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THE ANALYSIS OF THE SLOPE STABILITY IN A BASALT STRIP MINE BY MEANS OF THE BACK ANALYSIS METHOD TO DETERMINE STRENGTH PARAMETERS

1. Introduction

The analysis of the rock slope stability is particularly difficult as the behaviour of the rock mass is determined by both properties of the rock mass as well as its cracks. The problem becomes more complicated when there are more joint sets, which are of a complicated orientation. In such cases, and when the geological structure is little-known, back analysis is useful to estimate the features of the rock mass. The analysis of the mechanisms of landslide movements within rock slopes, particularly the possibility of comparison of the state before and after the landslide occurrence, is the base for back analysis [7]. The data analysis of geodetic monitoring of the area is also useful.

In the article presented, based on the factual example of the rock slope affected by landslide movements, the possibility of using back analysis to estimate strength parameters of the rock mass and calibration of calculation models are introduced.

The main object of the analyses was to estimate the stability of north-western part of the open cast in 'Bazalt Gracze' mine, where the landslide occurred in 2011 [2]. On the analyzed area, the slope stability which was determined by width (thickness) of the left basalt pillar as well as geological structure. The rocks under-laying the basalt deposit are silty basalt residual soil and mudstones. The rock mass in the area under research was disturbed by long-term exploitation, seismic interaction caused by conducted DB as well as by the traffic of heavy vehicles. Because of these facts it was impossible to do any field research on the landslide area that occurred in 2011, it was decided to use the back analysis

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to estimate the strength properties. Parameter determination was done using back analysis, which was conducted for the area of the presently stabilized landslide in 2004, which is adjacent to the landslide that occurred in 2011. It led to the assumption that the features of the rock mass in both areas should be approximate. The determined parameters were then used to analyse the stability conditions for the landslide area that occurred in 2011, for the state before and after the landslide occurrence. It made it possible to determine the range of landslide danger zone on the upper level of the slope. It was essential for safe location of the damaged part of the road.

2. Description of 'Bazalt Gracze' Mine in Gracze

The basalt mine in Gracze is situated in Opolskie Province, in Niemodlin commune territorial division. The mine is one of the oldest mines of that type in Poland, and its history dates back to the 16th century [8]. The mined basalt deposit is the upheval of WSW-ENE strike, and dimension of 100 m by 130–170 m of width, leading up to a height of 197 m above sea level. The deposit is surrounded by silty formations, marls, chalk formations and silty basalt residual soil. The mine carries out mining by means of cut-and-cover method in the slope deep-seated quarry of 8 levels of mining. At present the depth of the mine reaches approximately 90 m. Mining is conducted by means of wall system with the average wall length of 15 m. The inclination of the slopes amounts to 80–85° (Fig. 1).

Fig. 1. Bazalt Gracze mine

3. Landslide Dangers in 'Bazalt Gracze' Mine

There are two areas of landslide hazard in the open cast in 'Bazalt Gracze' mine. The first of them is the area of presently stabilized landslide from 1995, which is situated in the central part of south-western slope [3]. The other one is north-western part of the open cast. In this part there are two landslides, which occurred within a short distance. The first one is the landslide that occurred on 28th June 2004, which is 150 m long and 270 m wide, the one which occurred on all mining levels. The rock volume that underwent landslide processes is estimated at approximately 700 thousand m^3 [1]. That landslide (Fig. 2, Fig. 3) occurred in the neighborhood of the road Gracze-Niemodlin.

Fig. 2. Landslide areas that occurred on 19th July 2011 and in 2004 [4]

On 19th July 2011, in the North-Western part of the open cast, there was a landslide that covered on area, which measured 170 m by 120 m. That landslide affected the upper part of the slope of about 75 m height, up to the floor level VII [6]. It resulted in damage to a 50 m stretch of the district road at Gracze-Rogi. The area affected by landslide processes is shown on the reconnaissance map (Fig. 2) and in the photo (Fig. 3).

Fig. 3. Open cast view with the marked landslide area in 2004 and 2011

4. The analysis of the slope stability of north-west part of open cast in Bazalt Gracze mine

4.1. Introduction

After the landslide in 2004, the ‘Bazalt Gracze’ mine was obliged to do a study, which would enable to determine the conditions of slopes and scarps stability, and to estimate any landslide hazard and to determine a protected zone. With reference to this, in the years 2004–2010 for the needs of ‘Bazalt Gracze’ mine, different individuals and institutions carried out scientific descriptions of the scarp and slope stability, which included geo-physic research. For the needs of this research, some laboratory tests were also carried out, which included 94 determinations of the strength to uniaxial compression on 5×5 samples. There was a considerable amount of information already enabling the estimation of estimate rock strength parameters. However, in the instance of weak or weathered rocks, the obtained parameters for the samples may be significantly different from real properties. It is connected with the fact that the rock samples are chosen from the ones, which are possible to be cut out and properly tested. Therefore, the obtained results are overstated in relation to real properties. Moreover, in the instance of heavily cracked rock mass, as with in ‘Bazalt Gracze’ mine, the behavior of the mass is more determined by cracks’ than by rock mass characteristics.

To estimate the hazard for the landslide area, where landslide movements occurred in 2011, stability calculations of the state before and after the landslide were carried out. The calculations of the state before the landslide occurrence and strength parameters determined in laboratory testing led to the conclusion that they are too low. Therefore, the next stage was to determine the parameters’ values by means of back analysis, using the information about the landslide, which occurred in 2004. For such determined parameters, some new calculations were carried out for the landslide in 2011, for the states before and after the landslide occurrence. Such an approach was aimed at the estimation of the actual stability state of landslide slope as well as to determine the range of landslide hazard zones.

4.2. Stability calculations for north-west slope (landslide area from 2011) for conditions before the landslide occurrence

To analyze the slopes stability in the area of the landslide that occurred on 19th July, 2011, the scientific elaboration from 2004, entitled ‘Expertise Referring to Stability Conditions and Parameters of Scarps and Slopes in the Basalt Mine Gracze’, was used [1]. The data of localization, geometry and geological structure of the soil profile within the analyzed slope were taken from this study as well as strength parameters and thickness volume of the rocks and soils.

The analysis was conducted on three intersections: Z-2, Z-3 and Z-4 with the mining, which came from or was present in the close neighborhood of the landslide area from 2011 (Fig. 4).

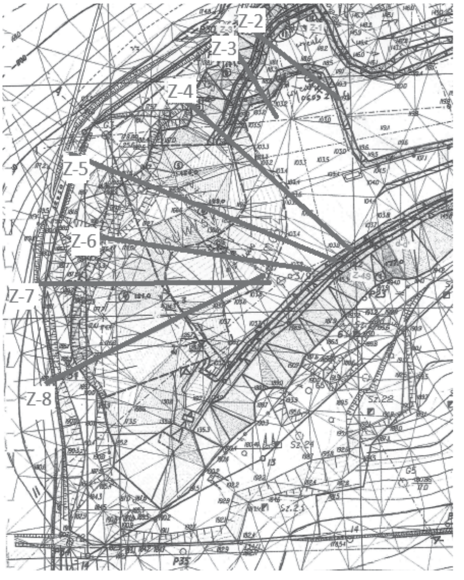

Fig. 4. Location of the analyzed intersections

To calculate, the parameters from the study mentioned above were taken [1], which are presented in Table 1. The scientific description [1] gives each separate layer the parameters' values for dry and wet conditions. Because of the fact that strength parameters' values for wet conditions are less profitable and also considering the fact that the landslides occurred during heavy rain falls, the stability analysis was conducted by means of the parameters for wet conditions.

TABLE 1
Output values of layers' strength parameters used in the analysis [1]

Geotechnical layers	Unit volume	Angle of internal friction	Cohesion
	[kN/m^3]	[°]	[kPa]
Marl	18.45	23.34	147
Basalt residual soil	22.55	15	40
Basalt	30.85	37	458
Silty sand, embankments	17.65	28	0
Tuff	17.42	15.8	75
Mudstone	20.58	14.58	88

Stability analysis was conducted by means of the limit equilibrium method, and its results were presented for Janbu method. The choice of this method for the analysis of the calculation results is connected with its use in other scientific descriptions conducted by the mine, which gives the possibility of a results' comparison.

The juxtaposition of the results obtained is presented in Table 2, whereas for the Z-3 intersection, which is located in the centre of the landslide area, the results were also presented in Figure 5.

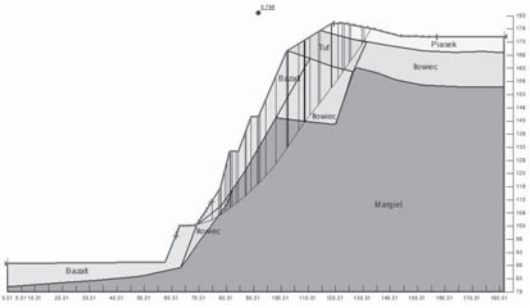

Fig. 5. Calculation results and slip surface for intersection Z-3

TABLE 2
Values of safety factor – output parameters

Intersection number	Calculation results for Janbu method
Z-2	0.804
Z-3	0.762
Z-4	0.779

The values of the safety factors for all the three intersections obtained by calculations are significantly lower than 1.0, which indicates the instability of the slope and the fact that the values of strength parameters are too low. There is the necessity of verifications of these parameters by means of back analysis conducted for the landslide from 2004.

4.3. Re-prognosis of the landslide that occurred in 2004

The stability analysis for the landslide area that occurred in 2004 was conducted by means of the limit equilibrium method, Janbu. To reproduce the situation before the landslide, intersections Z-5, Z-7 and Z-8 were used, which were located in the landslide zone (Fig.4); they were corrected in accordance with height-situational map showing the state of the open cast on 31st. Dec. 2003 [5]. The values of the parameters shown in Table 1, which come from the study carried out in 2004 [1], were accepted as starting point for calculations of the state before the landslide occurrence.

On the bases of calculations made for intersections Z-5, Z-6, Z-7 for geometry before the landslide in 2004, low values of safety factor were obtained. Therefore, such results are correct as they are reflected in the landslide event. The lowest value of indicator *FS* = 0.706, was obtained for intersection Z-5, which was located in the central part of the landslide

(Table 3). Similar, although of a higher value of FS = 0.85 was obtained in the study from 2004 [1]. Figure 6 shows the slip surface in intersection Z-5 of the slope (its shape is approximated to the slip surface show in scientific description from 2004).

TABLE 3
Juxtaposition of safety factors' values for parameters from Expertise (2004)

Intersection number	Calculation results for Janbu method
Z-5	0.706
Z-7	0.791
Z-8	1.055

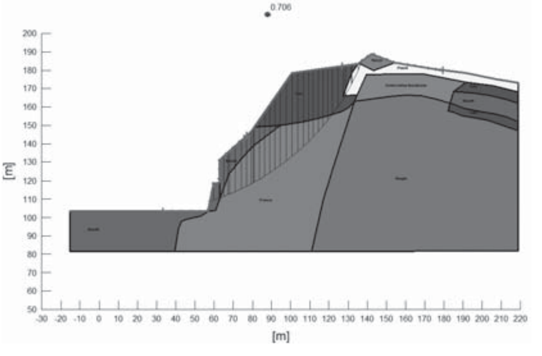

Fig. 6. Stability analysis intersection 5, the state before the landslide occurrence — starting parameters

The next stage of the analysis was to try to determine strength parameters by means of the back analysis method. In order to attain that, during the next stages of calculations, strength parameters' values for particular layers were increased till stability indicator value approximated 1.0 was obtained. That value corresponds with the conditions of limit equilibrium. During the next stages, cohesion and friction of the mass was increased by 10%. Limit equilibrium state of the system for intersection Z-5, going through the central part of the landslide, was obtained with 40% increase in strength parameters' values (Table 4, Fig. 7). Whereas, for intersection Z-7, the same state was obtained with a 30% increase in strength properties. Calibration was not conducted for intersection Z-8 as that intersection for starting parameters was already in limit equilibrium state.

TABLE 4
Safety factor values during the increase in strength of geotechnical layers

Intersection number	Calculation results for Janbu method
Z-5 (140%)	1.013
Z-7 (130%)	1.026
Z-8 (100%)	1.055

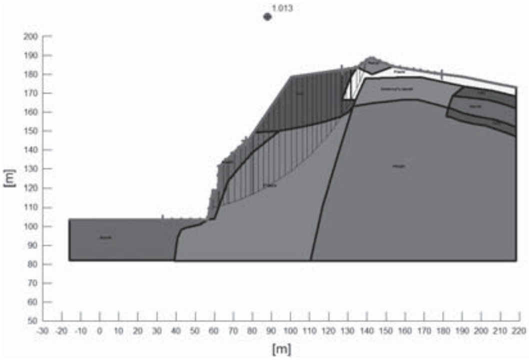

Fig. 7. Stability analysis intersection z-5, state before landslide occurrence — 140% initial parameters' values

On the basis of the results of the above analysis (Table 4), strength parameters' values for geotechnical layers, which were the deposition of strata in the location of the next landslide occurrence in June 2011. Data is presented in Table 5.

TABLE 5
Parameters determined by means of back analysis method for calculations of slope stability in the area of the new landslide (from June 2011)

	Unit weight [kN/m³]	**Angle of internal friction [°]**	**Cohesion [kPa]**
Marl	18.45	31.137	205.8
Basalt residual soil	22.55	20.563	56
Basalt	30.85	46.537	641.2
Dusty sand, embankments	17.65	36.666	0
Tuff	17.42	21.612	105
Mudstone	20.58	20.010	123.2

4.4. Stability analysis for the region of the landslide occurrence in 2011 including corrected strength parameters

On this stage, equilibrium calculations for north-west slope area were done by making use of the parameters determined on the grounds of back analysis. The results of the calculations were presented in Table 6, and for Z-3 intersection in Figure 8.

TABLE 6
Safety factors' values for initial parameters increased by 40%

Intersection number	**Factor of safety**
Z-2	1.120
Z-3	1.064
Z-4	1.108

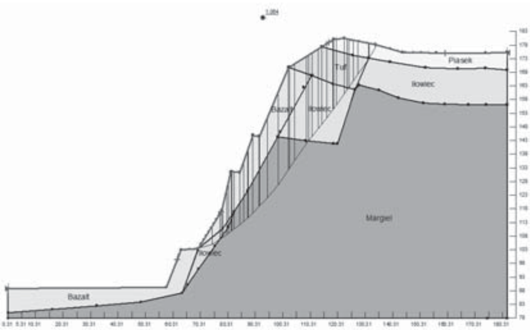

Fig. 8. The slip surface for intersection Z-3

The analysed intersection Z-3 is characterized by a lowest safety factor near value 1.0 (1.064), and the located slip surface corresponds with the cracks that appear on the upper surface of the slope. Therefore, it can be assumed that the strength parameters determined by means of back method show the factual properties of the rock mass, and can be used to determine the hazard zone affected by landslide processes in the analysed area.

4.5. Stability analysis for the hazard state estimation in the area of the landslide from 2011

Determination of the zones endangered by landslide in north-west part of the open cast in ‘Bazalt-Gracze’ mine, were conducted for the actual slope geometry, which means taking into consideration the changes that occurred as a result of the arisen landslide processes. For calculations strength parameters were taken, which were determined by means of back analysis (Table 5).

While estimating the stability of north-west part of the open cast area, a stability analysis for intersection Z-3 was done. They were selected for the calculations as it occurred in the central part of the landslide area. The results obtained for stability calculations for the intersection Z-3 are shown in Figure 9. The determined slip surface is characterized by a low safety factor that amounts to *FS* = 0.767, which indicates that the slope is still unstable. It was proved by the observations made in 2011.

To determine the size of the area endangered by landslide processes, beyond which new part of the damaged road which can be rebuilt, additional calculations were done in order to identify slip surface for which safety factor amounted to above 1.5. It is assumed that for such *FS* values, the landslide processes occurrence is slightly probable. Moreover, according to The Act by Minister for Transport and Marine Economy, dated 2nd March 1999, the minimal indicator value for scarps and slopes of road earthen structures, should not be lower than 1.5.

The result of calculations for intersection Z-3 is shown in Figure 10. On the grounds of them, it can be stated that the range of the endangered zone for intersection Z-3 amounts to about 30 m from the edge of the open cast.

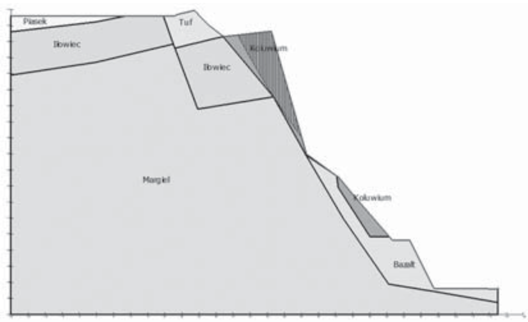

Fig. 9. Slip surface for intersection Z-3 determined for *FS* = 0.767 from Janbu method

The range of direct zone endangered by landslide determined by means of observation of cracks which cracks occurred and slots amount to 8–35 m from the edge of the open cast, so is approximate to the one determined from stability analysis.

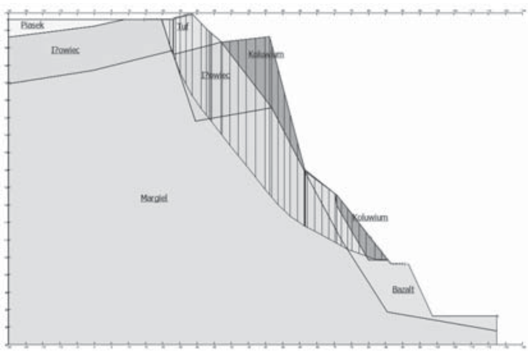

Fig. 10. Range of slip surface determined for *FS* = 1.482 from Janbu method for intersection Z-3

5. Summary

The presented stability analysis of north-west part of open cast in 'Bazalt-Gracze' mine was conducted on the grounds of data determined by means of back analysis. Back analysis in the presented case was made which data which came from the landslide area, which occurred in 2004 (Fig. 2, 3), adjacent to the area where the new landslide occurred in 2011. The parameters were based on that and were verified by doing calculations for the state before the landslide (for the landslide area from 2011). In that way, the safety factor *FS* = 1.064 (Fig. 8) was obtained for the intersection located in the central part of the landslide. It indicates great probability of landslide movements' initiation in this region, and also appropriate choice of parameters. For such determined data, stability analysis was done for the slope geometry, which was re-profiled by the landslide. It made it possible to determine the zones of direct landslide hazard.

On the grounds of these calculations, it can be stated that back analyses can be used to reliably determine the features of the centre, in such cases when it is impossible to conduct a field examination, and laboratory testing does not enable to determine appropriately its parameters. In the case presented, using simple methods to calculate stability, a very good compatibility of the results was obtained compared with factual observations. For the cases when there is lack of detailed recognition and accurate data which describes the rock mass, using sophisticated measuring instruments for stability analyses, may lead to substantial mistakes. It results in a lack of important data indispensable for building calculation model. On the presented example of the real landslide slope, it can be assumed that using simple calculation methods, which are based on limit equilibrium methods, is very profitable in such situations, but what is more, it enables reliable results to be obtained.

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