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Numerical Modelling of Slope Instability

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Abstract

This article is dealing with stability of the highway cut in Eastern Slovakia. The cut is situated in rock environment of the Carpathian flysch, which in area of the cut mostly consists of shale with different degree of weathering. The cut is supported by an anchored pile wall. Rock environment is changing from the surface to the depth from alluvium clays, sands and completely weathered shale to fresh shale. The potential slip surface was investigated after evaluation of data from geotechnical monitoring, so stability of the pile wall has to be analyzed. Finite element analysis was done and two material models were compared to results of geotechnical monitoring. Deformation analysis and the safety factor are discussed. Two models were compared in these terms: Mohr - Coulomb material model and jointed rock material model. These models are introduced because of shale anisotropy and simplification of behavior model via jointed rock model. Jointed rock model was introduced as an anisotropic model and required geotechnical parameters for calculations are discussed in comparison with the Mohr – Coulomb material model. Anisotropic behavior of shale will be discussed and analyzed. Short recommendations for the use of these models are presented in the paper.

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Keywords: Mohr-Coulomb model, jointed rock model, slope stability, pile wall.

1. Main text

This article is focused on deformation and stability analysis of pile wall. The pile wall was designed to support highway cut in eastern Slovakia. Based on the results of geotechnical monitoring (GTM), which was done and is still running, the instability of the slope behind pile wall was observed. GTM consists of the geodetic points on the pile wall measurements, ground water level (GWL) measurements and inclinometric measurements. Stability

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analysis was done in following steps:

- interpretation of the GTM results to identify slope instability and slip surface
- deformation and stability analysis using numerical and analytical methods
- geotechnical design of the remediation for increasing the cut stability

Mohr – Coulomb model and Jointed rock model were selected in numerical calculation to show more realistic modelling of excavation effect in rock masses for support design using anisotropic material models.

2. Geological conditions and geotechnical parameters

Highway cut is situated in eastern Slovakia in the environment of Carpathian flysch, which in mentioned area consists of shale with different degree of weathering. Pile wall is divided into two parts “A” and “B” due to different geological conditions (Fig. 1).

Pile wall in part “A” is embedded to medium strong shale. This layer is in direction to the surface changing to disintegrated weak and very weak shale and extremely weak decomposed shale (character of clay with intermediate plasticity). Deluvial clays (clay with intermediate plasticity and sandy clays) can be observed near the surface, above the shale (Fig. 2). Most important factor for the cut instability is unfavourable shale inclination of 20 – 25 degrees to the cut. The inclination have been created due to tectonic movements in this area. Based on the results of GTM measurements deep slip surface was expected in this part. Slip surface was drawn based on the two inclinometers measurements 30 INK-1 and 30 INK-2 (Fig. 1).

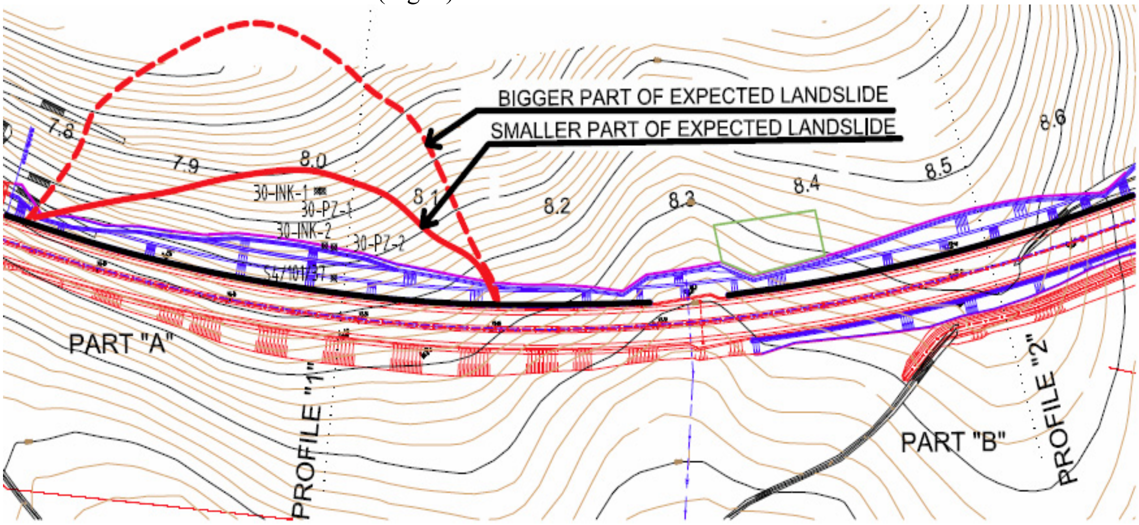

Figure 1: View of the cut with the location of the engineering geological profiles.

The free length of the anchors was too short to provide the satisfying safety of the internal stability of the system. Geotechnical parameters used in calculations for slope stability are presented in Table 1. JR model as an anisotropic model was chosen only for the fresh and strong shale (due to the genesis, which is significantly anisotropic). Shear strength parameters are the same for MC and JR model because JR model is using the MC failure criterion (PLAXIS Material models manual, 2011). Parameters introduced in Table 1 are and density (γ) and saturated density (γ_{sat}) of the soil, shear strength parameters ϕ_{ef} and c_{ef} (angle of the internal friction and cohesion), deformation modulus (E_{def}) and Poisson ratio (ν). Subscript 1 in the JR model parameters means direction perpendicular to the layers and subscript 2 means direction parallel with layers. Inclination of the layers is defined via angle α.

3. Material models

3.1 Mohr – Coulomb model

Table 1. a) Input parameters for the MC model b) Input parameters of the shale for JR model.

a)	γ (kN/m3)	γ_{sat} (kN/m3)	ϕ_{ef} (°)	c_{ef} (kPa)	E_{def} (MPa)	ν (-)
F4-CS	19.8	20.51	20.3	14	5.5	0.35
R6 (F6-CI)	20.06	21.06	20	19	6	0.4
R5	20.9	21.57	27	30	40	0.25
R3	25.5	26	30	60	400	0.2

b)	γ (kN/m3)	γ_{sat} (kN/m3)	ϕ_{ef} (°)	c_{ef} (kPa)	E.1 (MPa)	ν.1 (-)	E.2 (MPa)	ν.2 (-)	G.2 (MPa)	α (°)
R3	25.5	26	30	60	400	0.25	150	0.35	25	160

Parameters of the Mohr – Coulomb model are defined in Table 1. MC failure criterion is written as:

$$\tau = c + \sigma'.tan\phi \tag{1}$$

In the case of the plane strain situation yield function *f(σ)* and plastic potential function *g(σ)* are written as:

$$f(\sigma) = \tau - (c.cot\phi + \sigma).sin\phi \tag{2}$$

$$g(\sigma) = \tau - \sigma.sin\psi \tag{3}$$

The MC model is defined as elastic – perfectly plastic. It must be noted that MC model is not good one for modelling deformations after excavation due to only one input E modulus, without different values of modules for the virgin loading, unloading/reloading.

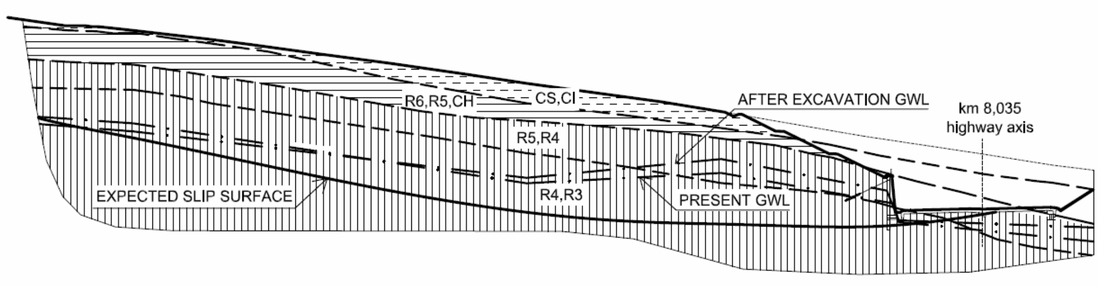

Figure 2: Engineering geological profile, input data for numerical model.

3.2 Jointed rock model

Jointed rock (JR) model is an anisotropic model, developed by PLAXIS. It was used only for the weak shale due to its naturally anisotropic behaviour. Very important feature of this model is selection of the inclination of the layers on which the anisotropy is defined. Different parameters for stiffness are used in MC and JR models. Parameters are defined perpendicular, subscript 1, and parallel, subscript 2, to the layers. The transformation from the Cartesian coordinates is done due to failure criterion on the inclined plane. After the transformation, the failure criterion on local coordinates (n, s, t) can be checked. Stress and strains transformations and definitions for the anisotropy were published by Zienkiewicz and Taylor (2005) or Králik (2009). Stresses are defined as follows (PLAXIS Material models manual, 2011), (Zienkiewicz and Taylor, 2005), (Králik, 2009):

$$\{\sigma_i\} = [T]_i^T.\{\sigma\} \tag{4}$$

$$\{\sigma_i\} = (\sigma_n\ \tau_s\ \tau_t)^T \tag{5}$$

$$\{\sigma\} = \left(\sigma_{xx}\ \sigma_{yy}\ \sigma_{zz}\ \sigma_{xy}\ \sigma_{yz}\ \sigma_{zx}\right)^{T} \tag{6}$$

In relation (4) $[T]_i^T$ transformation matrix 3x6 is calculated for the plane with inclination (angle *α)*. The failure criterion on the inclined plane i was checked. Yield function *f(σ)* and plastic potential function *g(σ)* are defined according to PLAXIS Material models (Plaxis, 2011):

$$\mathrm{f_i}(\sigma) = |\tau_s| + \sigma_n.\tan\phi_i - c_{\,i} \tag{7}$$

$$\mathrm{g_i}(\sigma) = |\tau_i| + \sigma_n.\tan\phi_i - c_{\,i} \tag{8}$$

4. Stability analysis

Stability analysis or the Safety Factor (SF) analysis is in PLAXIS code defined as a “phi – c reduction”. Shear strength parameters ϕ and c are proportionally reduced until equilibrium state of stress was reached. This method was proposed by Brinkgreve and Bakker (1991) as robust and complex method for stability analysis. SF in terms of MC failure criterion:

$$SF = \frac{c + \sigma'.tan\phi}{c_c + \sigma'.tan\phi_c} = \frac{c}{c_c} = \frac{\phi}{\phi_c} \tag{9}$$

Subscript *c* denotes critical parameters (which are reduced), and σ´ is effective normal stress.. The parameters are reduced and its minimal values when failure occurs is needed, failure criterion is reached and it can leads to non convergence. Computation does not reach equilibrium; loads are not reached in iteration procedure. Due to this problem Brinkgreve and Bakker (1991) proposed in direct deformation regulation in form of the arc – length control Králik (2009), Fusek and Halama (2011), Memon and Su (2003). Arc – length method is described by plenty of the other authors and the developments for the special cases are still doing (Barton, 2013; Chazvinian et al., 2013).

5. Results and discussions

Engineering-geological profile for geotechnical parameters to calculation model was chosen as the nearest profile to the inclinometers measurements with movement in the shale layers (Fig. 1 and Fig. 2). This provides good way to model and compare the results. Measurements from the inclinometer 230/35A-INKP were chosen to compare deformations of pile wall and calculated deformations. It is situated directly behind the wall. Horizontal deformations, which were computed after the final excavation, are shown in Fig. 3 and Fig. 4.

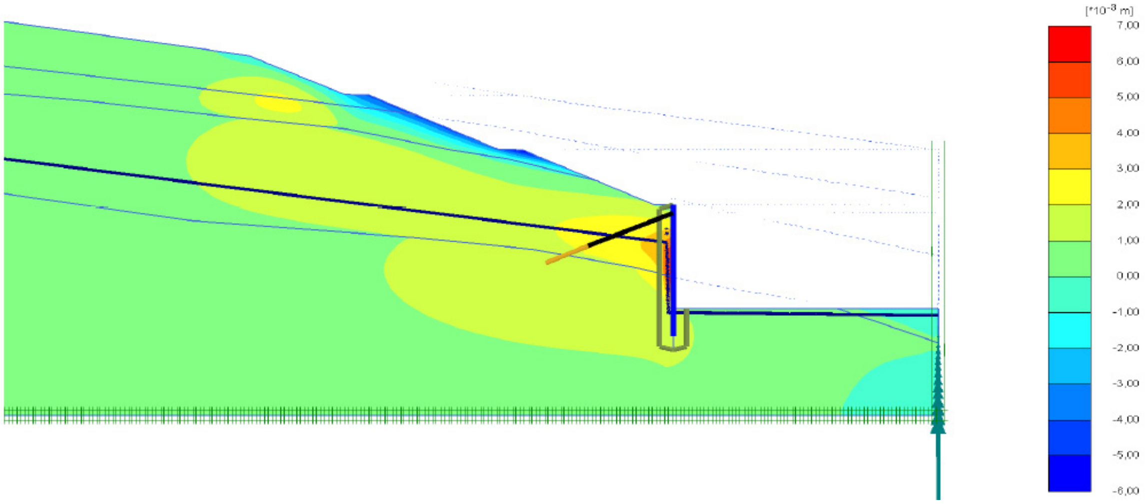

Figure 3: Horizontal deformations computed with MC model after the final excavation.

It is clear that in JR model bigger area was activated than in the MC model and a bigger deformation occurs in JR model. Deformations in comparison to GTM measurements from the JR model are far closer like in the MC model (Fig. 5). Area in the JR (in weak shale layer) model smoothly follows the inclined layers and it cause also the activation of the upper layers. It must be noted that neither in MC model nor in JR model expected slip surface was not reached, neither in final excavation step nor in slope stability analysis using “phi – c reduction”.

The values of Safety factor for the MC model were SF=1.68 and for JR model SF=1.83 (Fig. 6). It is clear that both models reach equilibrium about the 50th step. Increasing of deformations due to the step in comparison with SF are unreal due to the artificial reduction of the parameters. This deformation could occurs only in the case of the progressive failure. In the case of the MC model, there is an exponential trend in increasing of deformations. On the other hand in the JR model, the raise of the deformation is still, also after the fixation of the SF, linear. Even if deformations are not real little bit similar values can be expected.

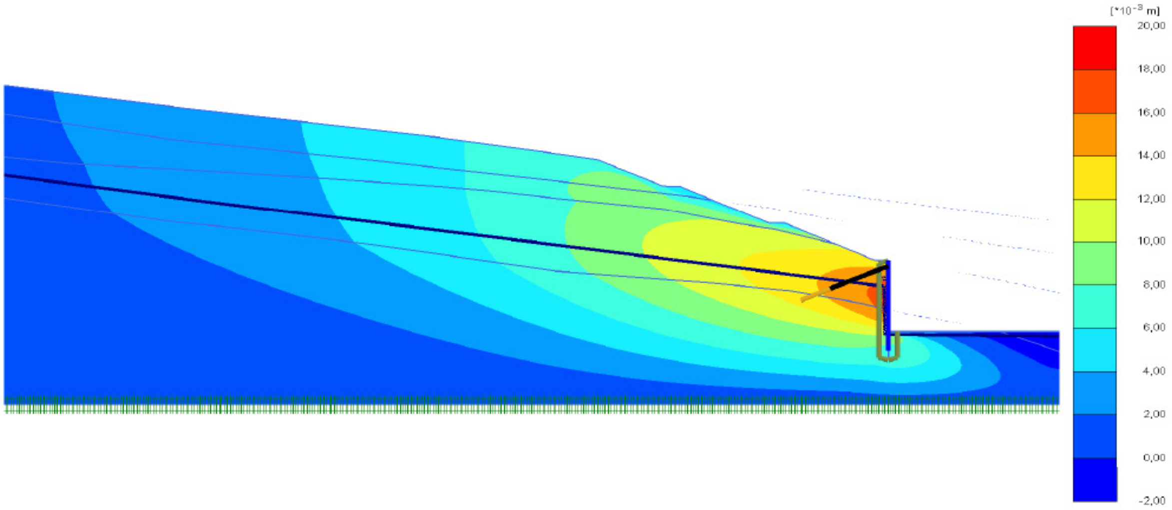

Figure 4: Horizontal deformations computed with JR model after the final excavation.

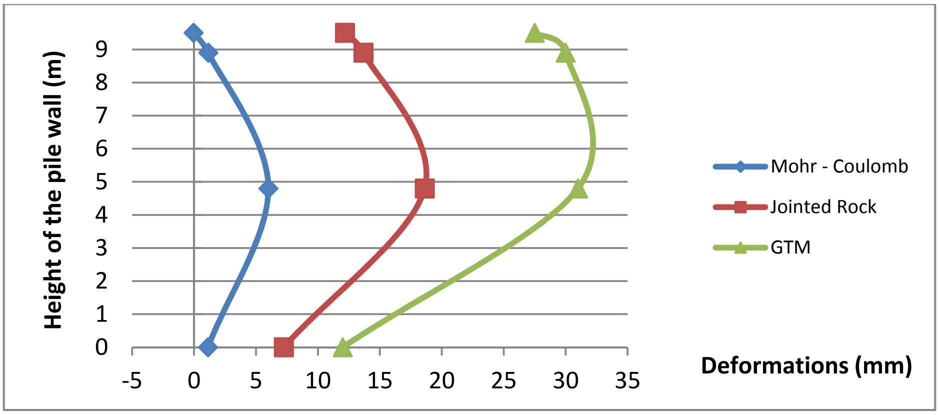

Figure 5: Comparison of the computed results with the GTM.

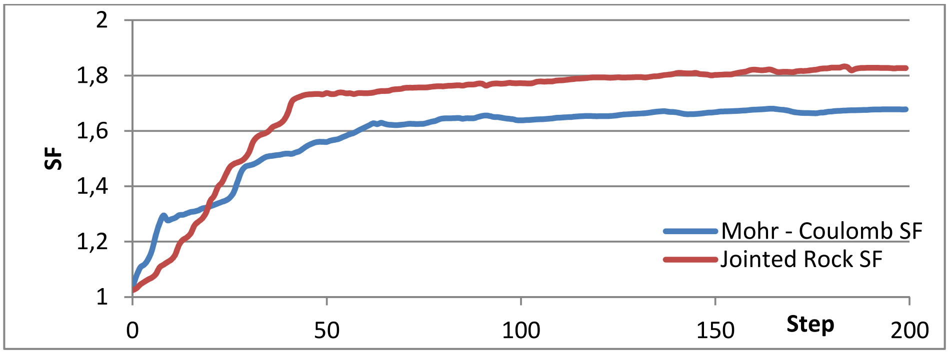

Figure 6: Increasing of the stability with the increasing step.

Deformations are much bigger in the case of the MC model than in JR model. It can be caused by the lower normal stresses, which are transformed on the inclined plane. These lower stresses can also cause the lower shear strength or lower shear stress, which could be reached. Very important feature of the JR model is that principal stresses are directly inclined around the angle α. It is not possible to reach this state of stress in the MC model.

6. Conclusion

This article was made to show the importance of the choosing correct material model. As it was proposed with correct material model, we can represent the nature of the complicated phenomena in shale, anisotropy of shale. Expected slip surface, drawn according to GTM, was not reached but the difference in both models is clear and also the advantage of choosing the inclination of the layers is important feature. According to the references, the FEM modelling of anisotropy is not so complicated problem and is clear for years. Further numerical research should be done in this field according to the soil mechanics, because all types of soil are of anisotropic nature. Not only numerical but also laboratory research must proceed. Not so many works are interesting about anisotropic behaviour, especially in shale. Further research should be focused on the parameters because it is most important feature of the numerical modelling.

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References

1. BARTON N.: Shear strength criteria for rock, rock joints, rockfill and rock masses: Problems and some solutions. Journal of Rock Mechanics and Geotechnical Engineering 5 (2013) 249–261
2. BRINKGREVE, R.B.J. BAKKER, H.L.: Non-linear finite element analysis of safety factors. Computer Methods and Advances in Geomechanics. Booker & Carter, Balkema, Rotterdatm 1991, pp. 1117-1122
3. FUSEK, M. HALAMA, R.: MKP a MHP. Matematika pro inženýry 21. století. 2011, p. 95
4. CHAZVINIAN, A., GERANMAYEH VANEGHI, R., HADEI, M.R., AZINFAR. M.J.: Shear behavior of inherently anisotropic rocks. International Journal of Rock Mechanics & Mining Sciences 61 (2013) 96–110
5. KRÁLIK, J.: Modelovanie v MKP ANSYS. STU Stavebná fakulta, Bratislava 2009, p. 177
6. MEMON, B.A. SU, X.: Arc – length technique for nonlinear finite element analysis. Journal of Zhejiang University SCIENCE. 2003, pp. 618-628
7. PLAXIS Scientific manual and Material models manual 2011
8. ZIENKIEWICZ, O.C. TAYLOR, R.L.: The Finite Element Method for Solid and Structural Mechanics. Elsevier Butterworth-Heinemann, Oxford 2005, ISBN 0 7506 6321 9, p. 631