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LANDSLIDE OF SANDSTONE BLOCKS WITH THE SURFACE OF SLIDING RUNNING ON THE LAYER OF UNDERLYING CLAYSTONES - ONE OF TYPE SLOPE DEFORMATION MODEL IN CARPATHIAN FLYSCH

SESUV PÍSKOVCOVÝCH BLOKŮ SE SMYKOVOU PLOCHOU UMÍSTĚNOU NA PODLOŽNÍCH JÍLOVCÍCH – JEDEN Z TYPOVÝCH MODELŮ SVAHOVÝCH DEFORMACÍ V KARPATSKÉM FLYŠI

Abstract

The essence of the study is the knowledge broadening concerning various stability processes in the slopes of the Carpathian flysch, which is one of the most active geological unites in the Czech and Slovak Republic as far as slope deformations are concerned. The aim of the grant is the qualification of the factors essential in the landslide type gravitational movement in the slopes of the Carpathian flysch. For this purpose, several basic type models of the slope geological structure were chosen in the first phase. In the following phases, the relationships between the degree of stability on one side and internal friction angle, cohesion, saturation, slope gradient and the on the other side, were analyzed. The partial study (in this article) deals with only one of them (Landslide of sandstone blocks with the surface of sliding running on the layer of underlying claystones). From analysing the results it follows that it is the saturation of the slope, the saturation of layers and the gradient of slopes that affect the stability most; the angle of internal friction and cohesion having a lesser influence.

Abstrakt

Podstatou studie je rozšíření poznání o stabilitním chování svahů v karpatském flyši, který představuje z hlediska četnosti výskytu svahových deformací jednu z nejpostiženějších geologických jednotek v České a Slovenské republice. Cílem grantu je kvantifikace faktorů rozhodujících o gravitačním pohybu sesuvného typu ve svazích karpatského flyše. Pro tento účel bylo v první fázi vybráno několik základních typových modelů geologické stavby svahů a v následujících fázích byly analyzovány vztahy mezi stupněm stability a úhlem vnitřního tření, soudržností, zvodněním, sklonem. Dílčí studie v tomto článku se zabývá jenom jedním z nich (sesuv pískovcových bloků se smykovou plochou umístěnou na podložních jílovcích). Z analýzy výsledků vyplývá, že největší vliv na stabilitu má zvodnění svahu, mocnost a sklon svahů, menší vliv má uhel vnitřního tření a soudržnost.

Key words: slope deformation, engineering geology, flysch zone

Introduction

The Carpathian flysch [1-14] was affected by a large number of slope gravitational movements iniciated and reactivated by anomalous precipitation especially after flood situation in 1997. The present day possibilities of information technologies make possible to take in consideration variable factors disturbing the equilibrium state of slopes in far broader extent. In order to deal easily with extensive data files and to use several variants of calculations, the methods of limit equilibrium were used. Each of the calculations was realised in four methods the results of which were compared. The study should thus become the contribution to the more objective knowledge and estimation of the stability conditions, and to the more effective decision-making about the ways of rescue measures in the Carpathian flysch as far as the landslides are concerned.

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Methods

GeoStar [2] implements a range of calculation methods for slope stability calculations using limit equilibrium. Together with well known advanced modified methods. These methods were developed during large scale Czechoslovak research projects for open east mining in the North Bohemian lignite basins. This chapter presents basic information on each method. The names of the methods were published and therefore the original names are used in this document an in the program itself. The names are formed from Czech abbreviations.

Table 1: Signification of symbols in names of methods [2]

Tabulka 1:Význam symbolů v názvech metod [2]

E-Effective stress	**K - Circular shear surface**	**J - Simple method**	**N - undistinguished shear strength**
or	or	or	or
T - Total stress	**O - General shear surface**	**P - Advanced method**	**R - Distinguished shear strength**

Existing combination names are in the following table

Table 2: Names of methods which have symbols in names [2]

Tabulka 2: Názvy metod, které mají v názvu symboly [2]

mark	Meaning	used in method name
E	effective strength	EKJ, EKP, EOJ, EOP
T	total strength	Total K, Total O
K	circular shear surface	EKJ, EKP, ProgresK,KJN,KPN,KPR, TotalK
O	general shaped shear surface	EOJ, EOP, Progres O, OJN, OPN, OPR
J	simple method	EKJ, EOJ, KJN, OJN
P	accurate method	EKP, EOP, KPN, OPN, KPR, OPR
N	undistinguished strength	KJN, KPN, OJN, OPN
R	distinguished strength (residual params used)	KPR, OPR
Progres	Progressive failure	Progres K, Progres O

In the formulas describing individual methods, the following set of symbols is used.

Table 3: Signification of symbols used in formulas [2]

Tabulka 3: Význam symbolů použitých ve vzorcích [2]

γ	unit weight	b_i , l_i	slice width, length of the shear surface in i-th slice
φ'_i , $\varphi'_{i,r}$	effective angle of shear strength, peak and residual value	h_i	height of the slice at centerline
c'_i , $c'_{i,r}$	effective cohesion, peak and residual, total cohesion	$t_{i,R}$, $t_{i,L}$	vertical distance between the point of action of the interstice force and the center of the slice base
k_{sx} , k_{sy} , k_w	seismic coefficients in x and y directions, external horizontal force coefficient	W_i	slice weight
Θ	the basic angle of internal forces	H_i	horizontal force (from external horizontal forces)
$f_{i,R}$, $f_{i,L}$	distribution function (left and right)	N_i	normal force
Tol	the calculation tolerance	T_i, $T_{i,r}$	tangential force - shear resistance
F_m, F_f , F	safety factor from the momentum and force condition, overall safety factor	$Z_{i,R,x}$,$Z_{i,L,x}$	interslice force, left and right
R	shear surface radius	u , U	pore pressure and lifting force

x_s , y_s , x_i, y_i	coordinates of the center of the shear surface or the momentum point, coordinates of the i-th slice	r_u	pore pressure coefficient
α_i	inclination of the shear surface in the i-th slice	*i*	i-index of the i-th slice

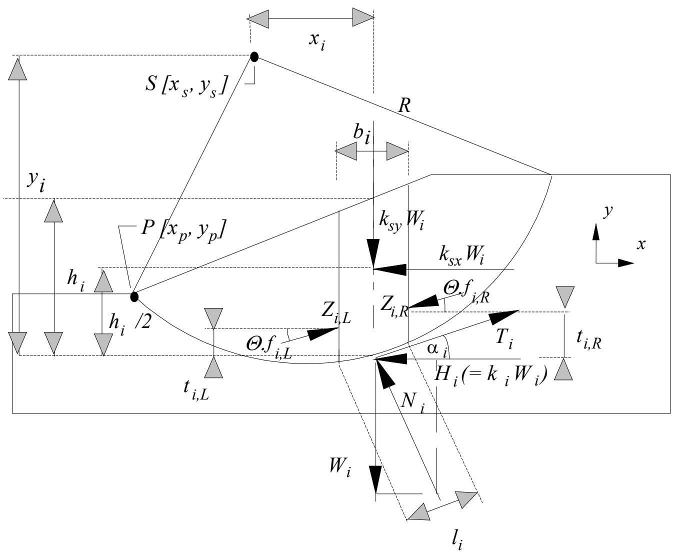


Fig. 1: Scheme of GeoStar methods

Obr. 1: Schéma metod GeoStaru

EOJ method

EOJ method is a simple method for general shape shear surface. In the basic formula $F = \frac{A}{B}$ (A is numerator and B is denominator) is solved using the method of successive approximations. The method is equivalent to the EKJ method and it does not involve interslice forces. The method strongly depends on the position of the momentum point.

$$A = \sum_i \left(\frac{W_i \cdot (1 - r_u) \cdot \tan \varphi'_i + c'_i \cdot b_i}{\cos \alpha_i + \sin \alpha_i \cdot \dfrac{\tan \varphi'_i}{F}} \right) \cdot \left(\sin \alpha_i \cdot (x_i - x_s) + \cos \alpha_i \cdot (y_s - y_i) \right)$$

$$B = \sum_i \left(W_i \cdot (x_i - x_s) \right) + \sum_i \left(H_i \cdot (y_s - y_i) \right)$$
$$- \sum_i \left(\frac{W_i - \dfrac{b_i}{F} \cdot \tan \alpha_i \cdot \left(c'_i - u_i \cdot \tan \varphi'_i \right)}{\cos \alpha_i + \sin \alpha_i \cdot \dfrac{\tan \varphi'_i}{F}} \right) \cdot \left(\cos \alpha_i (x_i - x_s) - \sin \alpha_i (y_s - y_i) \right)$$

EOP method

EOP is equivalent to the EKP method. It is an advanced method for general shape shear surfaces. It involves interslice forces with distribution function and it follows all equilibrium conditions.

From force equilibrium it follows that

$$F_f = \frac{\sum_i \left(N'_i \cdot \tan \varphi'_i + c'_i \cdot \dfrac{b_i}{\cos \alpha_i} \right) \cdot \dfrac{1}{\cos \alpha_i}}{\sum_i \left(W_i + \tan \Theta \cdot f_{i,R} \cdot Z_{i,R,x} - \tan \Theta \cdot f_{i,L} \cdot Z_{i,L,x} \right) \cdot \tan \alpha_i + \sum_i H_i}$$

from momentum equilibrium

$$F_m = \frac{\sum_i \left(N'_i \cdot \tan\varphi'_i + c'_i \cdot \frac{b_i}{\cos\alpha_i} \right) \cdot \left(\sin\alpha_i \cdot (x_i - x_s) + \cos\alpha_i \cdot (y_s - y_i) \right)}{\sum_i \left(W_i \cdot (x_i - x_s) \right) + \sum_i \left(H_i \cdot (y_s - y_i) \right) - \sum_i \left(N'_i + \frac{u_i \cdot b_i}{\cos\alpha_i} \right) \cdot \left(\cos\alpha_i \cdot (x_i - x_s) + \sin\alpha_i \cdot (y_s - y_i) \right)}$$

Interslice forces are calculated recursively like for the previous EKP method according to

$$Z_{R,x} = \frac{Z_{L,x} \cdot \left(1 + \tan\Theta \cdot f_R \cdot \tan(\alpha - \varphi'_m)\right) + \frac{c' \cdot b}{F} \cdot \left(1 + \tan\alpha \cdot \tan(\alpha - \varphi'_m)\right)}{1 + \tan\Theta \cdot f_R \cdot \tan(\alpha - \varphi'_m)}$$
$$- \frac{u \cdot b \cdot \left(\tan\alpha - \tan(\alpha - \varphi'_m)\right) + W \cdot \tan(\alpha - \varphi'_m) + H}{1 + \tan\Theta \cdot f_R \cdot \tan(\alpha - \varphi'_m)}$$

again,

$$\varphi'_m: \qquad \tan\varphi'_m = \frac{\tan\varphi'}{F}$$

The normal force is

$$N'_i = \frac{W_i (1 - r_u) - \frac{c'_i b_i}{F} \cdot \tan\alpha_i + \tan\Theta \cdot \left(f_{i,R} \cdot Z_{i,R,x} - f_{i,L} \cdot Z_{i,L,x} \right)}{\cos\alpha_i + \sin\alpha_i \cdot \frac{\tan\varphi'_i}{F}}$$

The course of the computation is the same as for the EKP and KPN methods.

The position of the interslice force load points is calculated, like in the EKP method, according to

$$t_{i,R} = \frac{Z_{i,L,x} \cdot \left(t_{i.L} - \frac{b_i}{2} \cdot \left(\tan\alpha_i - \tan\Theta \cdot f_{i,L} \right) \right) - Z_{i,R,x} \cdot \frac{b_i}{2} \cdot \left(\tan\alpha_i - \tan\Theta \cdot f_{i,R} \right)}{Z_{i,R,x}}$$

Spencer O method

Spencer method for general shaped shear surfaces is an advanced method assuming the interslice forces are

$$Z_{i+1} = \frac{\frac{c'_i \cdot b_i}{\cos\alpha_i \cdot F} - W_i \cdot \sin\alpha_i + \frac{\tan\varphi'_i \cdot \left(W_i \cdot \cos\alpha_i - \frac{u_i \cdot b_i}{\cos\alpha_i} \right)}{F}}{\cos(\alpha_i - \Delta_{i+1}) \cdot \left(1 + \tan\varphi'_i \cdot \frac{\tan(\alpha_i - \Delta_{i+1})}{F} \right)}$$
$$+ \frac{Z_i \left(\cos(\alpha_i - \Delta_i) \cdot \left(1 + \tan\varphi'_i \cdot \frac{\tan(\alpha_i - \Delta_i)}{F} \right) \right)}{\left(\cos(\alpha_i - \Delta_{i+1}) \cdot \left(1 + \tan\varphi'_i \cdot \frac{\tan(\alpha_i - \Delta_{i+1})}{F} \right) \right)}$$

The inclination of interslice forces on the i-the vertical is $\Delta_i = f_i \cdot \tan\Theta$ and for moments it is true that

$$J_{i+1} = 0.5 \cdot Z_{i-1} \cdot \left(\sin\Delta_{i-1} \cdot (b_i + b_{i-1}) - \cos\Delta_{i-1} \cdot (b_i \cdot \tan\alpha_i + b_{i-1} \cdot \tan\alpha_{i-1}) \right)$$

The course of calculation is:

- for given Θ find F according to the first formula so that Z_n=0.
- from moment equilibrium find Θ so that $\sum_i J_i = 0$.

Janbu method

The Janbu method does not fully compare to other methods of slope stability. The basic formula for the factor of safety is

$$F = \frac{\sum_i \left(\frac{c'_i + \left(\frac{W_i + \Delta Z_{i,y}}{b_i} - u_s \right) \cdot \tan \varphi'_i}{1 + \frac{\tan \alpha_i \cdot \tan \varphi'_i}{F}} \cdot b_i \left(1 + \tan^2 \alpha_i\right) \right)}{\sum_i \left(\left(W_i + \Delta Z_{i,y} \right) \cdot \tan \alpha_i \right)}$$

which can also be written as $F = \sum_i A_i \Big/ \sum_i B_i$

The following formulas are used to calculate the quantities required:

$$\Delta Z_{i,x} = B_i - \frac{A_i}{F}, \qquad i = 2,3,\dots,n \ , \ Z_{i,x} = Z_{i+1,x} + \Delta Z_{i,x}, \qquad i = 2,3,\dots,n$$

$$Z_{1,x} = Z_{n+1,x} = 0$$

These formulas are used in the calculation

$$Z_{i,y} = Z_{i,x} \cdot \tan \alpha_i + t_i \cdot \frac{\Delta Z_{i-1,x} + \Delta Z_{i,x}}{b_i + b_{i-1}}, \qquad i = 2,3,\dots,n \ , \ Z_{1,y} = Z_{n+1,y} = 0$$

$$\Delta Z_{i,y} = Z_{i+1,y} - \Delta Z_{i,y}, \qquad i = 2,3,\dots,n$$

The algorithm using above formulas is:

- $\Delta Z_{i,y} = 0, \qquad i = 2,3,\dots,n$
- $t_i = h_i/3, \qquad i = 2,3,\dots,n$
- using direct iteration calculate *F* according to the basic formula. Put $\tilde{F}_j = F$
- calculate new values of $\Delta Z_{i,y}, \qquad i = 1,2,\dots,n$
- if $j > l$ and $\left|\tilde{F}_{j-1} - \tilde{F}_{j-2}\right| > Tol$ use direct iteration again to get *F* from the basic formula. Put $\tilde{F}_j = F$.
- if $j > l$ and $\left|\tilde{F}_{j-1} - \tilde{F}_{j-2}\right| < Tol$, than $\tilde{F}_{j-1}$ is the resulting factor of safety.

Type model - Partial project

Type model is comprised of the sandstone blocks sliding on moderate aslope underlying claystone (fig. 2). It represents deep creep movement, common space of rupture was considered for calculation. The geotechnical parameters of underlying claystone bed are: effective cohesion 20 kPa angle of internal friction 25°, unit weight 21 kN/m^3. Geotechnical parameters of sandstones (Novosad in Abuzbeda, 1997) are: effective cohesion 150 kPa, angle of internal friction 39°, unit weight 24,4 kN/m^3. The parametric project was processed on the base of limit equilibrium method namely EOJ, EOP, SPENCER, JANBU.

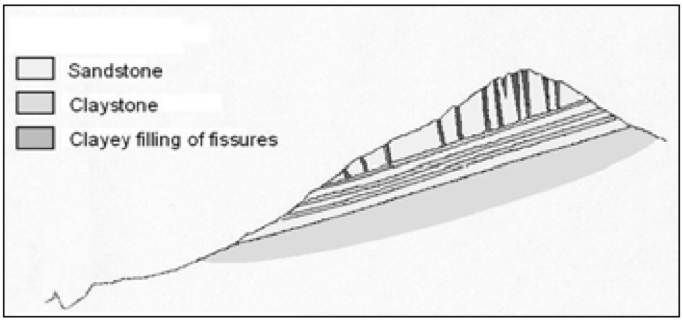
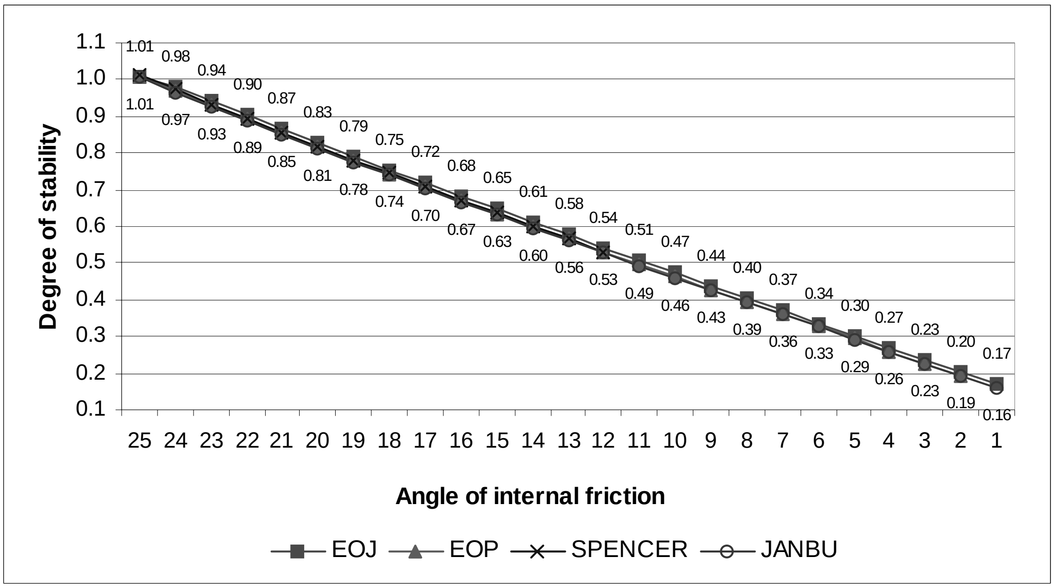


Fig. 2: Type model slope deformation

Obr. 2: Typový model svahové deformace

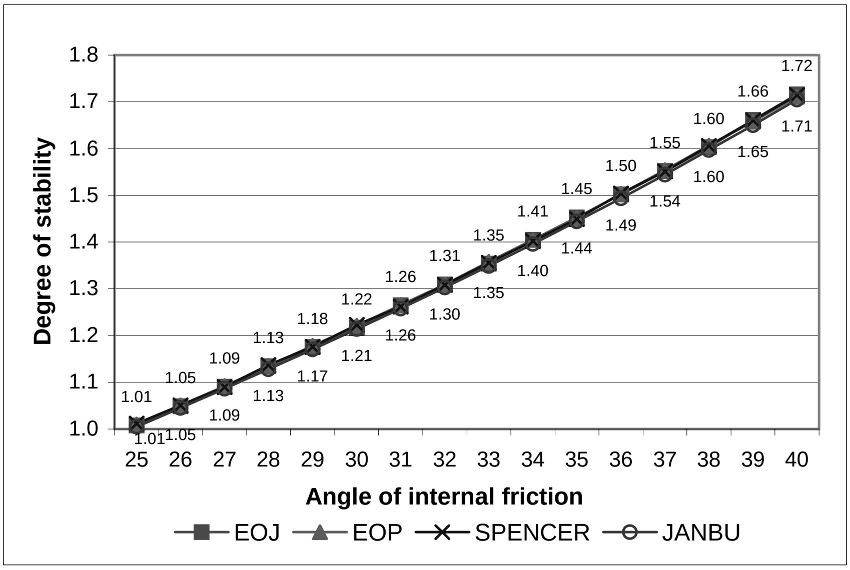
Degree of stability of the initial profile with the above mentioned geotechnical properties where equal to 1 in accordance with JANBU method. The real values of geotechnical parameters are initial for type model of Flysch Zone. The values near the real values and peripheral values of parametrical project represent less real and extreme geotechnical parameters. They were used for the investigation of the trends of degree stability changes.

Effective *angle of internal friction* of underlying claystone, where is located the longest part of the space of rupture, was the first investigated parameter. Initial value 25° in which was the degree of stability equals to 1,01 according to EOJ, EOP, SPENCER, JANBU method. For 1° reducing of effective angle of internal friction led to decreasing of 0,03-0,04 of degree of stability according to EOJ, EOP, SPENCER, JANBU method. It means reducing of 3° of angle of internal friction came to 0,1 change of degree of stability (Graph 1). Rising of 3° of angle of internal friction increased degree of stability of 0,1. Higher value of angle of internal friction increase the influence on stability degree, 1° of angle of internal friction correspond to 0,06 (Graph 2). The difference between the individual methods is insignificant, what is unusual.



Graph 1: Dependence of stability degree on decrease of effective angle of internal friction of underlying bed with parameters: unit weight 21 [kN/m^3]; effective cohesion 20 [kPa]; saturation 1

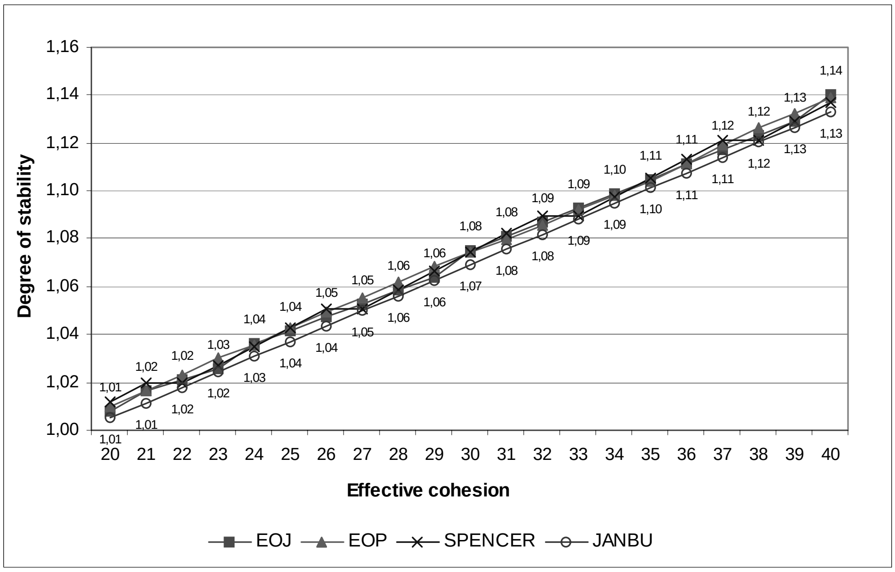
Graf 1: Závislost stupně stability na snížení efektivního úhlu vnitřního tření u spodní vrstvy s parametry: objemová tíha 21 [kN/m3]; efektivní soudržnost 20 [kPa]; saturace 1



Graph 2: Dependence of stability degree on increase of effective angle of internal friction of underlying bed with parameters: unit weight 21 [kN/m^3]; effective cohesion 20 [kPa]; saturation 1

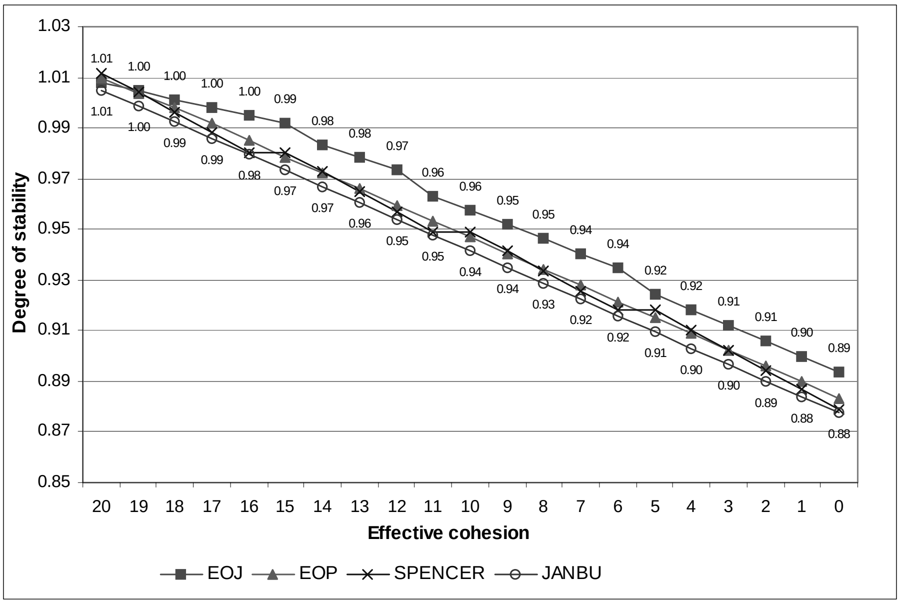
Graf 2: Závislost stupně stability na zvýšení efektivního úhlu vnitřního tření u spodní vrstvy s parametry: objemová tíha 21 [kN/m3]; efektivní soudržnost 20 [kPa]; saturace 1

Further investigated parameter was *effective cohesion*. Initial value of underlying bed was 20 kPa. Increase of 1 kPa of cohesion led to change of 0,01 of degree of stability (Graph 3). Decrease of cohesion came to reducing of degree of stability within the same period, the difference between EOJ and EOP, SPENCER, JANBU method equals to 0,01 (Graph 4).



Graph 3: Dependence of stability degree on rising of effective cohesion of underlying bed with parameters: unit weight 21 [kN/m^3]; effective angle of internal friction 25 [°]; saturation 1

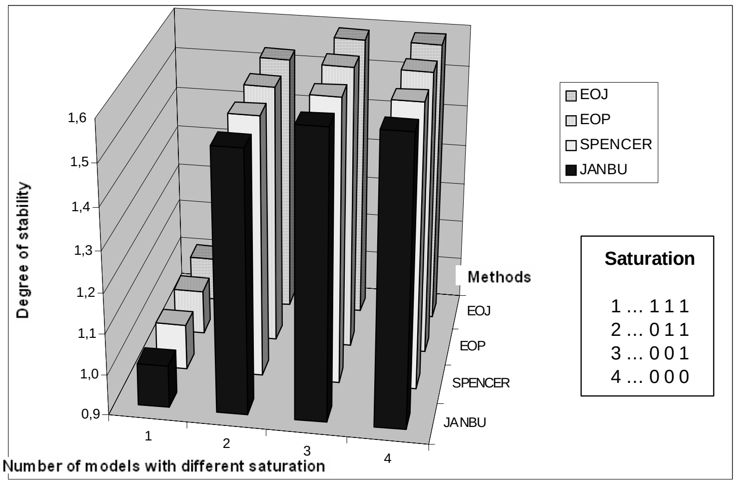
Graf 3: Závislost stupně stability na zvýšení efektivní soudržnosti u spodní vrstvy s parametry : objemová tíha 21 [kN/m^3]; efektivní úhel vnitřního tření 25 [°]; saturace 1



Graph 4: Dependence of stability degree on decrease of effective cohesion of underlying bed with parameters: unit weight 21 [kN/m^3]; effective angle of internal friction 25 [°]; saturation 1

Graf 4: Závislost stupně stability na snížení efektivní soudržnosti u spodní vrstvy s parametry : objemová tíha 21 [kN/m3]; efektivní úhel vnitřního tření 25 [°]; saturace 1

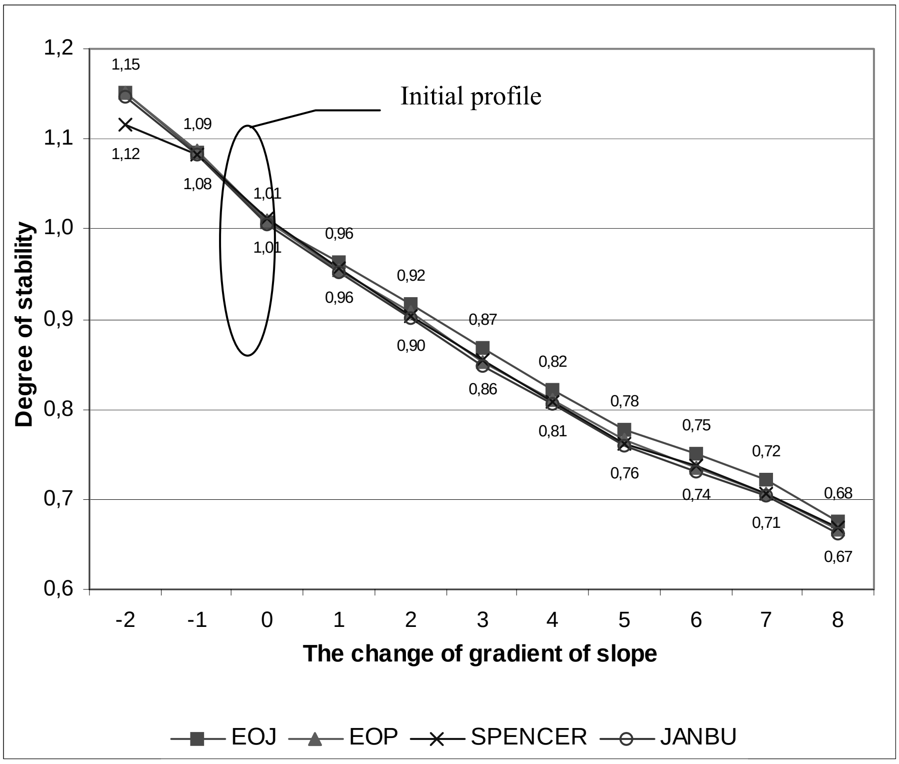
Discovering of *water influence* on slope stability represents very significant factor. Presence of water in slope was expressed by saturation. Saturation value of the beds under the groundwater level equals to 1, saturation value of beds above the groundwater level equals to 0. A slope with all saturated layers represented the initial project profile. In this case the stability degree equals to 1,01 in accordance with EOJ, EOP, SPENCER, JANBU method. Groundwater level of second investigated profile was located under the sandstone blocks. Degree of stability equals to 1,53. Groundwater level of the third type profile was limited on the undermost layer. Degree of stability reached the value of 1,59 in this case. The same stability degree was in case of non-saturated layer (Graph 5).



Graph 5: Dependence of degree of stability on saturation

Graf 5: Závislost stupně stability na saturaci

Gradient of slope influences the slope stability and it is very significant factor. Gradient of slope of type model equals to 28°. Dependence of stability degree on gradient of slope change is shown on Graph 6. Increase of 2° of gradient of slope led to reducing of 0,01 of stability degree, initial degree of stability represents value 1,01 according to EOJ, EOP, SPENCER, JANBU method with the 28° gradient of slope. 4° higher value represents degree of stability 0,86. However, decrease of gradient of slope came to significant rising of stability degree, e.g. by 0,2 value for gradient between 26° and 28°.



Graph 6: Dependence of degree of stability on the change of gradient of slope

Graf 6: Závislost stupně stability na změně sklonu svahu

Conclusion

The partial project deals with the stability analysis of slope models of the Carpathian Flysch, where gravitational deformation of the landslide type occurs. The stability behaviour was assessed according to changes in selected parameters embedded into basic 6 models. These simplified models represented prevailing types of the geological structure of slopes. The partial project deals with only one of them (Landslide of sandstone blocks with the surface of sliding running on the layer of underlying claystones). As the basic parameters conditioning slope movements the following items were observed: the angle of internal friction, cohesion, the gradient of slope and the saturation. To quantify the influence of changes in the presented parameters, the methods of limit equilibrium and their confrontation were employed.

From analysing the results it follows that it is the saturation of the slope, the saturation of layers and the gradient of slopes that affect the stability most; the angle of internal friction and cohesion having a lesser influence. From the practical point of view, this study can be exploited under analogous conditions, e.g. when assessing the impact of draining the slope deformed. The difference in the degree of stability with all the methods employed moves in the value 0.5 depending upon the fact whether the slope is fully saturated with water, or whether the uppermost layer is waterless. After changing the gradient of slope by 2 o, values of the degree of stability vary in the range from + 0.1 to -0.1. Similarly, changes in the degree of stability can be expected also in the case of changing the angle of internal friction and cohesion, although these differences are substantially less marked. It follows from the confrontation of calculations made by individual methods that the all methods have approximately equal results.

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