ACTA MONTANA IGt AS CR (1993)
Series A, No. 4(90), 81—92

ANALOGY IN STABILITY EVALUATION OF HIGH ROCK-CUTTING SLOPES

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Abstract: Empirical engineering-geological approach has been used for the evaluation of stability conditions of unusually high slopes in connection with opencast coal mining at the foot of the Krušné hory Mts. in Bohemia. The dependence between slope gradients, their height and manifestations of instability has been studied with the aim to assess the critical slope gradients in crystalline rocks in the forefield of open-pit mine ČSA. Analogous comparative data obtained in similar geological and geomorphological conditions in the model region of Krupnik in SW Bulgaria, have been used to this purpose. The applied analogy based on the in-situ documentation of actual behaviour in selected slopes both in Bulgaria and Czechoslovakia is inexpensive and time-saving and enables the control of designs of new slopes of quarries and structural cuttings to be effectuated. It is applicable, provided the comparative material is available about behaviour of slopes in analogous engineering-geological conditions.

Key words: slope stability; empirical approach to slope stability; forecasting of slope behaviour

1. INTRODUCTION

The heights of open-pit slopes are continuously increasing with the expanding extraction of mineral raw materials by open-pit mining. Similarly, the heights of rock-cutting slopes increase with the modernization of highway and railway communications. Each new designed slope should be accompanied, according to regulations in different countries, by a reliable stability calculation. We are, however, witnessing the fact that for the stability calculations of slopes up to several hundred metres high, we are almost unable to gather a sufficient quantity of reliable input data, unlike the situation with low slopes with heights of only tens of metres. Requirements put on the preliminary surveying increase, it could be said, with the second till third power of the slope height. It is therefore in most cases quite unrealistic to secure the required extent of prospecting works for reasons of financial costs, time, and capacity. The engineering geology tries to overcome this gap by empirical approach, based on in-situ documentation of already existing slopes, by experience and intuition. An analogy between the behaviour of actually existing slopes and those still to be designed is used (Ross-Brown, 1973; Zika *et al.*, 1988).

An example of the application of analogy is the evaluation of critical gradients of high slopes in crystalline rocks in the forefield of the North Bohemian brown-coal basin on the basis of data comparison with the model region of SW Bulgaria. The comparable data being obtained within the international cooperation between the Institute of Geotechnics, Academy of Sciences of the Czech Republic and the Laboratory of Geotechnics, Bulgarian Academy of Sciences.

2. MODEL REGION OF KRUPNIK

This is a region of high seismicity, where the last big earthquake took place in 1904, when it attained the intensity of 10 MSK. The territory lies in SW Bulgaria, at the southern border of the Simitliya basin, following the direction SW–NE. The basin is filled with coal-bearing sediments and dates back to the Upper Miocene to Pliocene age (Avramova-Tačeva *et al.*, 1984). The southern outcrop part reminds of the outcrop of the North Bohemian brown-coal basin in the section of Jezerka-Albrechtice.

The tectonic southern border of the Simitliya basin, bound to the Krupnik deep fault, is lined by steep mountain slopes up to 500 m high. The rock environment is formed by granitoids with the character of granites to granitic gneisses. Bright, at places schistous (slaty) rocks, permeated by frequent fault zones, are involved. The faults contain tectonically crushed rocks, frequently degraded to fine fragmentary breccia. An outstanding tectonic fault zone (thickness about 30 m, dipping 60° into the basin) has been established by oblique holes at the foot of the slope bordering the Simitliya basin. It contains tectonically crushed and in the depth weathered rocks. This is an analogy of the weakened zones that separate the basin block of crystalline rocks from the mountain block of crystalline rocks at the foot of Krušné hory Mts. in NW Bohemia.

According to Avramova-Tačeva *et al.* (1984), the slope limiting the Simitliya basin from the South demonstrates the features of a recent fault slope. It is conspicuously faulted by slope deformations. In the territories of the largest erosive removal at the toe of the fault slope on the right bank of the Struma river, the slope is found in unusually labile condition. The slope, about 400 m high, finds itself in the condition of deep creeping, the steepest lower section, over 100 m high, being permanently displaced by motions of tumbling character. The general inclination of the entire slope is about 35°. An immediate cause of the recent instability of the slope is found in relieving the slope toe by the erosive activity of the Struma river. Unlike the actually stable slope sections, the unstable sections are relieved by removal of Pliocene and Quaternary sediments of 100 to 120 m thickness. There exists an analogy with the slopes of the Krušné hory Mts. in the forefield of open-pit mine ČSA, if they were relieved, at their toe, by removal of the sedimentary fill of the North Bohemian brown-coal basin.

The model landslide territory has been mapped including the detailed measuring of relief forms in several profiles. Based upon the documentation of exposures, the structurally geological condition of the crystalline series has been evaluated. It has

been found that not a single of the evaluated systems of discontinuity surfaces and weakened zones can be considered preferential with regard to the stability of the evaluated slope.

During the mapping and outcrop documentation, also the displacement forms on the surface of the territory (Fig. 1) have been checked. In the upper part of the

Fig. 1. Intensive disintegration of the surface on the sliding slope at Krupnik in SW Bulgaria. Photo J. Rybář.

slope, a subsidence of the parts loosened by tensile stress has been found, in the intermediate parts the translational (shifting) movements prevail. In addition to that, in the lower part the rock blocks lean out downwards the slope and tensile cracks appear as a manifestation of external rotation. Several alternatives of the

possible course of the deep failure of the slope were considered for the elucidation of the development of deformations recorded and documented on the surface. A chart mostly corresponding to the character of the documented deformations is shown in Fig. 2. The deep disintegration of the rock mass is pointed at there. In the upper part of the slope, a gradual (step-like) shear zone is being formed, which corresponds in plan to a pan-like limitation of the separation area. The partial fault surfaces did not interconnect yet in the medium and lower part of the slope and thus the landslide area is not limited clearly in that part. In the lower part of the slope, the failure has the character of deep bending of blocks, which are separating along the steeply dipping surfaces of discontinuities in the direction of longitudinal tectonic lines.

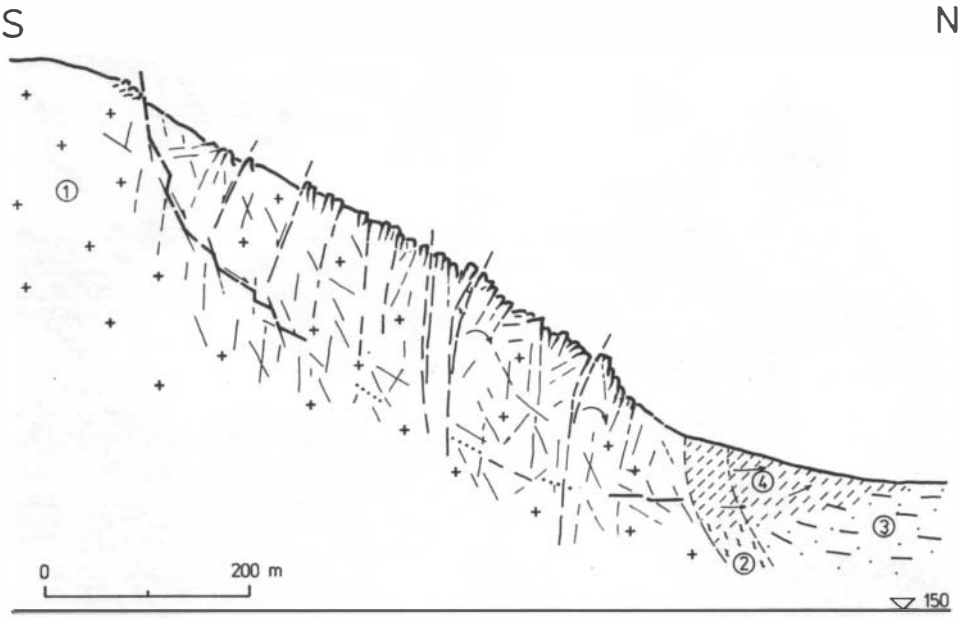

Fig. 2. Characteristic profile of the model region in SW Bulgaria. Crystalline rock: 1 – granites subjected to slight metamorphosis, solid, in places weathered; 2 – tectonically weathered zone. Pliocene: 3 – coarse fragmentary sediments. 4 – faulted zone of the forefield of the rock massif.

The joint Bulgarian-Czechoslovak research activities confirmed that the investigated sliding slope is bound to the structure of the Krupnik deep fault with recent tectonic movements. The activity of this tectonic line is quite conclusive from several details of the relief study, especially in the contact zone of crystalline rocks with the basin fill of the Pliocene age. The existence of recent motions on tectonic fault planes has been best proved by direct measurements by mechano-optical devices of the Institute of the Geotechnics of the Academy of Sciences of the Czech Republic (patent by B. Košťák). The established subhorizontal shear deformations are typical of tectonic displacements (Košťák and Avramova-Tačeva, 1986).

Also the detection of increased radon concentration and increased temperatures in cracks along the fault zone can be considered as an indirect indicator of the tectonic activity.

3. MODEL REGION OF JEZERKA

Unlike the model region of Krupnik, the model region Jezerka in the forefield of open-pit mine ČSA in the North-Bohemian brown-coal basin has been surveyed more closely. The initiative was given by the intention to maximally break out the coal outcrop part of the basin at the footing of steep slopes of the Krušné hory Mts. This intention encountered strong criticism by geological engineering experts, first in open-pit mine ČSA, which as the first in the North Bohemian coal basin approached with the giant open-cast technological equipment the footing of the Krušné hory Mts. The engineering geology and related engineering field experts proved that without special measures, the dangerous deep faulting of the mine forefield, including the crystalline rocks of the adjacent mountain slopes, cannot be avoided. Displacements hazardous not only to the future mining development in the opencast mine, but also to the preservation of the original character of mountain

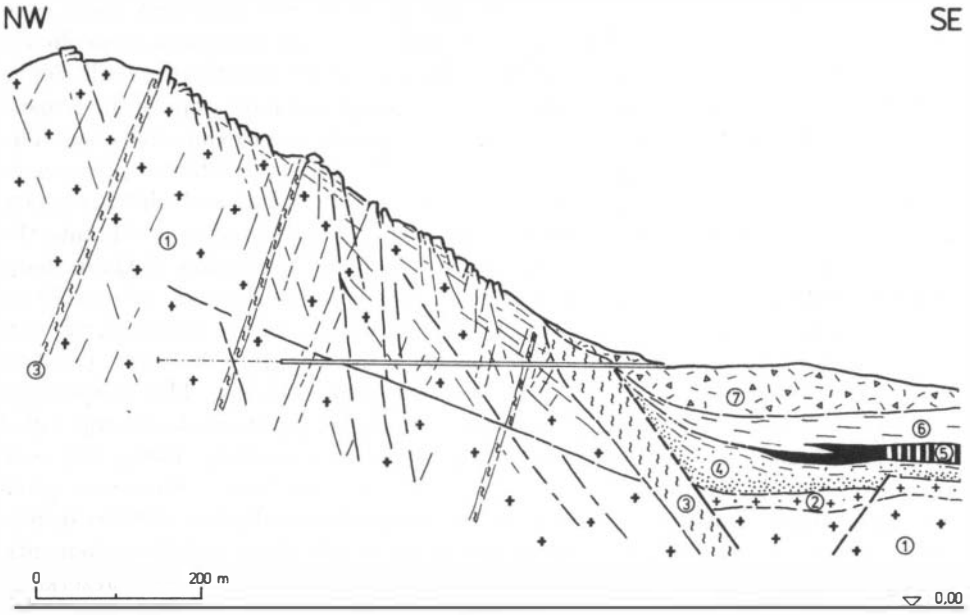

Fig. 3. Illustration of the geological profile of the model region Jezerka in Bohemia. Crystalline rocks: **1** – solid orthogneiss; **2** – kaolinized orthogneiss; **3** – weakened zone (tectonically crushed rocks, locally altered). Miocene sediments: **4** – underlying strata series (in lower positions mostly of fragmentary and sandy character, in upper locations mostly clayey); **5** – coal seam, partly affected by underground mining; **6** – overlying clayey strata series. Quaternary sediments: **7** – clayey sands and debris (accumulations of rockfalls and deluvial sediments).

slopes, could take place. Therefore, compared with original conception, also in open-pit mine ČSA a part of the coal reserves had finally to be bound in residual pillars at the toe of the Krušné hory Mts. slope. With the aim to minimize the losses of coal reserves in these residual pillars, many additional geological, hydrogeological, engineering-geological, and geotechnical survey activities were realized. Several problems had to be answered by intensive research. It turned out gradually that with high variability of geological structure and geotechnical rock parameters on extremely high slopes, it was impossible, by further expansion of the volume of survey works, to attain a substantially higher level of knowledge. In this situation, the author applied empirical and engineering-geological methods of the high slope evaluation. They used, for the assessment of the stability of faulted slopes in the crystalline rocks of the Krušné hory Mts., the analogy with the stability behaviour of fault slopes in SW Bulgaria.

Fig. 3 illustrates one alternative interpretation of engineering-geological conditions in the profile plane drawn through the axis of the pioneer adit under the Jezerka hill. It includes available results of superficial engineering-geological and structural-geological mapping, bore-hole prospecting, documentation of prospecting mine openings, and geophysical survey. Systems of surfaces and zones of discontinuities of various hierarchy were defined. With the exception of the zone of subsurface disintegration (Fig. 4), in the solid mass of crystalline rock there were not found any such systems of discontinuity surfaces, which could have an explicitly determining importance for the stability behaviour of the investigated fault slope.

The model region beneath Jezerka lies on the peripheral fault slope of the Krušné hory Mts., in a section that belongs to morphologically most expressive ones. The fault slope has a young fresh character here. The main relief-forming processes involve slope deformations of catastrophic character, including rock slides, planary and rolling-away dashing, stone falling. The traces of slope erosion recede into the background. At the toe of the slope, there lie large accumulations of Quaternary deposits, mostly tumbled-down rock detritus, attaining the thickness of over 70 m. These accumulations are mostly of the Pleistocene age. Some details of the surface of downfallen and tumbled-down masses at the slope toe, however, point to the occurrence of younger, apparently Holocene displacements. The morphologically conspicuous detritic stream, in whose frontal part lay the rock outcrop called Šibeniční hůrka, corresponded to the youngest phase of dashing. Today, this rock formation has already been drawn by the ČSA opencast mine. Numerous small undrained depressions on the surface of the accumulation (Rybář, 1982 in Rybář, 1987) may be considered a proof of the recent age of this phase of slope movements. Růžičková *et al.* (1987) range the main part of rock tumbling beneath Jezerka to the period from the end of the Pleistocene to the beginning of the Holocene.

The young character of the slope under Jezerka and the enormous accumulations of Quaternary deposits with fresh landforms supported the conception of recent tectonics in the contact zone of the Krušné hory Mts. and the North-Bohemian brown-coal basin in the area of open-pit mine ČSA. Also the existence of the so-called Komořany lake, which in the middle age still filled the natural tectonic depression on the surface of the part of basin close to the Krušné hory Mts., can

Fig. 4. Disintegration of the surface part of the slope beneath Jezerka in NW Bohemia. Photo Z. Kudrna.

be considered an evidence of the recent tectonics. Compared with the Krupnik region, the recent tectonic movements in the Krušné hory Mts. region are more difficult to be demonstrated. In spite of that, the interpretation of the set of long-term high-sensitivity measurements in the forefield of opencast mine ČSA enabled already conclusions to be drawn about the tectonic activity in the massif of the Krušné hory Mts. (Košťák, 1990).

Slopes, displaced by recent and fossil slope movements (Zika, 1985) were documented in the Bulgarian model region. The relationship between the slope gradient and its height was evaluated graphically (Fig. 5). Slopes, which appear entirely

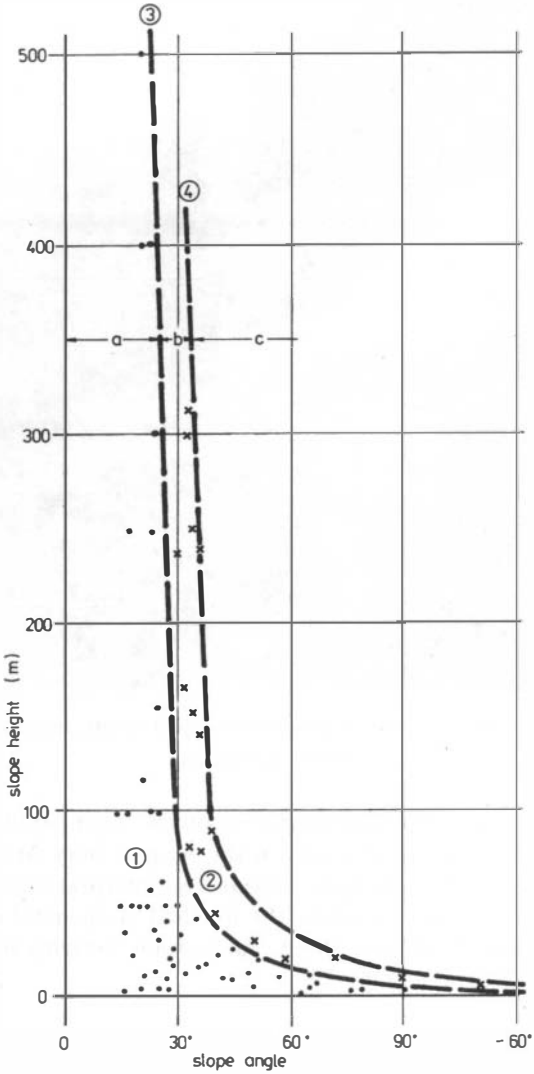

Fig. 5. Relationship between the gradient and height of slopes in granitoids within the model region in Bulgaria. *a* – zone of slopes with long-term stability; *b* – zone of slopes with short-term stability; *c* – zone of unstable slopes; **1** – stable slopes; **2** – slopes with evident signs of movements; **3** and **4** – borders between zones *a*, *b* and *c*.

stable, are shown in the *a* zone of the graph. All slopes, whose characteristic lies within the *b* zone, must be considered unstable from the long-term viewpoint; only a short-term stability can be considered here. Points in zones *a* and *b* could be well limited by envelope curves 1 and 2. There is also zone *c* to the right of curve 2, where no points were recorded. Each slope, which would correspond to such a point,

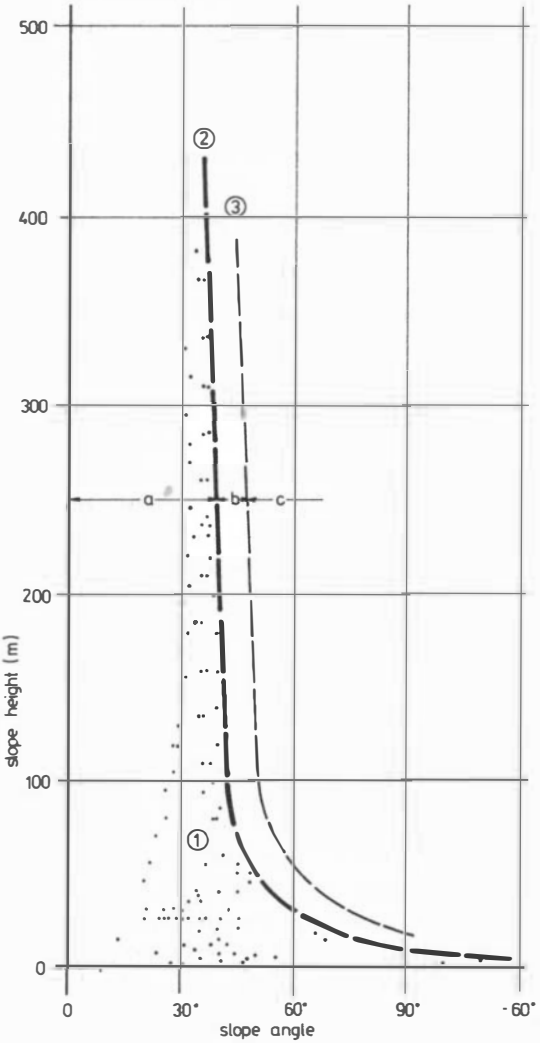

Fig. 6. Relationship between the gradient and height of slopes of crystalline rocks within the model region of Jezerka in Bohemia. *a* – zone of slopes with long-term stability; *b* – zone of slopes with short-term stability; *c* – zone of unstable slopes; **1** – stable slopes, **2** and **3** – borders between zones *a*, *b* and *c*. Zone *a* and border curve **2** were drawn on the basis of in-situ documentation and observations, zones *b* and *c* and border curve 3 were constructed by analogy with the graph in Fig. 5.

would be unstable even from the short-term viewpoint; it would fail immediately and modify itself into a more gentle slope.

By analogy, also the dependence between the slope gradient and slope height was illustrated graphically in Fig. 6 for the forefield of open-pit mine ČSA. Unlike the model region at the border of the Simitliya basin, no part of the crystalline slopes could be considered unstable now, so that all points lie within zone *a*. Envelope curve 1 characterizes the limit gradient of slopes with various heights, if the long-term stability of slopes should be preserved. The course of curve 2 was extrapolated in analogy to the Bulgarian region. Zone *b* was limited in this way within which the parameters of economically designed slopes should be contained. This means to allow even steeper slope gradients than those of long-term stability, at the risk of the occurrence of landslides. The use of acceptable risk rate in the design of opencast mine slopes must be connected with the condition of consistent observance of the technology of mining and introduction of a proper system of observation and control of all deformation phenomena and changes of hydrogeological conditions within the quarry and in its forefield. The reliability rate of this proceeding must be checked continuously by the actual behaviour of freshly formed slopes during the course of mining.

The method has been checked also for other types of rock media than those of crystalline rocks, including the sedimentary fill of the North Bohemian brown-coal basin (Zika *et al.*, 1988). The mutual relation between the height and gradient of the slope and the time was expressed by means of an imaginary model. Theoretical considerations agree with the in-situ observations of ageing of open-pit slopes and structural cuttings. This was confirmed, for example, by Perry and O'Reilly (1990) who investigated the effect of age and slope geometry on the percentual occurrence of slope failures of cuttings for British motorways.

5. CONCLUSIONS

The method of analogy applied to the evaluation of stability conditions in selected regions of crystalline rocks in Bulgaria and Czechoslovakia issues from the in-situ observation of actual behaviour of slopes. Its advantage is given by the fact that results are not afflicted by unreliability in the determination of input parameters, established by in-situ and laboratory rock tests.

The method is not expensive and time-consuming and enables the control of correctness of designs of new opencast slopes and structural cuttings to be effectuated, these projects relying often on demanding and sometimes unrealistic geotechnical solutions of stability. It is applicable, provided the comparative material is available about behaviour of slopes in analogous engineering-geological conditions.

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METODA ANALOGIE PŘI HODNOCENÍ STABILITY VYSOKÝCH SVAHŮ SKALNÍCH ZÁŘEZŮ

Pavel Zika, Jan Rybář a Elka Avramova-Tačeva

V souvislosti s vytvářením nezvykle vysokých svahů při těžbě hnědého uhlí na úpatí Krušných hor v Čechách bylo pro hodnocení stabilitních poměrů využito inženýrsko-geologických empirických přístupů. S cílem vymezit kritické sklony svahů v horninách krystalinika v předpolí lomu ČSA byla sledována závislost mezi sklony svahů, výškou svahů a projevy nestability. Byly využity srovnávací údaje získané v podobných geologických a geomorfologických poměrech v modelové oblasti Krupnik v jihozápadním Bulharsku. Užitá analogie, opírající se o terénní dokumentaci skutečného chování vybraných svahů v Bulharsku a v Československu, je finančně a časově nenáročná a umožňuje kontrolu správnosti projektů nových svahů lomů a stavebních zářezů. Je použitelná, pokud je k dispozici srovnávací materiál o chování svahů v obdobných inženýrsko-geologických poměrech.