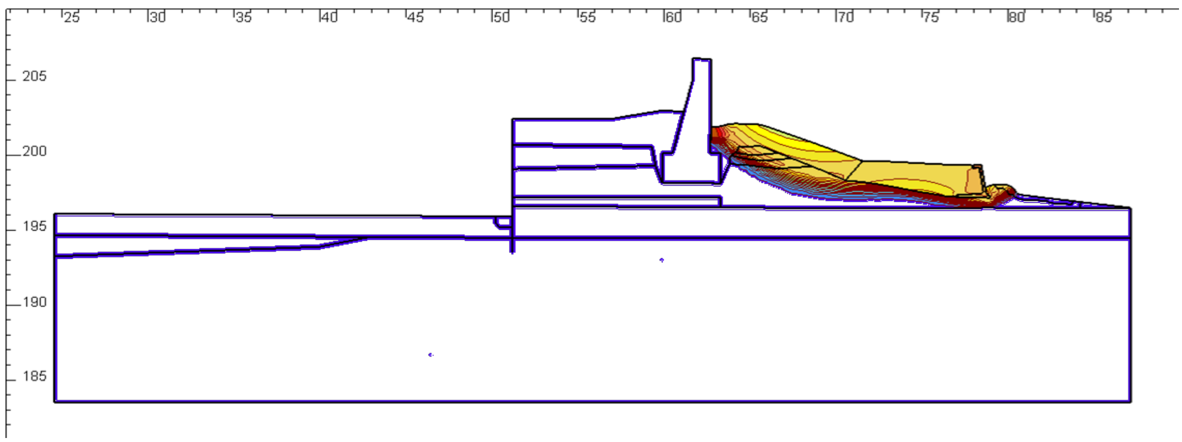


Figure 13: Failure mode, before the flood and in the descending phase of the flood.

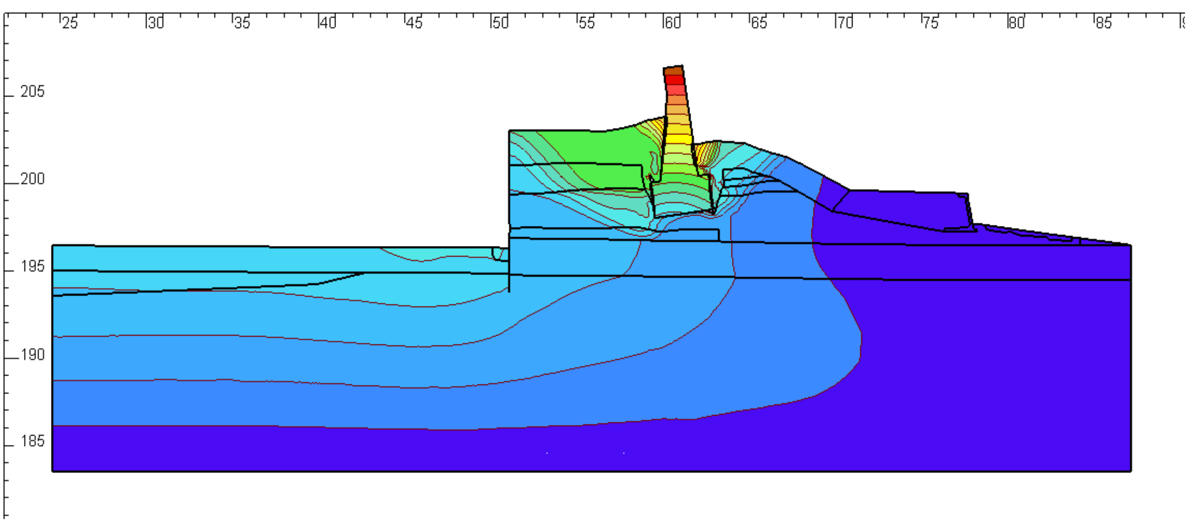


Figure 14: Failure mode during culmination of the flood.

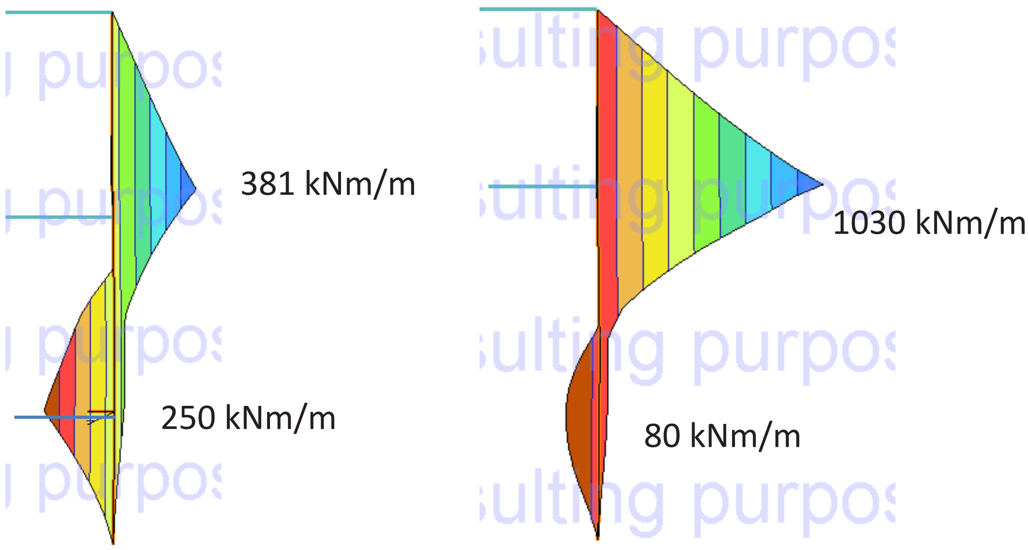
Table 3: Obtained values of SF for deep excavation.

	Before the flood	Culmination phase	Descending phase
Existing state	2.63	2.12	2.09
Open excavation (no baseplate)	2.63	2.09	2.09
Final state	2.63	2.09	2.09

Stability analysis of the embankment shows complicated nature of the problem – totally different failure modes were obtained in the different phases of the flood (compare Fig. 13 [slope stability loss and horizontal movement of the bottom retaining wall before the flood and during descending phase] and Fig. 14 [rotation of the upper retaining wall during culmination of the flood]).

Obtained values of the SF show almost no influence of the investment on the embankment stability (see Table 3).

Obtained envelopes of the bending moment in the sheet pile walls (with SF = 1.25, EC-7 approach) are presented in Fig. 15. It is worth noting that maximal value of the bending moment on the retained side of the wall is obtained in the variant with flood before baseplate



a) b)

Figure 15: Envelopes of the bending moments in the diaphragm wall: (a) flood after baseplate installing and (b) flood before baseplate installing.

installing, but maximal bending moment on the excavated side of the wall is obtained in the variant with flood after baseplate installing. Maximal bending moment obtained in the variant when flood appears before baseplate installing is about 2.7 times higher than moment in the variant with flood occurrence after baseplate installing.

5 Final remarks

Presented approach to numerical modeling allows to rational evaluation of the embankment and excavation behavior during flood (with excavation support influence included). Numerical analysis is a valuable tool for designing of excavation support in such a situation. Excavation and embankment should not be analyzed separately – there is an interaction between them. Excavation could have strong negative effect on embankment stability (especially in flood conditions). Flood phenomena could strongly affect internal forces in the excavation support construction. Internal forces (mostly bending moments in the sheet pile or diaphragm wall) strongly depend on when (on which excavation stage) flood appears. Maximal bending moment ratio between situations when flood occurs before or after baseplate installation is about 2.7 in the presented example. Uplift could be a crucial phenomenon, decisive on safety of the excavation and embankment – especially when vertical stress in the bottom of not-permeable or low-permeable soil layer decreases due to excavation.

Even shallow excavation located close to the embankment could be a serious danger, demanding a support down to impermeable layer. Analyzed phenomena are complicated, especially when excavation support construction is complicated too.

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