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APPLICATION OF NUMERICAL MODELLING TO THE COMPREHENSIVE ANALYSIS OF SLOPE STABILITY

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Summary

Paper deals with the comprehensive methodology for the numerical simulation of potentially unstable slopes combining engineering geological, hydrological, hydrogeological and geotechnical computational model for the assessment of slope stability.

Engineering geological model based on available survey data characterizes the rock environment using individual quasi-homogenous units. Model is defined on the basis of documented lithostratigraphic units in exploration probes and field relief documented by advanced methods, including satellite radar interferometry and laser surface scanning.

On the basis of engineering geological model, the hydrological model using MIKE SHE software (Finite Difference Method) was performed. Hydrological model includes simulation of surface runoff, evapotranspiration and flow in unsaturated near-surface zone. The model was calibrated on the basis of available field data. Outputs from this model were used as input initial conditions of the following hydrogeological model.

Software FEFLOW based on the Finite Element Method was subsequently used to the creation of hydrogeological model focused on the water flow and distribution of pore pressures of groundwater in individual quasi-homogeneous units in saturated zone. The infiltration condition determined by the hydrological model is considered and a flow model with variable saturation is applied.

Finally, the geotechnical stability model of slope following the engineering geological, hydrological and hydrogeological models was performed. The occurrence of plastic and failure zones (assuming elastic-perfectly plastic Mohr-Coulomb constitutive model) inside the slope was simulated by using software MIDAS GTS NX based on the Finite Element Method. Stability factor SSRF (Shear Strength Reduction Factor) is evaluated based on the Shear Strength Reduction Method) as the ratio of actual shear strength and minimum shear strength required to maintain stability.

Paper deals also with the comparison of stability factor of natural slope obtained from 3D and 2D numerical model. Generally, in the case of natural slope the condition of plane strain is not

fulfil, 2D model is not realistic and 3D model is needed, especially in case of concave morphology of slope.

1 INTRODUCTION

Slope stability assessment is one of the most important tasks in geotechnical engineering which must consider a comprehensive approach to the modelling and combine the basic principles of soil mechanics, hydraulics and general engineering mechanics. Stability of slopes is influenced by following fundamental factors – geometrical factors (terrain morphology, height, inclination, …), internal factors (geological structure of rock massif, strength and deformational properties of soil, influence of groundwater, filtration and retention properties of soil material, distribution of pore pressures, degree of saturation, …) and external factors (anthropogenic interventions, earthquakes, hydrodynamic effects of water, extreme precipitation, …). The objective implementation of previously mentioned factors into the numerical simulation determines the reliability of modelling results.

Compared to other structural materials (as concrete etc.), the soil mass is more complicated three-phase porous media consisting of solid particles and liquids and gasses in pores. The proportion of water and air in the pores is variable, it depends on many factors including soil character and its texture, weather, surface vegetation etc. The behaviour of soil is essentially dependent on the grain size, the grain shape and its surface character, on the closeness of packing of the grains, water content and corresponding degree of saturation. In unsaturated soils with negative water pore pressure a change in volume, shear strength and hydraulic properties is significant.

Generally, total stresses inside the soil mass can be expressed according Bishop´s theory as the superposition of effective stresses which are transmitted through the particle contact and water- pore pressure u_w and air-pore pressure u_a depending on saturation S:

$$\sigma tot. = \sigma ef. + \chi(S)u_w + (1-\chi(S))u_a \tag{1}$$

$\chi(S)$ – function of saturation S

$\chi(S=1) = 1$: fully saturation

The typical stress - strain behaviour of soil during loading is not elastic for the entire range of loading. In fact, real behaviour of soil is more complicated (Fig. 1), plastic irreversible deformations are manifested, they attain dominating influence near ultimate strength condition especially. No mathematical model cannot completely describe the complex behaviour of real soils. Each constitutive model accepts some idealization and simplification, it captures essential features and disregards some others. Constitutive model of soil can work assuming associated flow rule (plastic potential function characterizing the plastic strain is identical to the yield function) or non-associated flow rule (plastic potential function is different from yield function).

The linear elastic- perfectly plastic constitutive models (no hardering/softening is assumed) are widely used in geotechnical practice due to their simplicity and easily determinable input material parameters. These constitutive models assume the linear elastic behaviour in the elastic range, after the yield values is exceeded, the plastic flow continues under the identical stress. The Mohr-Coulomb (MC) model is the most common linear elastic-perfectly plastic constitutive model which describes a linear relationship between the shear and applied normal stresses (or maximum and minimum principal stresses) of soil material.

Yield function f for Mohr-Coulomb model in p-q space can be expressed in the following form (*p* – mean principal stress, *q*- deviatoric stress):

$$f(p,q,c,\varphi) = q - \left(\frac{(6p+q)}{3}\right) sin\varphi - 2ccos\varphi \tag{2}$$

where *c*- cohesion, *φ*–friction angle.

The geometric shape of corresponding yield surface in the principal stress space corresponds to the hexagonal cone shape, on a deviatoric plane is characterized by a hexagon shape with corner points, which implies singularities and difficulties during the numerical calculation.

Drucker and Prager replaced this hexagonal shape of yield surface by a simple cylindrical cone, in the deviatoric plane it corresponds to a circle. Its yield function *f* can be expressed by the formula:

$$f(p,q,\alpha,\kappa) = \sqrt{\left({q^2}/{3}\right)} - 3\alpha p - \kappa \tag{3}$$

where

$$\alpha = \frac{2sin\varphi}{\sqrt{3}(3 - sin\varphi)} \tag{4}$$

$$\kappa = \frac{6ccos\varphi}{\sqrt{3}(3 - sin\varphi)}$$

This Drucker-Prager criterion is quite widely used in geotechnical analysis, but experimental research shows that its circular shape does not agree well with experimental data [1]. The stress-strain response predicted by the Drucker-Prager model corresponds to the experimental results, but the strength value matches better with the Mohr-Coulomb model predictions. Drucker-Prager model predicts greater strength at lower deformation compared to Mohr-Coulomb model (MC model is more conservative) [2].

The Drucker-Prager plasticity model may be useful to model soft clays with low friction angles. However, this model is not generally recommended for application to geologic materials [3].

Because the soil strength is crucial parameter determining slope stability, the Mohr-Coulomb constitutive model is generally more preferred to slope stability analysis than the Drucker-Prager model.

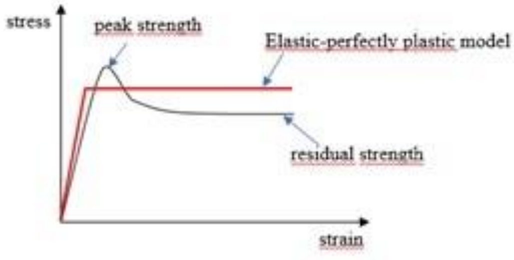

Figure 1: Characteristic stress-strain curve of soil

The numerical approach to the assessment of a slope stability is also significantly affected by the character of slope (natural, anthropogenic slope), Anthropogenic slope (embankment, earthfill dam etc.) has regular geometry usually, the localization of individual material units is usually a-priori known with high reliability, often this slope consists of one or two materials only, the slip zone has simpler shape and finally, the slope is artificial dewatered or the recharge into the slope body is eliminated. On the other hand, the natural slopes represent complex phenomena to model, both in space and time. They are characterized by complicated terrain morphology, which consists of concave and convex parts, by complicated geological structure, including the orientation of geological structures with respect to slip surface, the soil material is significantly non-homogeneous. Previously mentioned factors, together with complicated hydrological and hydrogeological conditions in slope and variable shape of slip zone, affect the computational approaches, dimensionality of simulation and necessity of coupled comprehensive approach to the modelling. The overall concept is presented in the Fig. 2. It provides a systematic methodology for the description and understanding of all geological and geomechanical processes that must be integrated for the successful assessment of potentially unstable slopes.

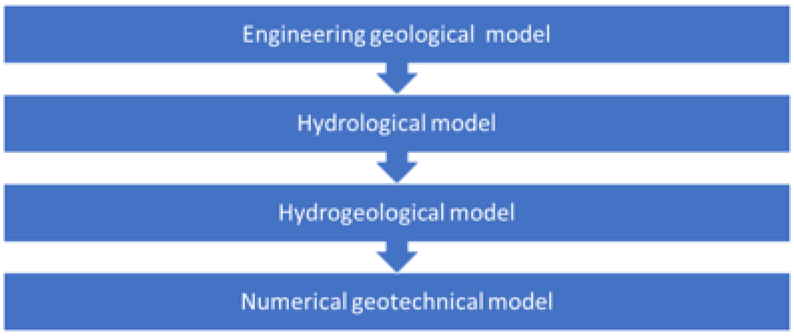

Figure 2: Comprehensive concept of slope stability solution

2 COMPUTATIONAL METHODS FOR SLOPE STABILITY ASSESSMENT

The computational methods used for the slope stability assessment are usually divided into two basic groups. The first group is based on the force, resp. moment equilibrium of the part of slope above the predefined slip surface. This conventional simple limit equilibrium method (slice method) has following limitations and simplifications:

- the predefined slip surface is required
- a rigid-plastic constitutive model with the Mohr-Coulomb limit state surface is commonly
- used in analyses (rigid slice)
- the mobilization of shear strength along the entire slip surface is assumed
- the deformation behaviour of slope is not involved into the calculation
- only quantification of stability can be obtained, no displacements can be evaluated
- stability factor is expressed as ratio of passive (anti-slip forces) and active forces (sliding forces)

Nowadays the numerical methods (including frequently used finite element method) are increasingly used for slope stability assessment due to many particular advantages over the previously mentioned limit equilibrium method. The stability slope factor based on the finite element calculation is very often evaluated by Shear Strength Reduction Method - SSRM using Mohr-Coulomb constitutive model [4]. By this technique, a series of elastic–perfectly plastic problems are analyzed with variably reduced shear strength parameters (cohesion and friction angle) obtained through dividing the actual strength parameters c and φ by a series of factors F, checking the conditions of failure (convergence of solution). The factor F initiating failure is taken as the stability factor of slope.

$$c_r = \frac{c}{F}, (tan\varphi)_r = \frac{tan\varphi}{F} \tag{5}$$

Zheng [5] shows that the stability factor calculated by the finite element-strength reduction technique are slightly greater than those obtained by the limit equilibrium method.

3 PLANAR(2D) VERSUS SPACE(3D) SLOPE STABILITY MODEL

Character of slope determines the numerical modelling approach to the stability analysis. Planar(2D) model of slope is solved under the plane strain condition and, unlike the anthropogenic slope, this condition is not usually filled for natural slopes because of specific factors mentioned in the previous chapter. Spatial(3D) model takes into account the spatial character of stress-strain space inside a natural slope and therefore is more realistic compared to a planar model. Many studies show that evaluated stability factor F(2D) obtained by planar calculation is lower or equal to the stability factor F(3D) based on 3D model. Differences between F(2D) and F(3D) can be more significant for natural slopes (up to 50%). Adriano [6] presented that differences between the F(2D) and F(3D) range between 15%-50% for concave and convex slopes, higher differences are investigated for concave slopes. Fig. 3 presents a comparison between stability factors Fs2D (based on the 2D model) and Fs3D (based on the 3D model) for concave and convex slopes [7].

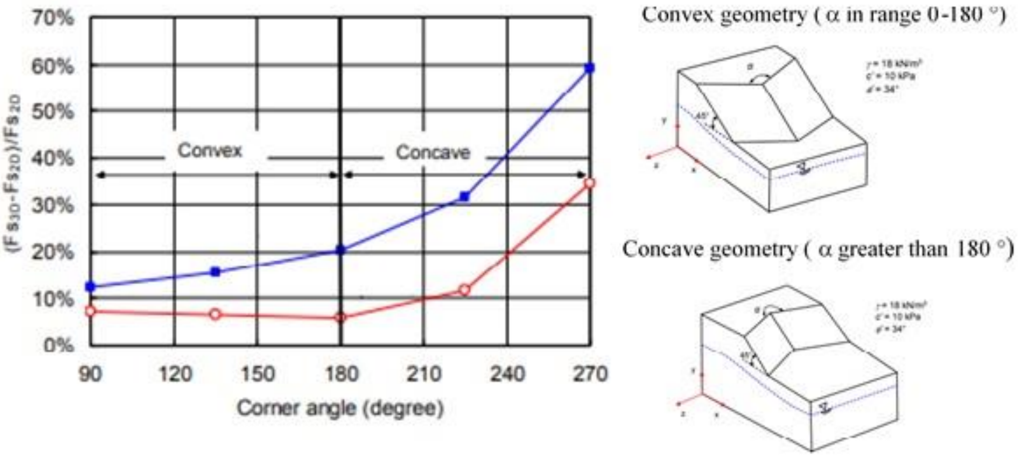

Figure 3: Comparison of Fs2D and Fs3D stability factors for convex and concave slopes [7]

4 APPLICATION OF COMPREHENSIVE APPROACH TO THE NATURAL SLOPE STABILITY ANALYSIS

Brief characterization of the analyzed real natural slope:

- extent of the landslide (approx. 200 m width, 500 m length)
- complicated morphology of natural slope, significant concave shape of slope;
- complicated geological profile – 8 quasi-homogeneous engineering geological units (fractured hard rocks covered by variably grained colluvium);
- the slope is affected by historical landslide activities;
- irregular shape of fully saturated shear zone of fined- grained colluvium;
- complicated hydrogeological conditions, two regional groundwater levels observed (colluvium and hard rock basement), perched aquifers etc.;
- three anthropogenic factors (railway embankment, man-made deposit, road cut) potentially impacted stability of the slope.

Considering the previously mentioned characteristics, the comprehensive 3D numerical modelling approach is needed for the stability analysis (Fig.4). The authors critically assessed the available archive data (exploration boreholes, reports etc.), generated 3D models using various software (RockWorks, GMS), and transferred engineering geological model to hydrogeological model built in FEFLOW and geotechnical simulation software (MIDAS GTS NX).

The engineering geological model characterized the rock environment by defining individual quasi-homogenous lithostratigraphic units and their associated geotechnical parameters. The terrain relief (DRM) was analyzed using advanced geoinformation technologies, including satellite radar interferometry and laser surface scanning. Engineering geological model formed the framework for subsequent set up of hydrogeological and geomechanical processes simulations.

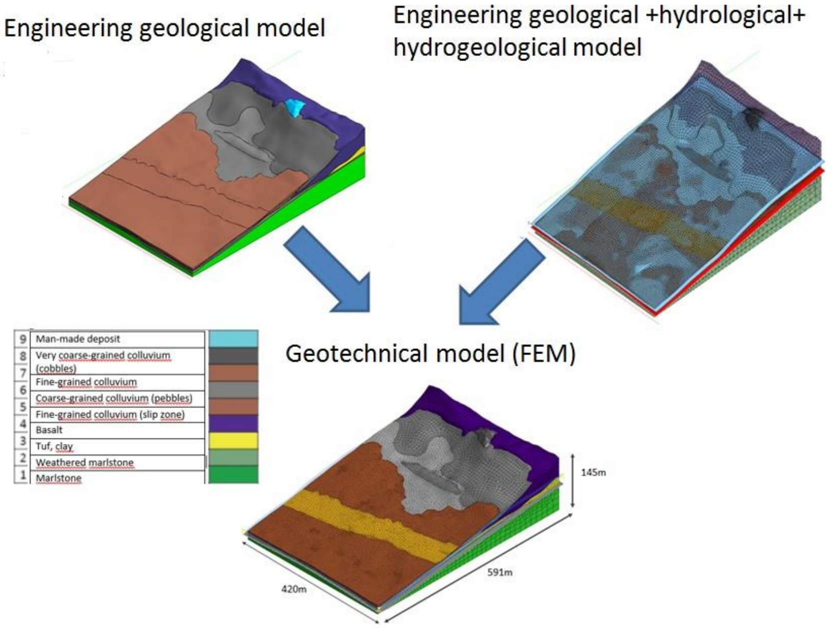

Figure 4: Scheme of comprehensive approach to the stability analysis of real natural slope

3D hydrological model was built in MIKE SHE software (based on Finite Difference Method) by DHI. The surface runoff, evapotranspiration, processes in the unsaturated shallow subsurface zone and in the deeper saturated zone were analyzed using available field data (2009-2013) for the calibration.

The achieved results of the hydrological model were introduced as boundary conditions into the 3D hydrogeological model. The transient variably saturated flow including saturation, moisture content, and distribution of pore pressure in individual quasi-homogeneous units were simulated using FEFLOW software (based on Finite Element Method) – see Fig.5.

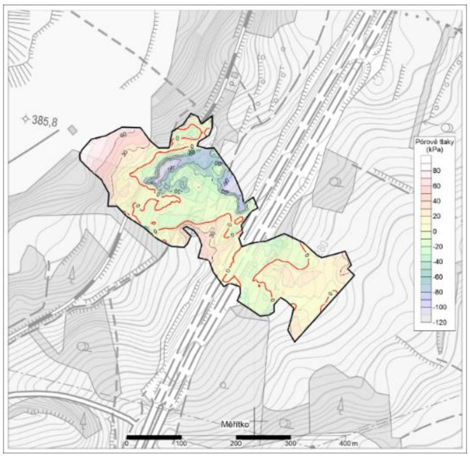

Figure 5: An example of output from variably saturated flow hydrogeological model (pore pressure on shear zone)

Based on the results of hydrogeological model, the 3D geotechnical stability model was performed. The software MIDAS GTS NX (Finite Element Method) was used for the assessment of stress- strain state in the analyzed slope assuming Mohr-Coulomb constitutive model. Due to the documented historical unstable area, the shear strength characteristics in the shear zone were assumed as residual. The stability factor was evaluated using Shear Strength Reduction Method.

The application of presented comprehensive approach enables to determine stability problematic areas, location of shear zones (surfaces), and stability factor of slope stability. The complex analysis of the results allows evaluating the key factors of the landslide activation, interconnection of slip surfaces and the mechanism of landslide formation (Fig.6-7).

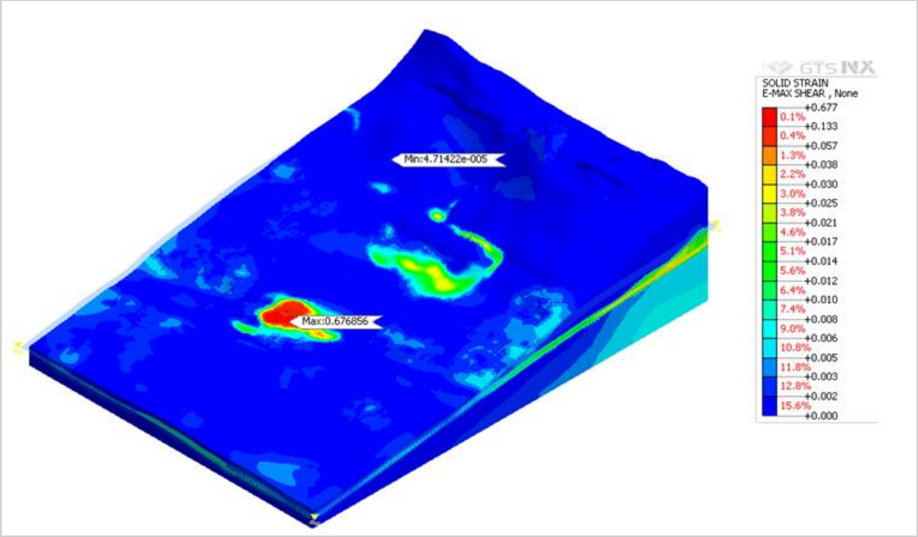

Figure 6: An example of output from geotechnical slope stability model (shear strain)- stability factor F=0.93

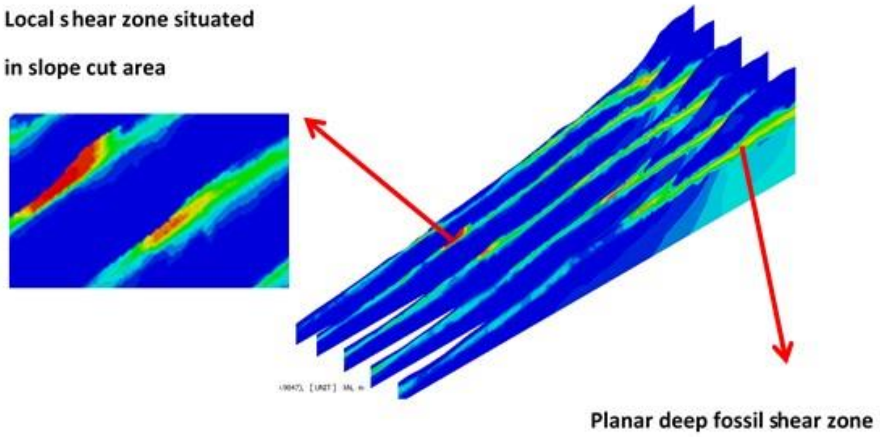

Figure 7: An example of interconnection of global and local shear zones in slope

5 CONCLUSIONS

- The comprehensive approach to stability analyses of slopes increases chances to avoid the misleading conclusions. The realistic behaviour and properties of the rock mass and its potential interaction with the building structure can be assessed and validated using a sequence of specific types of models, simulating processes affecting the rock mass stability.
- Complicated terrain morphology, geological structure including orientation of geological structures relative to slip surface, hydrological and hydrogeological conditions of the site, complex geometry of the slip surface (shear zone) and impact of anthropogenic factors of nonlinear shape requires application of 3D numerical modelling.
- The reliability of the results of numerical models is essentially determined by the

reliability of constitutive material model and the reliability of input data in heterogenous and anisotropic environment.

- The geotechnical risk faced by an engineering project is inversely proportional to the level of details and accuracy of the conceptual model of site developed through ground investigations. The better the model reflects actual conditions, the lower the residual risk.

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