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THE TELEVIEWER LOGGING DATA ANALYSIS TOWARD THE MINE DESIGN OPTIMIZATION: A CASE-STUDY OF THE CATOCA OPEN PIT, REPUBLIC OF ANGOLA

The Catoca open pit, which develops the kimberlite pipe of the same name, is located in the northeast of the Republic of Angola. The project of mining from the actual elevation of +840 m downward included a significant increase in the heights and slope angles of the benches. In this connection, it became necessary to describe comprehensively the structural defects in the gneiss rock mass to accommodate the ultimate pit limit. To this effect, 13 boreholes were drilled in gneiss with a view to performing the acoustic and optical televiewer logging. The interpretation of the obtained data points out two dominant systems of joints in the open pit mine field, which indicates the unity of the structure and lithology of the deposit. Based on the obtained characteristic of jointing and using the project data on the open pit design, the kinematic analysis was performed. The increased potential of the inplane slip-type failure structures was found for the northern and southern pitwall benches. The northern and eastern pitwall is favorable for the development of the V-type slip deformation. The probabilistic kinetic analysis by the method of limiting equilibrium was carried out within the allocated sectors of the open pit; the analysis exhibited the high factor of stability of the actual pitwall design. Increase in the angle and height of the benches will initiate inadmissibly hazardous areas on the southern and eastern pitwall in terms of the deformation types considered. The risk of the impact on personnel and equipment in the hazardous areas can be reduced to an acceptable level through the implementation of instrumental monitoring. On the basis of the obtained FoS and PoF ratios, the design solutions adopted for the ultimate pitwall limit design in the Catoca diamond mine can be conditionally assumed as an optimum. Maximization of economic effect of mining is achievable through the increase in the slope angles on the northern and southern pitwall up to 70°. In this case, the high probability of the slope instability in this design should be profoundly addressed by the risk management.

Keywords: Catoca diamond mine, televiewer, tectonic jointing, rock mass, kinematic analysis, kinetic analysis, factor of safety, optimal pit parameters
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Introduction

An objective point of any opencast mining technology is the optimized open pit design to balance reasonably the operational safety with the economic efficiency [1, 2]. The ultimate pitwall parameters should ensure stability of slopes for the whole period of the pit life and enable full extraction of minerals. A pitwall design (widths, heights and angles of benches) includes the critical analysis of the ultimate stability factors. These factors are the petrology and physical and mechanical properties of rocks, different-size structural defects (disjunctions, primary foliation, gneissosity, etc.), stress–strain behavior and hydrology. In hard rock masses, the discontinuity is a governing factor of stability of geotechnical structures and, therefore, should be studied comprehensively both at mining front and deep in enclosing rock mass.

The revised Catoca open pit mining project sets a new design for the benches (as against the initial decision) starting from the actual elevation of +840 m, which means the increased heights and angles of slopes. This engineering solution to be implemented requires a detailed description of rocks and their structure. To this effect, 13 vertical boreholes were drilled into the biotite and amphibole gneiss rock mass enclosing the Catoca kimberlite pipe [3, 4], and televiewer imaging was carried out in the boreholes (**Fig. 1**).

For a long time, the only technique of cross-section data acquisition in boreholes was the core orientation logging. The quality of information depended on drilling accuracy, precision of core orientation in four cardinal directions, as well as on a documentor's skills and experience. Today the acoustic and optical televiewer borehole logging is increasingly often used to meet the challenge [5, 6]. The main advantages of this method are: the measurement continuity along a borehole even in the heavily faulted areas (these areas are of specific geomechanical concern); the possibility to examine rocks in the conditions of their natural occurrence at minimum mechanical impact; the high accuracy and speed of measurement; the automated processibility of data. On the other hand, the method is incapable to assess directly the friction behavior of joint surfaces (undulation, roughness, mineral filler). Used jointly, the televiewer logging and core logging allow levelling down the disadvantages and provide the comprehensive and accurate data on geomechanics and structure of rocks for the mine design and optimization [7]. This article presents a case-study of the joint televiewer-and-core logging in the Catoca open pit diamond mine.

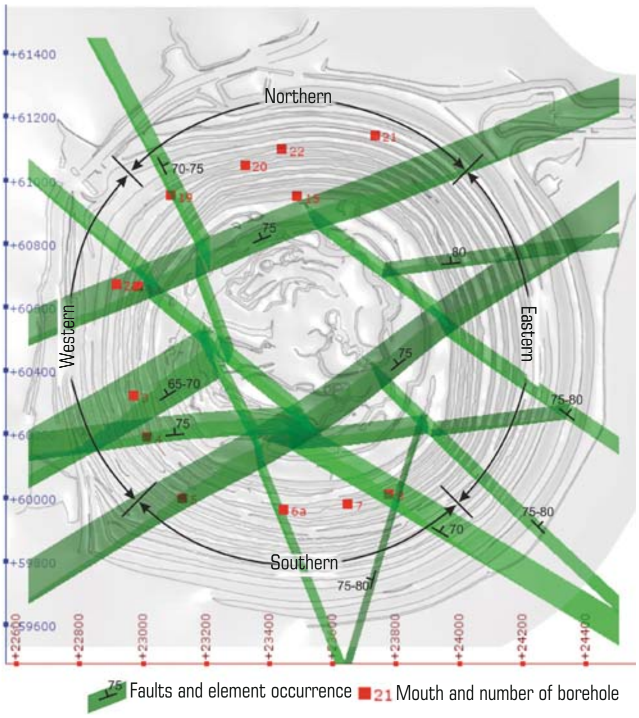

Fig. 1. Block faulting in enclosing rock mass of Catoca kimberlite pipe (top view)

Results and discussion

The televiewer data analysis used the polar diagrams of jointing per each borehole. The information on jointing was obtained from the linear borehole logging, and the line-sampling error was corrected using the Terzaghi method [8, 9]. The jointing variability in the cross-sectional area of rock mass was investigated with the help of the cumulative circular diagrams of the northern, southern, western and eastern pitwall (**Fig. 2**). The lack of the borehole data on the eastern pitwall was compensated by the structural mapping of this pitwall slope.

Irrespective of a series of faults which condition the block structure on a large scale [10], the diagrams show an approximately similar degree of the structural damage of rock mass. This implies the Catoca pipe area belongs in the structurally and lithologically uniform domain. Each diagram contains a couple of maximums fitting the systems of joints of the north-eastern strike and counter dip (see fig. 2, **Table 1**).

The joint systems contain open, partly open, closed and healed joints. Genetically, the joints are connected with the general gneissosity of rock mass, and either inherit primary foliation or are the disjunctives of later tectonic activity, which is proved by the filling of some joints with veinlets of secondary minerals. The eastern pitwall diagram (see fig. 2*d*), alongside with the described systems, contain a high-angle maximum matching the north–northwestern strike system (Set 3) formed at the final stages of the crustal stress evolution according to [10].

Domination of the counter-dipping flat and inclined joints favor initiation of planar and V-type deformations given the actual pitwall design. The kinematic analysis was performed to find feasibility of such-type failures in different areas of the pitwall [11] (**Fig. 3**).

Table 1. Main systems of joints on Catoca pitwall

Pitwall	Joint system	Dip azimuth, deg	Dip angle, deg
Northern	Set 1	331	64
	Set 2	179	47
Western	Set 1	344	63
	Set 2	164	59
Southern	Set 1	330	62
	Set 2	172	50
Eastern	Set 1	340	69
	Set 2	172	50
	Set 3	245	88

No shear strength testing of weakness planes (joints) was carried out, and the friction angle of these planes was assumed to be 25°, which agreed with the residual angle of internal friction determined in host gneiss rocks. **Table 2** compiles the kinematic analysis data and the number of structural defects inside the critical domains per pitwall areas and deformation types. Table 2 also gives the dip azimuths of the benches, which have the highest deformation potential according to the kinematic sensitivity analysis.

The inplane slip deformation takes place when rock mass contains joints dipping toward the open pit at an angle smaller than the slope angle but higher than the friction angle of the joint surfaces [12]. Moreover, the dip azimuth of the joint surfaces should differ from the dip azimuth of the bench slope not less than by 20°. The implemented kinematic analysis

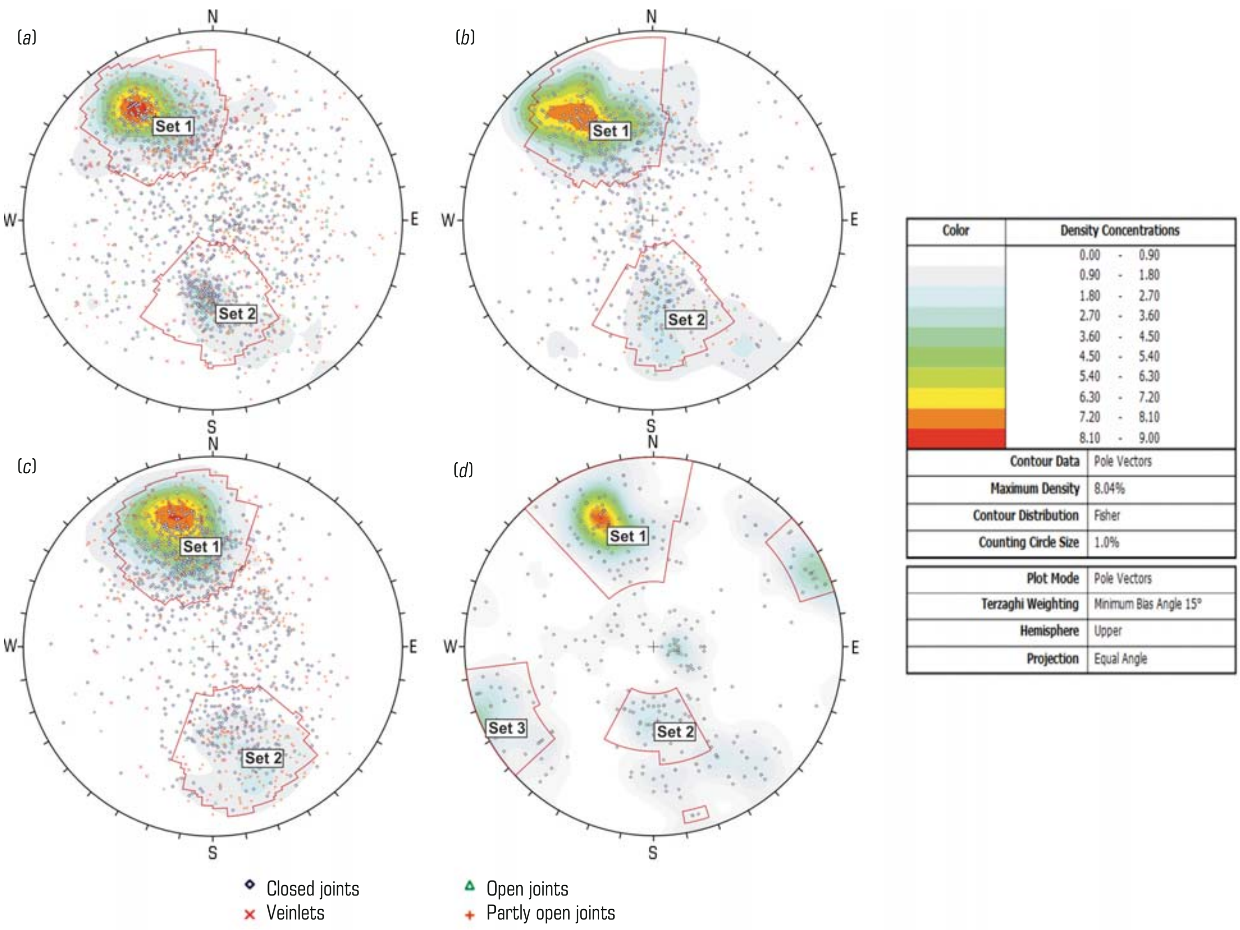

Fig. 2. Cumulative diagrams of Catoca pitwall jointing:
a–western pitwall; *b*–northern pitwall; *c*–southern pitwall; *d*–eastern pitwall. Angle-preserving projection, upper hemisphere

Table 2. Kinematic analysis results

Pitwall	Dip azimuth of benches on the pitwall, deg	Dip azimuth of benches with the highest deformation potential, deg	Friction angle of weakness planes, deg	Joints* in the critical domain, %, slope angle 60°	Joints* in the critical domain, %, slope angle 75°	Deformation potential
Inplane slip						
Northern	135–225	175	25	9.39	12.32	High
Western	45–135	95	25	3.94	5.38	Low
Southern	315–45	345	25	17.33	31.47	High
Eastern	225–315	315	25	4.48	10.20	Low
V-type slip						
Northern	135–225	225	25	19.93	21.33	High
Western	45–135	75	25	0.06	0.06	Low
Southern	315–45	45	25	6.51	7.51	Low
Eastern	225–315	254	25	16.66	16.76	High
*For V-type slip deformation, we determined percent of intersected planes of joints in critical domain.						

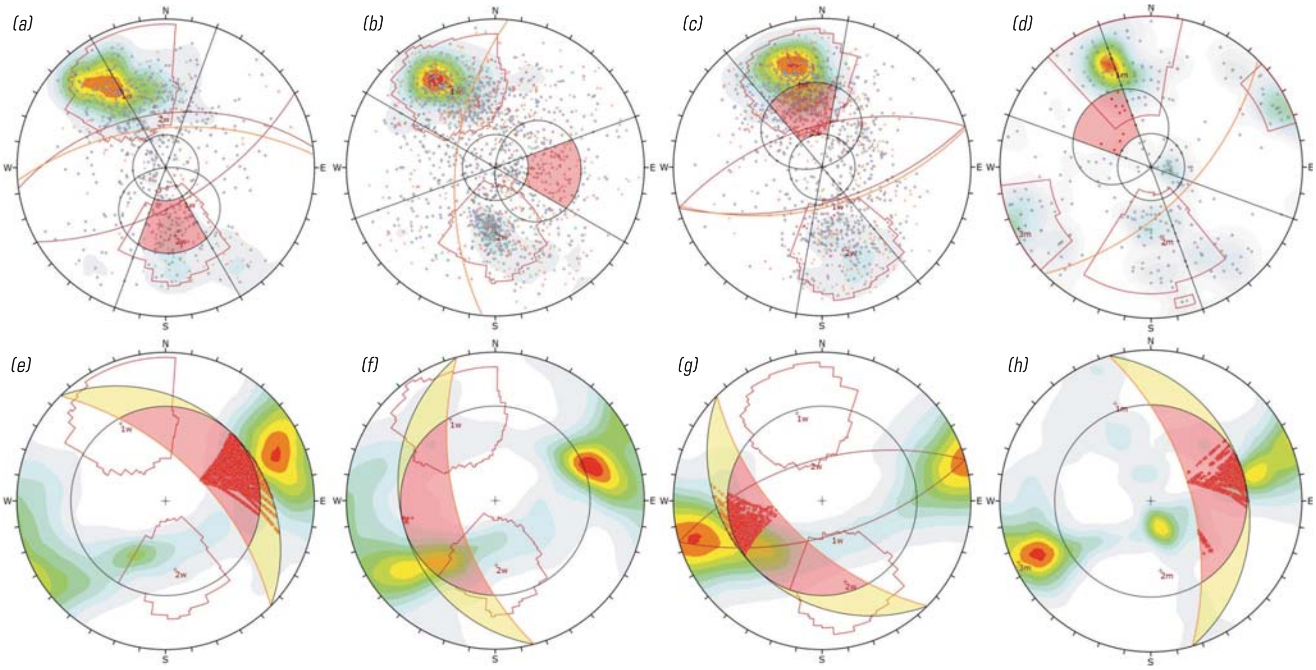

Fig. 3. Kinematic analysis patterns of planar (*a–d*) and V-type (*e–h*) deformation:

a, *e*–northern pitwall; *b*, *f*–western pitwall; *c*, *g*–southern pitwall; *d*, *h*–eastern pitwall. Angle-preserving projection, upper hemisphere

shows that such combination of orientations of benches and joints is typical of the northern pitwall, where the inplane slip can occur along joint system No. 2 (see Set 2, fig. 2), and of the southern pitwall, where the inplane slip can occur along joint system No. 1 (see Set 1, fig. 2), which is proved by the increased percent of joints in the critical domain (see Table 2).

The V-type deformation is initiated by a pair of intersecting structural defects such that the line of their intersection propagates toward the open pit void [13]. The intersection lines dissect wedge-shaped blocks out of rock mass, and slipping can happen either along one of these lines or along one of the wedge-shaping planes. Such structures are observed in the northern, eastern, southeastern and northeastern sites of the pitwall, formed by the intersections of joints from high-density systems Set 1 and Set 2 (see fig. 2). The maximum number of intersections of joints in the critical domain is intrinsic to the northeastern pitwall (dip azimuth of 225°): 19.93% of total intersections. The least potential of the V-shape structuring is a feature of the western, southern, northwestern and southwestern pitwall where the intersections of joints trend not toward the mined-out pit area but into the depth of rock mass.

Stability of slopes and any geotechnical structures with the developed structural defects depends on the balance maintained between the restraining and shearing forces and is expressed in terms of the factor of safety (FoS). As a determinate rock mass external loading/resistance ratio, FoS is an admissibility criterion of a mining project. However, high randomness of properties of values included in this criterion necessitates a probabilistic analysis of stability and an estimate of probability of failure (PoF). Recently, PoF serves as the main admissibility criterion as it includes variability of load-bearing capacity of rocks and a project reliability assessment [1, 14]. The probabilistic method allows embracing uncertainties of each input parameters as random values [15]. As a result, the method produces a set of FoS values calculated using the Monte-Carlo Simulation. In this case, PoF is a probability of FoS < 1.0 in all Monte-Carlo simulations.

Table 3. Matrix of solutions after probabilistic analysis of inplane and V-type slip*

Inplane slip						V-type slip					
Bench height, m	FoS/PoF Slope angle, deg					Bench height, m	FoS/PoF Slope angle, deg				
	60	65	70	75	80		60	65	70	75	80
Northern pitwall						Northern pitwall					
20	4.11/0	4.44/0	2.65/0	1.85/0	1.64/0	20	2.58/0	2.29/0	2.1/0	1.9/0	1.84/0
30	3.15/0	3.36/0	2.17/0	1.64/9.4	1.51/26.7	30	2.1/0	1.84/0	1.84/0	1.84/0	1.84/0
40	2.69/0	2.84/0.1	1.95/10.6	1.56/23.6	1.48/31.9	40	1.84/0	1.84/0	1.84/0	1.83/0	1.54/0
50	2.43/0	2.55/4.9	1.83/18.9	1.52/28.9	1.46/33.4	50	1.84/0	1.84/0	1.84/0	1.56/0	1.54/0
60	2.27/0.4	2.35/11.0	1.75/22.7	1.5/30.3	1.45/33.8	60	1.84/0	1.84/0	1.76/0	1.54/0	1.54/0
Southern pitwall						Eastern pitwall					
20	5.12/0	21.06/0	4.77/0	3.04/0	2.48/0	20	3.13/0	2.68/0	2.39/0	2.27/0	2.27/0
30	3.61/0	14.23/0	3.37/0	2.22/12.5	1.85/39.5	30	2.32	2.27/0	2.27/0	2.27/0	1.88/0
40	2.88/0	10.84/0.1	2.69/14.7	1.84/37.6	1.56/52.1	40	2.27/0	2.27/0	2.27/0	1.85/0	1.58/0
50	2.46/0	8.82/8.9	2.3/30.1	1.62/46.6	1.4/57.3	50	2.27/0	2.27/0	2.08/0	1.58/0	1.58/0
60	2.18/0.4	7.5/17.7	2.05/37.1	1.48/51.3	1.3/59.3	60	2.27/0	2.27/0	1.81/0	1.58/0	1.58/0

*The colors of cells match the colors in Table 4.

Table 4. Interpretation of factor of stability (FoS) and probability of failure (PoF) according to [19]

Criterion	Interpretation
FoS > 1.6; PoF < 1%	Stable slope (pitwall)
FoS > 1.6; PoF > 1%	Mining induces risks, either admissible or not; risk level is possible to be reduced thanks to an all-inclusive control program
FoS < 1.6; PoF < 1%	Critical slope (pitwall): geometrics needs some adjustment in order to increase average FoS up to admissible level
FoS < 1.6; PoF > 1%	Unstable slope (pitwall): geometrics requires substantial adjustment; pitwall rock mass needs reinforcement and monitoring

In the enclosing gneiss rock mass hosting the Catoca pipe, the random values are assumed to be the dip angles and dip azimuths of joints in the identified joint systems. The circular diagrams in Figs. 2 and 3 point out a substantial variation in the orientations of the joint systems even within the same cluster. The type and parameters of the statistical distribution were determined in STATISTICA.

The strength properties of joints, such as angle of friction and cohesion, were assumed to be constant as no shear resistance testing of tectonic fractures was carried out in gneiss. For the bulk density of rocks, based on the lab-scale tests, the normal distribution is found with the average value of 2.65 t/m^3, standard deviation of 0.06, relative minimum of 0.09 t/m^3 and relative maximum 0.13 t/m^3. For the bench geometrics (height and effective slope angle), the normal distribution is conditionally adopted with the standard deviation 2 and relative minimum/maximum 5° for the slope angle, and with the standard deviation 0.2 and relative minimum/maximum 1 m for the bench height.

Table 3 gives the kinetic analysis results on the inplane and V-type slip by the method of limit equilibrium in the pitwall areas with the high deformation potential according to the kinematic analysis (see Table 2). Modeling of different combinations of the bench slopes and heights provided a matrix of solutions. It should be noticed that in the variant of the V-type deformation, the slip along the intersection line of the planes of joints was analyzed. The variant of slip along one plane having the worst orientation relative to the bench was discarded as the variant was included in the analysis of the inplane slip deformation.

Theoretically, the limit equilibrium is achieved when FoS is 1 but actually this value is increased in order to account for the variability and uncertainty of the input parameters [1, 16]. In the probabilistic method, the rock mass behavior under impact of mining is assessed using FoS and PoF from the special regulatory relations [17, 18]. **Table 4** describes the admissibility criteria for any permanent or half-permanent slope at the minimal value of the probability of failure.

At the actual design of the Catoca pitwall with the benches up to 20 m high and with the slopes not more than 60°, the values of FoS and

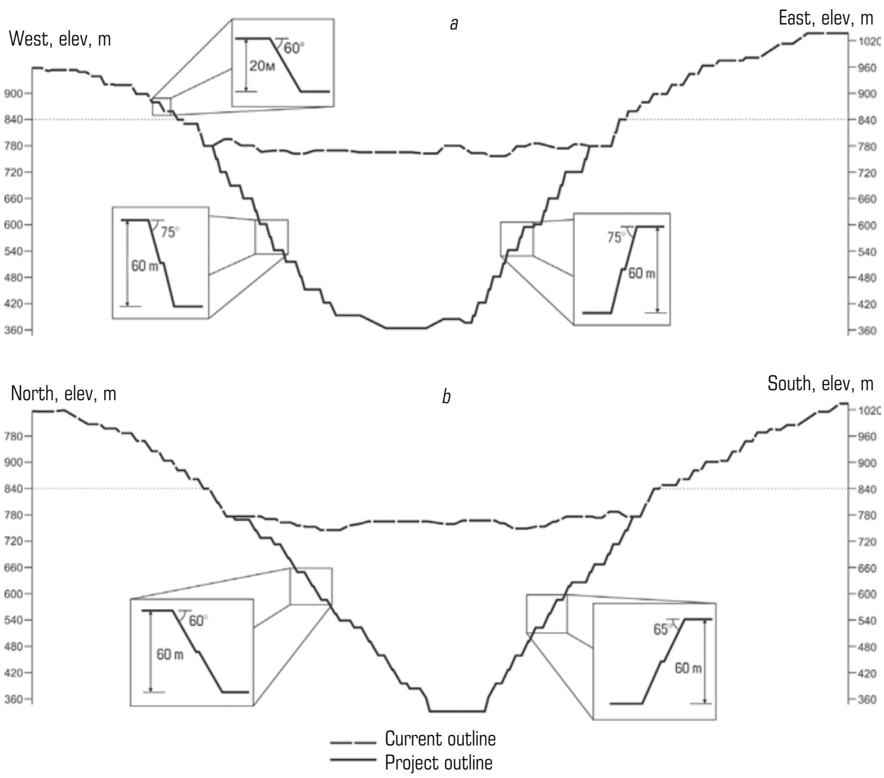

Fig. 4. Cross dimensions: a–along Y = +60 500, b–along X = +23 500 (see fig. 1)

PoF (see Table 3) point at the stability of the structures on the whole pitwall. The factors of stability are much higher than the standard values and the probability of failure is 0. The further operations in the open pit mine include the switch to the double benches 60 m high with the slope angles of 75° on the western and eastern pitwall, 65° on the southern pitwall and 60° on the northern pitwall (**Fig. 4**).

In the new design, the benches on the northern pitwall satisfy both criteria of deformation admissibility. At the ultimate pit limit, the benches on the southern pitwall may suffer irreversible deformation in the form of the inplane slip along the joints of system No. 1 (Set 1) at the probability of 17.7%. The mining operations on this pitwall are risky, and instrumental monitoring of 3D displacement of rock mass in real time and over the whole working zone can reduce the risk [20, 21]. The eastern pitwall is in the limit condition in terms of the V-type slip deformation because of the unsatisfied criterion FoS (see table 3). However, FoS value is close to a standard, the permissible levels of both criteria are generally conservative (see table 4) and the probability of failure is zero. For this reason, we think it is allowable to assume the obtained values as satisfactory in terms of the mining safety. In analogy with the southern pitwall, the real-time monitoring can reduce the risk of deformations which can impair safe operation of personnel and equipment in the hazardous zone.

Conclusions

Slope failures induced by large-size structural defects in rock mass are the governing hazards in opencast mining technologies [1]. The Catoca diamond mine at the same-name kimberlite pipe in the Republic of Angola constitutes no exception to this statement. The qualitative and quantitative estimation of the structure of the gneiss rock mass meant to accommodate most benches reveals the predominant propagation of joint systems Set 1 and Set 2 having the northeastern strike and the counter dip. The televiewer logging as an advanced technique of data acquisition allows the higher reliable information on rock mass structure at the reduced uncertainty of input data.

The kinematic analysis of the revealed jointing and the Catoca pitwall design data has found the increased potential of the inplane slip deformation on the northern and southern pitwall. The benches on the northern and eastern pitwall are favorable for the V-type slip deformation. The probabilistic kinetic analysis of the pitwall by the method of limit equilibrium has confirmed the stability of all geotechnical structures given the actual pitwall design. The project increase in the angle and height of benches can induce hazards on the southern and eastern pitwall. The risk can be reduced through introduction of instrumental monitoring.

On the whole, the increase in the height and slope of benches ensures an appreciable buildup in the production capacity of the open pit mine owing to the boost in ore extraction at the reduced stripping. On the strength of the obtained FoS and PoF ratios, the project ultimate pitwall limit design solutions for the Catoca pit can be conditionally assumed as the optimum. It is possible to maximize the economic efficiency of the open pit mine by increasing the slopes of benches on the northern and southern pitwall up to 70°. The high probability of the slope instability given such pitwall design is the subject of the comprehensive risk management.

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