Effect of Blast-induced Ground Vibration on Factor of Safety of Pit Wall Stability

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http://doi.org/10.29227/IM-2020-02-19

Submission date: 06-03-2020 | Review date: 22-09-2020

Abstract

The regulated maximum peak particle velocity (PPV) from blasting operations of an open-pit coal mine is less than 2 mm/s to prevent mainly any public disturbance such as ground vibration and air blast. However, the blast-induce ground vibration can also decrease the stability of pit slope, which has not been intensively studied. A claystone pit wall, which is geotechnically investigated as having a plane failure type and the natural condition factor of safety (FS), has been selected for this study. The FS is selected to measure the effect of blast-induced ground vibration on the slope stability. The limit equilibrium, pseudo-static 1 (), and pseudo-static 2 () methods are used to determine the FS. The vibration results of blasting monitored at three slope positions: crest, middle, and toe, from two areas at the same pit wall, are recorded by blasting seismographs. Maximum charge weight per delay and the distance from blast areas to seismographs are collected to construct the scaled distance. The percentage change of FS of three methods from both areas compared to natural condition FS are all less than 4 percent considered that the slope stability is safe from blasting vibration (less than 15 percent). The relationship between the FS and maximum PPV from the limit equilibrium, pseudo-static 1 (), and pseudo-static 2 () methods indicate that the adverse maximum PPVs given the unity FS are 16.60 and 4.58, and 4.74 mm/s, respectively. The regulated PPV less than 2 mm/s at the mine is reasonable to prevent any possible plane failure. However, many impact parameters have not been included in this study, and their effects may disturb the pit wall stability.

Keywords: *blast-induced ground vibration, slope stability, factor of safety, limit equilibrium analysis, pseudo-static analysis*

1. Introduction

Blasting of rock is probably the most important operation in a mine to fragment and heave rock for being loading and hauling to the next processes. The energy released from the chemical reaction in the process of blasting is not only be utilized for the desired outcomes such as fragmentation or moving the rock but also caused the unwanted outcomes such as vibration or airblast. The level of vibration from blasting is basically regulated by government organizations to prevent any disturbance to humans and to damage the constructions nearby. In addition, the levels of vibrations can affect the stability of the mine pit wall. The slope stability of a claystone pit wall was investigated geotechnically and specified having a plane failure. The controlled peak particle velocity (PPV) of the mine is limited to less than 2 mm/s that is very stringent compared to the government standard. Most of regulated PPV is for controlling blasting vibration and airblast. The blast-induce ground vibration affecting the stability of pit slope has not been intensively studied, especially when the mine goes deeper. This paper studies the effect of blast-induced ground vibration on the slope stability of a selected pit wall. The attenuation of vibration in scaled distance and factor of safety (FS) are studied. Three different methods to calculate the factor of safety are introduced, and the results will be related to the scaled distance. The maximum charge weight per delay and distance can be determined to keep the FS more than unity.

Literature review

The Melo and Sharma (2004) constructed both horizontal and vertical seismic coefficient time histories using FLAC (a two-dimensional finite difference program) analysis to determine appropriate values of those seismic coefficients. A mean value of the ratio of weighted average of k_H to PGHA (peak ground horizontal acceleration) was 0.459 closed to k_H = PGHA/2 recommended by Hynes and Franklin (1984). And the ratio of the mean of the weighted average results for k_H and k_V was approximately four. They explained that the vertical pseudo-static forces contained considerably shorter amplitudes when compared to the respective horizontal pseudo-static forces.

According to Das and Maheshwari (2019), the change of a factor of safety (FS) due to the change of vertical seismic acceleration from a different type of soil. They assumed the value of the vertical seismic coefficient k_V=k_H/2 and possible two-third of k_H (IS, 2016). The results have shown that the decreasing of FS affecting k_V was small compared to k_H.

Kong (2013) studied an energy approach to assessing the stability of slopes subject to blasting induced ground vibration. He combined the empirical correlation of shear strength and stiffness of rock joints developed by Barton (1990) into the energy approach. The potential plane failure peak particle velocity (PPV) of 9.9 mm/s is selected to determine the allowable charge weight per delay using the energy approach. From 15 trial blasts, the vibration monitoring records demonstrated that the PPVs were less than 9.9 mm/s and had only of about 25 to 80% of that value, so the potentially unstable wedge block remained in place.

Nenad et al. (1999) combined the numerical modelling (the FLAC finite difference code and the UDEC distinct ele-

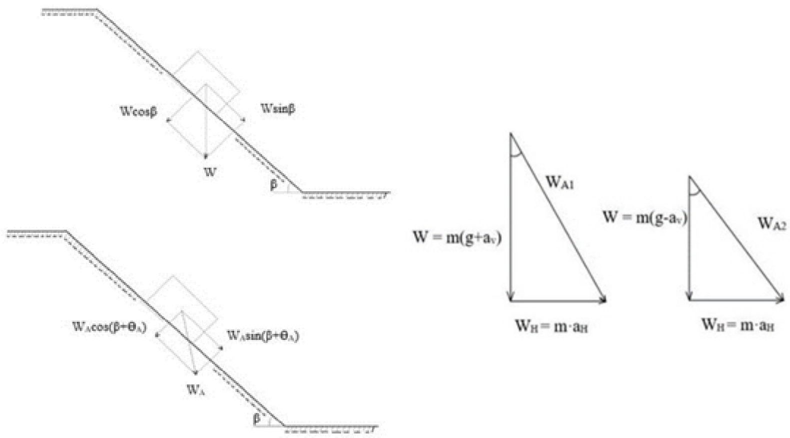

Fig. 1. Effect of vibrations in a block resting on an inclined plane (modified from Jimeno et al., 1995)
Rys. 1. Wpływ drgań w bloku spoczywającym na pochyłej płaszczyźnie (zmodyfikowane na podstawie Jimeno et al., 1995)

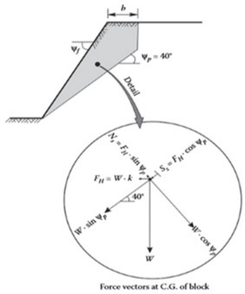

Fig. 2. Slope model showing the magnitude of horizontal seismic force F_H including normal and shear components (Wyllie & Mah, 1977, p.305)
Rys. 2. Model nachylenia przedstawiający wielkość poziomej siły sejsmicznej F_H z uwzględnieniem składowej normalnej i ścinającej (Wyllie & Mah, 1977, s. 305)

ment code) and the field measurements of the blast-induced ground vibrations into the blast design rules that relate distance between the slope and the blast, charge weight per delay and number of blasts necessary to cause the failure of the slope. The critical acceleration was determined by both numerical methods given in the range 0.64–0.8g. This value was a much higher value than the calculation from Newmark's equation (0.1g) (1965), that is based on the pseudo-static approach to modelling of slope stability under dynamic load. They suggested that, in terms of slope stability, improvements could be achieved by having larger inter-row delay time on the side of the blast, further from the slope. In addition, a reduction in the intensity of the blast-induced slope vibration could be achieved by introducing a hole-by-hole firing sequence using surface Nonel with constant downhole delays.

Based on the limit equilibrium analysis, Terzaghi (1950) simplified the seismic effect to vertical and horizontal constant acceleration which turn to an inertial force acting on the slope. The inertial force is used to calculate the slope stability. This method is called "the quasi-static method." Another method based on the limit equilibrium analysis is "time history analysis of slope stability." This method calculates the inertia force based on blast vibration velocity or acceleration time curve on each slice of the sloping plane and then determine the slope stability factor. The slices method of rigid limit equilibrium method is combined to conduct the entire blasting process during the time step. The safety factor time curve can be obtained. Two more methods for slope stability analysis from blasting vibration in the past research works are "dynamic finite element method" and "safety criterion based on vibration velocity" (Yan, Zhang, and Huang, 2014).

Yan, Zhang, and Huang (2014) studied the dynamic response characteristics of slope under the effect of blasting seismic wave using the software Geo-slope. Stability analysis and calculation of safety factors under blasting conditions at three representative points, namely, the slope crest, middle slope and slope toe were determined. The study found that the vibration-induced sheer stress increases along the slope from top to toe while displacement decreases. The paper cited that when the difference of a factor of safety (FS) between natural condition (static FS) and under the influence of blasting vibration (dynamic FS) is less than 15%, it has no impact on the stability of the slope and the ratio of dynamic FS to static FS is generally required to be greater than 0.9.

2. Theory

The slope stability analysis has been many approached, such as static equilibrium methods, probabilistic methods, finite difference, or element methods. The most used and simple method is the limit equilibrium method to evaluate the possibility of slope failure using slope geometry and rock mass conditions (Piteau & Martin, 1982).

Limit equilibrium analysis

The basic concept of the limit equilibrium concept is when the driving forces are just equal to the resisting forces

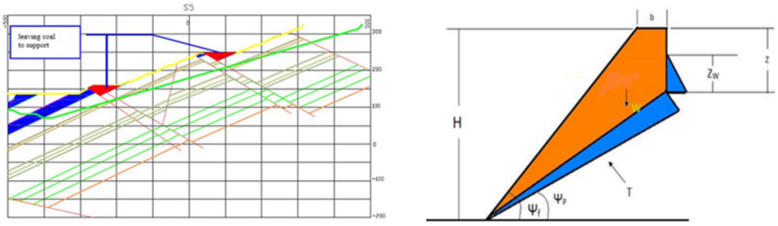

Fig. 3. Cross-section of the study areas (top) and plane failure geometry (bottom) (Geotechnical Report 1985)
Rys. 3. Przekrój poprzeczny badanych obszarów (góra) i geometria zniszczenia płaszczyzny (dół) (Raport Geotechniczny 1985)

Tab. 1. Physical and Geotechnical information of the experimental areas // Remark * calculated from equations
Tab. 1. Informacje fizyczne i geotechniczne terenów doświadczalnych

Slope height (*H* (m)	11	12
Dip of the sliding plane (ψ)(degrees)	22	21
Slope face angle (ψ)(degrees)	67	67.5
Cohesion (*c*	40	40
Friction angle (ϕ	14	14
Unit weight of sliding block (γ (kN/m^3)	18.83	18.83
Depth of tension crack (*Z* (m) *	6.44	7.22
Area of sliding plane (*A* (m^2) *	12.16	13.35
Weight of sliding block *W* (kN) *	13.42	16.61
Factor of safety (no vibration) *	1.566	1.529

at any point of time, the slope is on the verge of failure. If the factor of safety (FS) is greater than unity, the slope will be considered stable, and if the factor of safety is less than unity, the slope will be considered unstable, as shown in equation 1 (assuming the slope is drained, an uplift force on sliding plane due to water pressure; U, and thrust force in tension crack due to water pressure; V, equal 0) (Wyllie & Mah, 1977).

$$FS = \frac{c \cdot A + W \cos\psi_p \cdot \tan\phi}{W \sin\psi_p} = \frac{resisting\ forces}{driving\ forces} \tag{1}$$

where c is the cohesion, A is the area of sliding surface, W is the weight of the block lying above the sliding surface, ψ_p is the dip or degree of the sliding surface, and ϕ is friction angle.

If the sliding surface is clean and contains no infilling, the cohesion is likely to be zero and equation 1 reduces to Equation 2, and FS will be unity when ψ_p equals ϕ. This condition is called "limit equilibrium."

$$FS = \frac{W \cos\psi_p \cdot \tan\phi}{W \sin\psi_p} \tag{2}$$

The FS from limit equilibrium analysis can be simplified to integrate the effects of ground acceleration or velocity from blasting. The ground acceleration is changed into a static force in the determined direction and is proportionated to the weight of sliding plane. An example of a block resting on an inclined plane, the seismic of blasting can reduce and swing the vertical weight component and increase the driving force down the slope, as shown in Figure 1.

The swing angle from vertical; θ, can be calculated by the basic trigonometry of the relationship between ground horizontal acceleration; a_H, and vertical ground acceleration; a_V, as shown in Figure 1. The θ angle caused by the longitudinal component of seismic vibration is shown in Equation 3.

$$\theta_A = tan^{-1}\left(\frac{a_H}{g \pm a_V}\right) \tag{3}$$

where g is gravitational acceleration 9.8 m/s^2. The FS from Equation 1 can be changed to Equation 4.

$$FS = \frac{c \cdot A + W \cos(\psi_p + \theta_A) \cdot \tan\phi}{W \sin(\psi_p + \theta_A)} \tag{4}$$

Pseudo-static analysis (pseudo-static 1(k_H))

Pseudo-static analysis is a modification of limit equilibrium analysis by incorporating the effect of seismic ground motions in from of static horizontal force; F_H, acting in a direction out of the face on the slope, as shown in Figure 2.

$$F_H = W \cdot k_H \tag{5}$$

where k_H is the horizontal seismic coefficient in units: g.

The value of the seismic coefficient can be determined from the magnitude of the ground motions, the slope materials, and the height of the slope as shown the relationship by Equation 6.

$$k_H = \frac{PGHA \cdot F_{PGA} \cdot \alpha}{2} \tag{6}$$

where PGHA is the peak horizontal ground acceleration level obtained from the seismic records for the site, F_{PGA} is the site coefficient to classified characteristics of the rock or soil and the magnitude of the ground motions, α is a wave scattering factor to take account the slope height.

Normally for slope design, k_H in Equation 5 is usually equal to PGHA/2 because the values of F_{PGA} and α are likely close to one. The k_H value presently can be calculated as a function of allowable displacement, earthquake magnitude and spectral acceleration. If allowable displacements are limited to 50 mm (2 inches), the k_H value is recommended to be (0.4·g) to (0.75·g), depending on the magnitude M (California Department of Conservation, 2008; Bray & Travasarou, 2009).

The pseudo-static factor of safety of the slope can be modified, as shown in Equation 7.

$$FS = \frac{c \cdot A + W(\cos\psi_p - k_H \cdot \sin\psi_p) \cdot \tan\phi}{W(\sin\psi_p + k_H \cdot \cos\psi_p)} \tag{7}$$

The horizontal seismic force or F_H increases the driving force ($+k_H \cdot \cos\psi_p$) and at the same time reduces the normal

Tab. 2. Ground velocity, acceleration, and distance from both blasting areas

Tab. 2. Prędkość względem ziemi, przyspieszenie i odległość od obu obszarów rażenia

Position	Peak particle velocity (mm/s)			Peak acceleration (mm/s^2)			Distance (m)
Area A	Trans.*	Vert.*	Long.*	Trans.	Vert.	Long.	
crest	0.473	0.914	0.670	0.020	0.023	0.020	408.08
middle	1.892	2.388	1.561	0.161	0.286	0.095	370.23
toe	0.347	0.615	0.489	0.015	0.025	0.016	391.47
crest	0.583	1.387	1.411	0.020	0.030	0.026	465.51
middle	0.599	1.182	0.678	0.023	0.036	0.023	430.21
toe	0.583	1.387	1.411	0.020	0.030	0.026	449.33
crest	0.875	1.103	1.198	0.026	0.030	0.026	168.64
middle	1.127	1.001	1.103	0.023	0.043	0.023	138.87
toe	0.520	0.930	0.134	0.012	0.038	0.008	153.69
crest	0.300	0.591	0.504	0.013	0.016	0.016	399.41
crest	0.394	0.835	0.481	0.013	0.020	0.013	524.43
middle	0.449	0.765	0.473	0.023	0.026	0.023	488.83
toe	0.260	0.544	0.205	0.010	0.012	0.008	508.19
Position	Peak particle velocity (mm/s)			Peak acceleration (mm/s^2)			Distance (m)
Area B	Trans.	Vert.	Long.	Trans.	Vert.	Long.	
toe	0.159	0.603	0.159	0.013	0.027	0.010	237.32
middle	0.905	1.333	1.683	0.045	0.055	0.088	408.83
toe	0.333	0.794	0.571	0.008	0.013	0.012	404.03
middle	0.492	0.810	1.333	0.023	0.033	0.055	395.21
middle	0.667	0.857	1.714	0.035	0.040	0.056	390.18
middle	0.810	1.556	2.175	0.050	0.068	0.108	383.71
toe	0.349	0.825	0.540	0.008	0.018	0.012	378.88
middle	0.698	1.064	1.127	0.030	0.035	0.056	399.40
toe	0.460	0.603	0.429	0.007	0.013	0.008	394.60
middle	0.730	1.032	1.556	0.028	0.031	0.066	401.92
toe	0.397	0.667	0.333	0.007	0.013	0.001	397.87

* abbreviation of Transverse, Vertical, and Longitudinal axis. The dotted line separates the blasts

Tab. 3. Factor of safety (FS) calculated from three methods and scaled distance (SD) at the maximum peak particle velocity (PPV)

Tab. 3. Współczynnik bezpieczeństwa (FS) obliczony trzema metodami i skalowana odległość (SD) przy maksymalnej szczytowej prędkości cząstek (PPV)

Position	limited equilibrium	pseudo-static 1 (k)	pseudo-static 2 (k , k)	SD at max. PPV
Area A FS=1.566				
crest	1.554	1.525	1.528	57.143
middle	1.497	1.289	1.300	51.843
toe	1.557	1.535	1.537	54.817
crest	1.553	1.525	1.528	65.184
middle	1.553	1.519	1.522	60.241
toe	1.553	1.525	1.528	62.919
crest	1.550	1.514	1.518	23.614
middle	1.552	1.519	1.523	19.446
toe	1.559	1.541	1.543	21.521
crest	1.557	1.539	1.541	55.929
crest	1.558	1.539	1.541	73.435
middle	1.552	1.519	1.523	68.450
toe	1.560	1.545	1.547	71.161
Area B FS=1.529				
toe	1.522	1.502	1.504	33.231
middle	1.488	1.439	1.444	57.247
toe	1.523	1.513	1.513	56.575
middle	1.504	1.482	1.484	55.341
middle	1.501	1.458	1.462	54.636
middle	1.480	1.430	1.435	53.729
toe	1.523	1.513	1.513	53.054
middle	1.502	1.468	1.471	55.928
toe	1.525	1.515	1.515	55.255
middle	1.499	1.472	1.475	56.279
toe	1.526	1.515	1.515	55.712

force ($-k_H \cdot \sin\psi_p$). The FS is reduced due to the seismic wave from blasting. The usual guideline for seismic applied FS of the slope stability should be more than 1.1 (Wyllie & Mah, 1977).

Pseudo-static analysis with integrated vertical ground force (pseudo-static 2 (k_H,k_v))

It may be appropriate to apply both horizontal and vertical seismic coefficients in the slope stability analysis. If the vertical coefficient is k_V and the ratio of the vertical to the horizontal components is r_k; $r_k = k_V/k_H$ then the resultant seismic coefficient k_T is shown in Equation 8.

$$k_T = k_H \cdot (1 + r_k{}^2)^{1/2} \tag{8}$$

The resultant seismic coefficient k_T is acting at the angle $\psi_k = \tan^{-1})k_V/k_H$ above the horizontal, and the vertical coefficient integrated FS is given by Equation 9.

$$FS = \frac{c \cdot A + W\,(\cos\psi_p - k_T \cdot \sin(\psi_p + \psi_k)) \cdot \tan\phi}{W\,(\sin\psi_p + k_T \cdot \cos(\psi_p + \psi_k))} \tag{9}$$

$$FS = \frac{c \cdot A + W\,(\cos\psi_p - U - V \cdot \sin\psi_p) \cdot \tan\phi}{W \sin\psi_p + V \cdot \cos\psi_p} \tag{10}$$

3. Information on field data and research methods

Two experimental areas at the low wall slope of one pit are selected. This slope has a bedding shear plane underneath having dip angle 20–25 degrees and dip direction from East to West direction (toward inside pit) as shown in Figure 3. The

Tab. 4. Factor of safety comparison of three methods and natural condition

Tab. 4. Współczynnik porównania bezpieczeństwa trzech metod i stanu naturalnego

Methods for FS Analysis	natural condition FS $_{static}$		under influence of blasting vibration average FS $_{dynamic}$		Δ FS (%)	
	area A	area B	area A	area B	area A	area B
limit equilibrium	1.566	1.529	1.550	1.508	0.997	1.344
pseudo-static 1 (k)	1.566	1.529	1.510	1.482	3.556	3.044
pseudo-static 2 (k , k)	1.566	1.529	1.514	1.485	3.335	2.901

shear plane can cause a plane failure. The geological of cap rock is classified as gray claystone. The geotechnical data to calculate the designed FS has shown in Table 1 (Geotechnical Report, 1985).

The factor of safety of these two areas (Area A and B) are determined by the Geotechnical Department of the coal mine using physical and geotechnical information in Table 1. The calculated factor of safety of each area is also shown in the table by using Equation 10 assuming the uplift force on sliding plane due to water pressure; U, and thrust force in tension crack due to water pressure; V, equal 0.

4. Research methods

Field measurements of ground vibration are conducted at those locations along the slope of the pit wall by placing seismographs at crest, middle, and toe position of the bench to measure particle movements. The coordinate and elevation of the blasting site and seismograph are collected to determine the distance. The maximum explosive weight per delay is approximately 50 kilograms.

Maximum charge weight per delay and distance from blast sites to measuring points were collected to construct a scaled distance. The limit equilibrium analysis is firstly used to determine the Factor of Safety (FS) and be modified by integrating the effect of seismic ground motions in the form of a horizontal static force that alters the θ angle as shown in equation 3. The FS will be reduced as the θ angle is added, as shown in equation 4. The result from this step will obtain the "limit equilibrium" FS.

Next study known as the pseudo-static stability analysis simulates the ground motions as a static horizontal force. The magnitude of this is the product of a seismic coefficient, k_H and the weight of the sliding block W. The seismic accelerations changed into a static horizontal force acting in the sliding direction are incorporated to the degree of failure plane angle (ψ) in Equation 7. The FS from the pseudo-static stability analysis will be affected by the horizontal force and diminished when the normal stress force is decreased, and the shear stress force is increased. The result from this step will obtain the "pseudo-static 1 (k_H)" FS.

The pseudo-static stability analysis is expanded to include the vertical force consideration by adding the vertical seismic coefficients, k_v. The steps will firstly determine the ratio of the vertical to the horizontal components is r_k and the resultant seismic coefficient k_T. Secondly the angle ψ_k is calculated, and the vertical coefficient is integrated into the FS given by equation 9. The result from this step will obtain the "pseudo-static 2 (k_H,k_v)" FS.

The three different FS calculation approaches; limit equilibrium, pseudo-static 1 (k_H), and pseudo-static 2 (k_H,k_v), will be compared among them and related to the scale distance to propose the appropriate maximum charge per delay that should not generate the FS below than unity.

5. Results

The seismographs were placed at three locations: crest, toe, and middle of the slope. Peak particle velocity, acceleration, the distance between seismograph and blast site, and maximum charge weight per delay (50 kilograms per hole) of Area A and B were collected. Thirteen and eleven blasts were conducted at Area A and B, consecutively. The results of both areas are shown in Table 2, and the calculated scaled distance are shown in Table 3.

The FS results calculated from three differences methods: limited equilibrium, pseudo-static 1 (k_H), and pseudo-static 2 (k_H,k_v), are shown in Table 4. Parameter k_H used to calculate pseudo-static 1 (k_H), is PGHA/2 , which PGHA is the peak horizontal ground acceleration considered from the vector sum of the transverse and longitudinal axis. The k_V used to calculate pseudo-static 2 (k_H,k_H), is k_H/4 (MELO & SHARMA, 2004).

6. Summary and analysis

Under the influence of blasting vibration (dynamic) FS from three different methods, limited equilibrium, pseudo-static 1 (k_H), and pseudo-static 2 (k_H,k_v), slightly decrease compared to the natural condition (static) FS of area A and area B 1.566 and 1.529, consecutively. The percentage change of FS of all three methods from both areas compared to natural condition FS is less than 4 percent as shown in Table 4. The percentage of change is less than 15% considering that the slope stability is safe from blasting vibration referred to previous research (Yue Yan, Yahui Zhang, and Chao Huang, 2014).

The upper limit scaled distance equation from this study is PPV=511.99 $(SD)^{-1.355}$ compared to the average scaled distance equation constructed from Rachpech et al. (2014) (the same mine pit) PPV=1867.8 $(SD)^{-1.359}$ as shown in Figure 4. This study was conducted at a distance range of half kilometres where Rachpech et al. studied on the longer distance blasts (with a variety of maximum charge weight per delay). Thus, the effect from blast vibration on the pit slope stability could be insignificant.

The FS from three different methods are compared and correlated to the maximum peak particle velocity (PPV), and the relationship is illustrated in Figure 5. From the linear regression equations, the maximum PPV that may trigger the FS below than 1.0 can be determined.

In order to have the FS more than unity, the suggested maximum PPV from limit equilibrium, pseudo-static 1 (k_H), and pseudo-static 2 (k_H,k_v) should be less than 16.60, 4.58,

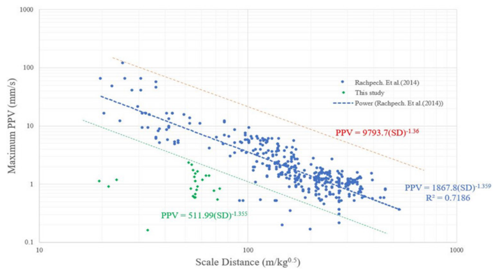

Fig. 4. Comparison of scaled distance graphs between this research data and Rachpech et al. (2014)

Rys. 4. Porównanie skalowanych wykresów odległości między danymi tego badania a Rachpech i in. (2014)

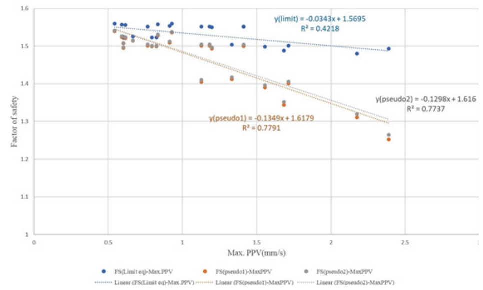

Fig. 5. The relationship between FS and maximum PPV from three analysis methods

Rys. 5. Zależność między FS a maksymalnym PPV z trzech metod analizy

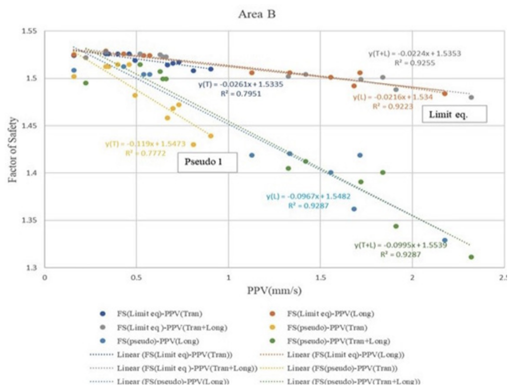

Fig. 6. An example of the relationship between FS and PPV separating into three horizontal axes (transverse, longitudinal, and vector sum of transverse and longitudinal) and two different analysis methods (limit equilibrium and pseudo-static 1 (k_H))

Rys. 6. Przykład zależności między FS i PPV rozdzielającymi się na trzy poziome osie (poprzeczna, podłużna i wektorowa suma poprzeczna i podłużna) oraz dwie różne metody analizy (równowaga graniczna i pseudo-statyczna 1 (k_H))

and 4.74 mm/s, consecutively. This result supports that the integration of k_V does not change much on the FS (less than 10 percent) compared to using only k_H in the pseudo-static analysis (Das & Maheshwari, 2019; WYLLIE & MAH, 1977). In case of using all data (from all three axes, not only a maximum PPV), the PPV from limit equilibrium, pseudo-static 1 (k_H), and pseudo-static 2 (k_H,k_V) given unity FS will slightly increase to 21.87, 5.64, and 5.86 mm/s, consecutively.

The lowest estimated PPV at 4.5 mm/s given a scaled distance approximately 285 m/kg0.5 (using the upper limit equation from figure 4) suggests that if maximum charge weight per delay is 50 kilograms, the distance of blast site from a pit wall should be more than 2.0 kilometres to prevent the FS below unity (or reducing maximum charge weight per delay less than 50 kilograms). The regulated PPV at the mine at less than 2 mm/s is reasonable to prevent any plane failure. Many impact parameters have not included in the study, and their effects still exist on the pit wall stability.

It is worth to mention that if the factor of safety on any plane drops below unity at some time under the influence of ground vibration, it does not imply a severe harmful to the stability. Lin and Whitman (1986) stated that the magnitude of permanent displacement at times that factor of safety is less than unity. The permanent displacement can be calculated using Newmark analysis.

An example of the relationship between FS and PPV illustrated in detail by separating into three horizontal axes (transverse, longitudinal, and vector sum of transverse and longitudinal) and analysis methods, limit equilibrium and pseudo-static 1 (k_H), from area B is shown in Figure 6. In the case of using the vector sum of transverse and longitudinal, the vector sum of transverse and longitudinal PPV are used.

Additional results are worth to mention from this study are:

The decreasing of FS compared to the natural condition (static) calculated by the limit equilibrium analysis is less than the pseudo-static analysis.

The FS calculated from pseudo-static analysis using horizontal accelerations from the transverse axis, in this study, decrease faster than using longitudinal axis and vector sum of transverse and longitudinal. This outcome is the same in area A.

The PPV at unity FS of area B is lower than area A, resulting in lower stability compared to area A. Area B has higher values of these following parameters; slope height (H), depth of tension crack (Z), area of sliding plane (A), and weight of the sliding block (W), than those of area A.

Literatura – References

1. BARTON, N., 1990. Scale effects or sampling bias? Closing lecture. 1st International Workshop on Scale Effects in Rock Masses. Loen, Norway, 7–8 June 1990. A.A. Balkema.
2. BRAY, J.D. & TRAVASAROU, T., 2009. Pseudostatic Coefficient for Use in Simplified Seismic Slope Stability Evaluation. Journal of Geotechnical and Geoenvironmental Engineering. 135(9), pp.1336-1340.
3. BUREAU OF INDIAN, 2002. IS 1893(2002). Indian standards criteria for earthquake resistant design of structures Part 1.
4. CALIFORNIA DEPARTMENT OF CONSERVATION, 2008. The ShakeOut Scenario USGS Open File Report 2008-1150 CGS Preliminary Report 25 Version 1.0 2008. Reston, Virginia: USGS.
5. DAS, S. & MAHESHWARI, B.K., 2019. Effect of vertical seismic coefficient in slope stability analysis. 7th Indian Young Geotechnical Engineers Conference. NIT Silchar, Assam, India, 15-16 March 2019.
6. EGAT, 2018. Geotechnical Report 1985. Mae Moh mine.
7. HYNES, M. E. & FRANKLIN, A. G., 1984. Rationalizing the seismic coefficient method. Miscellaneous Paper GL-84-13. U.S. Army Corps of Engineer Waterways Experiment Station, Vicksburg, Mississippi, pp. 21-34.
8. JIMENO, C.L, JIMENO, E.L. & CARCEDO, F.J.A., 1995. Drilling and Blasting, Brookfield, VT, USA: A.A.Balkema Publishers.
9. LIN, J.S., & WHITMAN, R.V., 1986. Earthquake induced displacement of sliding blocks. Journal of Geotechnical Engineering, ASCE, 112(1), Jan 1986.
10. KONG, W.K., 2013. Blasting vibration assessment of rock slopes and a case study, slope stability. In: DIGHT, P.M., ed. Australian Centre for Geomechanics. Perth, pp.1-10.
11. MELO, C. & SHARMA, S., 2004. Seismic coefficients for pseudostatic slope analysis. 13th World Conference on Earthquake Engineering. Vancouver, B.C., Canada, August 1-6, 2004. paper no. 369.
12. NENAD, D., IAN, B., PETER, C., GIDEON, C. & GLEN. H., 1999. Effect of Blast Vibration on Slope Stability. EXPLO 99. November 1999. pp.1-22.
13. NEWMARK, N.M., 1965. Effects of Earthquakes on Dams and Embankments. Geotechnique, 15(2), pp.139-159.
14. PITEAU, R. & MARTIN, D.C., 1982. Mechanics of Rock Slope Failure. 3rd International Conference of Stability in Surface Mining. Vancouver, Canada, 1-3 June 1982. pp.113-169.
15. RACHPECH, V., BUNNAUL, P., JULAPONG, P. & WALTHONGTHANAWUT, T., 2014. Local ground parameters of blasting vibration models for different geological structures at Mae Moh lignite mine, Thailand. Songklanakarin J. Sci. Technol. 36(1), Jan. - Feb. 2014, pp.89-95.
16. TERZAGHI, K., 1950. Mechanisms of Landslides. Engineering Geology (Berkey) Volume, Geological Society of America, reprinted in From Theory to Practice in Soil Mechanics, New York: John Wiley and Sons.
17. WYLLIE, D.C. & MAH, C.W., 1977. Rock Slope Engineering. 4th ed. Madison Avenue, New York, NY: Spon Press.
18. YAN, Y., ZHANG, Y. & HUANG, C., 2014. Impact of Blasting Vibration on Soil Slope Stability. In: BUND, V., ed. Electronic Journal of Geotechnical Engineering (EJGE), 19(2014), pp. 6559-6568.

Wpływ wibracji gruntu wywołanych podmuchami na współczynnik bezpieczeństwa stabilności zboczy odkrywki

Regulowana maksymalna szczytowa prędkość cząstek (PPV) z operacji wybuchowych w kopalni odkrywkowej wynosi mniej niż 2 mm / s, aby zapobiec głównie wszelkim zakłóceniom społecznym, takim jak wibracje gruntu i podmuch powietrza. Jednak wibracje gruntu wywołane podmuchami mogą również zmniejszyć stabilność zbocza wykopu, co nie było intensywnie badane. Do badania wybrano ścianę iłowca, która została zbadana geotechnicznie jako mająca typ zniszczenia płaskiego i znana jako naturalny współczynnik bezpieczeństwa (FS). FS jest wybierany do pomiaru wpływu wibracji gruntu wywołanych podmuchami na stabilność zbocza. Równowaga graniczna, metody pseudo-statyczne 1 (k_H) i pseudostatyczne 2 (k_H, k_v) są używane do wyznaczania FS. Wyniki drgań robót strzałowych monitorowane w trzech położeniach zboczy: w wierzchołku, w środku i na palcach z dwóch obszarów na tej samej ścianie wykopu są rejestrowane za pomocą sejsmografów strzałowych. Maksymalny ciężar ładunku na opóźnienie i odległość od obszarów wybuchu do sejsmografów są zbierane w celu obliczenia wyskalowanej odległości. Procentowa zmiana FS trzech metod z obu obszarów w porównaniu ze stanem naturalnym FS wynosi mniej niż 4 procent, co oznacza, że stabilność zbocza jest bezpieczna przed drganiami wybuchowymi (mniej niż 15 procent). Zależność między FS i maksymalnym PPV z równowagi granicznej, pseudo-statyczna 1 (k_H) i pseudo-statyczna 2 (k_H, k_v) wskazuje, że niekorzystne maksymalne PPV przy jednostkowej FS wynoszą 16,60 i 4,58 oraz 4,74 mm / s, odpowiednio. Regulowany PPV poniżej 2 mm / s w kopalni jest rozsądnym rozwiązaniem, aby zapobiec możliwej awarii. Jednak wiele parametrów uderzenia nie zostało uwzględnionych w tym badaniu, a ich wpływ może naruszyć stabilność zboczy odkrywki.

Słowa kluczowe: *wibracje gruntu wywołane podmuchami, stateczność zbocza, współczynnik bezpieczeństwa, analiza równowagi granicznej, analiza pseudostatyczna*