RISK ASSESSMENT OF OPEN PIT LAKE USING IN SITU OBSERVATIONS AND ADVANCED NUMERICAL MODELLING – APPLICATION ON MOST LAKE

OCENA RYZYKA DLA POKOPALNIANEGO ZBIORNIKA WODNEGO Z WYKORZYSTANIEM OBSERWACJI IN SITU I ZAAWANSOWANEGO MODELOWANIA NUMERYCZNEGO – PRZYKŁAD JEZIORA MOST

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Almost all post-exploitation open pit mines in the world are shaped as a final reservoir intended to be filled with water. In Europe, the creation of water lakes is the most common way of reclaiming post open pit mines. The safety and the security of mine lakes is one of the mine regions priorities. Several hazards related to mine activities should be assessed. Qualitative and quantitative approaches were suggested based on the existing data. One of the main hazards identified is the slope stability of lake banks. To develop a reliability methodology for assessing the long-term stability of flooded open pit mines, a large-scale numerical model of the lake was carried out and was applied on lake Most, which is one of the largest mining lakes in Europe (Czech Republic). The large-scale numerical model was built, based on site observations, large-scale LiDAR data and geotechnical data. The results highlighted the reliability of the methodology to combine the geometric model with the geological model to create a large-scale numerical model, and to identify local potentially instable zones..

Keywords: *mining hazards, mining lake, slope stability, risk assessment, LiDAR, 3D numerical modelling*

Niemal wszystkie poeksploatacyjne wyrobiska odkrywkowe na świecie są ukształtowane jako wyrobiska końcowe przeznaczone do napełnienia wodą. W Europie tworzenie zbiorników wodnych jest najpowszechniejszym sposobem rekultywacji kopalń odkrywkowych. Bezpieczeństwo i ochrona jezior pokopalnianych jest jednym z priorytetów regionów górniczych. Należy dokonać oceny kilku zagrożeń związanych z działalnością górniczą. Na podstawie istniejących danych zaproponowano podejście jakościowe i ilościowe. Jednym z głównych zidentyfikowanych zagrożeń jest stabilność zboczy wzdłuż brzegów jezior. W celu opracowania metodologii długoterminowej oceny stabilności zalanych kopalń odkrywkowych wykonano wielkoskalowy model numeryczny jeziora i zastosowano go na jeziorze Most, które jest jednym z największych jezior pogórniczych w Europie (Czechy). W oparciu o obserwacje terenowe, wielkoskalowe dane LiDAR oraz dane geotechniczne zbudowano wielkoskalowy model numeryczny. Wyniki podkreśliły wiarygodność metodologii łączenia modelu geometrycznego z modelem geologicznym w celu stworzenia wielkoskalowego modelu numerycznego oraz identyfikacji lokalnych potencjalnie niestabilnych stref.

Słowa kluczowe: *zagrożenia górnicze, jezioro pogórnicze, stateczność skarp, ocena ryzyka, LiDAR, modelowanie numeryczne 3D*

Introduction and objective

Almost all post-exploitation open pit mines in Europe and in the world are shaped as a final reservoir intended to be filled with water. These artificial lakes are currently (and in the future) dedicated to recreational purposes, including energy installation purposes. To ensure safe utilization of these localities by the public, it is necessary to assess their potential risk of instability. Slope instability is the major long-term hazard. The RFCS RAFF project aims to research issues related to pit lakes. The stability of pit lake slopes after flooding remains an area of uncertainty. Examples of geotechnical failures in slopes and banks of pit lakes are quite well documented, for example those at pit lake Pątnów (Szafranski et al., 2001), Zülpich Mitte and Concordia Lake near Nachterstedt (Vinzelberg and Dahmen, 2014). Back analysis is generally carried out to understand the cause of these phenomena and to suggest mitigation strategies.

The redevelopment of mine lakes is a great concern in mining regions where different natural and mining hazards can exist and should be analysed. In the context of reconverting these lakes, a risk assessment should be carried out by the different actors and stakeholders involved, notably the public authorities and mining departments, the mining operators and the future operators, managers, or owners of the reconverted site.

Hazards sources in pit lakes

Two sources of hazards can occur in the lake site: natural and mining hazards. A mining hazard corresponds to the occu-

Tab. 1. Mining hazards associated with open pit mining and the mining heap (Ineris, 2018), x: corresponds to the configuration of the lake where the phenomenon can occur

Tab. 1. Zagrożenia górnicze związane z eksploatacją odkrywkową i hałdami (Ineris, 2018), x: odpowiada konfiguracji jeziora, w którym to zjawisko może wystąpić

	"Ground movement" hazard				
Flank configuration	Settlement	Surficial landslide	Deep landslide	Mudslide	Boulder fall
Pit – stopes			x		x
Slag heaps - Embankments	x	x	x	x	

rrence of a physical phenomenon of mining origin. A thorough description of possible mining hazards is presented below.

Ground movement

Ground movement is one of major mine hazards that can be observed. The hazards are a function of the nature of the ground. Table 1 represents the „ground movement" hazards for a lake created in a mine site. Five ground movements are identified and described. Their occurrence depends on the configurations of flanks of the lake: pit and slag heaps (dumps).

The „ground movement" hazards can interact with natural hazards (earthquake, change in water conditions, etc.) and could produce cascading effects, for example: the failure of a mine slag heap leads to the ground sliding into the lake, the increase in the water level of the lake generates flooding of the basin near the lake. The assessment of ground movement hazard requires an analysis of the various instabilities that occurred on the site during the operation phase, their consequences and the corrective actions undertaken. The analysis must study the potential modes and mechanisms of failure, the volume involved and the consequences, and put forward mitigation and hazard reduction solutions: modification of the initial slope, reinforcement and consolidation, movement control, upstream and downstream drainage, etc.

Erosion hazard

The erosion hazard mainly concerns embankments and slag heaps with a significant proportion of fine materials. Water flowing through the porous soil can cause the detachment and transport of certain soil particles. External rapid erosion can lead to ground rupture, causing flooding of the land downstream of the lake. Internal can be exacerbated by the presence of pipelines in or under the mining deposit or embankment, of root channels and of the action of burrowing animals. The momentum of the particles can cause severe deterioration to the structure, with the contents spreading downstream. The consequences of the erosion can be characterized by the loose land on lake slopes which is exposed to cyclical variation of lake water levels, erosion, and local, even global, instability under certain hydraulic conditions. Repeated wave action can also increase erosion and can cause lake slopes to retreat.

Fire - heating and combustion

The fire hazard can affect wooded lake slopes or mining slag heaps with a significant coal to lignite ratio, due to the internal combustion of the coal. The phenomenon can be triggered by forest fires on the site, after it has been reforested, or in its vicinity. The consequences of this hazard can have multiple repercussions on the site but also on the surrounding zones: burns, asphyxiation and intoxication of people in the vicinity of the fire and combustion area; triggering of forest fires in the vicinity of the lake, particularly during periods of drought. During these periods the risk is significant, and the occupation of the lake is at its highest; collapse or subsidence of the slag heaps leading to overflow and flooding of the land downstream of the lake; contamination of water by heavy metals from the combustion which releases mineral salts.

Assessment of mining hazards

Open-pit lakes are vulnerable to natural hazards (earthquakes, floods, soil instabilities, and epidemic crises) which can constitute the primary source of risks. The characterisation of the hazard level is based on a qualitative assessment of the factors related to the triggering of the feared phenomena such as landslides or flooding (Cirella et al. 2014). The main hazards associated with open pit mines, and consequently with the future lakes, are presented in Table 2 (Spandis et al., 2021). For analysing the lake site, we have distinguished two phases: the first phase corresponds to the construction or flooding (impoundment) of the lake and the second one corresponds to the post-operational phase which may include reclamation or reuse of the lake. Three levels are recommended for characterising the mining hazard associated with lakes and reservoirs: low, medium, or high. According to the feedback and experts, the probability of each hazard existing in this mining lake context is indicated for the short- and long-term. The significance of the hazard with regard to the creation of the lake and its operation is assessed according to the nature of the hazard and its evolution after impoundment. Some hazards retain the same significance before and after impoundment (e.g., landslides) while others become more significant such as creep, heating due to the increasing of the vulnerability of the elements at risk.

Long-term slope stability of the Lake Most

To develop a reliability methodology for assessing the long-term stability of flooded open pit mines, a slope stability study of the lake area was carried out with a large-scale 3D numerical model using Flac3D, which utilizes an explicit finite difference formulation that can model complex soil and rock behaviours. The 3D model is based on the site observations, large LiDAR data, geological, hydraulic and geotechnical data.

The Lake Most site (Czech Republic, Fig. 1) was selected, as a case study, to perform large-scale stability analyses based on in-situ observation, a 3D geometric model and a large-scale numerical model using strength reduction method. The Lake Most (located below the hill Hněvín) was formed on the site of the former royal town of Most, which had to give way to brown coal mining in the second half of the 20th century. Coal mining was terminated in August 1999. The lake was established in the

Tab. 2. Probability of „presence" of hazards associated with lake creation, during the impoundment phase (short term ST) and after (long term LT)
Tab. 2. Prawdopodobieństwo „występowania" zagrożeń związanych z powstaniem jeziora w fazie retencjonowania (krótkoterminowych ST) i później (długoterminowych LT)

Probability of the presence of hazards associated with the presence of a mining lake			
Hazard		During construction (ST)	Following impoundment (LT)
Ground movement	Settlement	Low	Low
	Surficial landslide	Average	Average
	Deep landslide	Average	Average
	Boulder fall, rockslides	Average	Average
	Mudslide	Low	Average
	Creep	Low	Average
Hydraulics	Overflow	Low	Average
	Flooding	Negligible	Average
	Erosion	Negligible	Average
Fire	Heating	Negligible	Average
	Combustion	Negligible	Average
Pollution		Negligible	Low

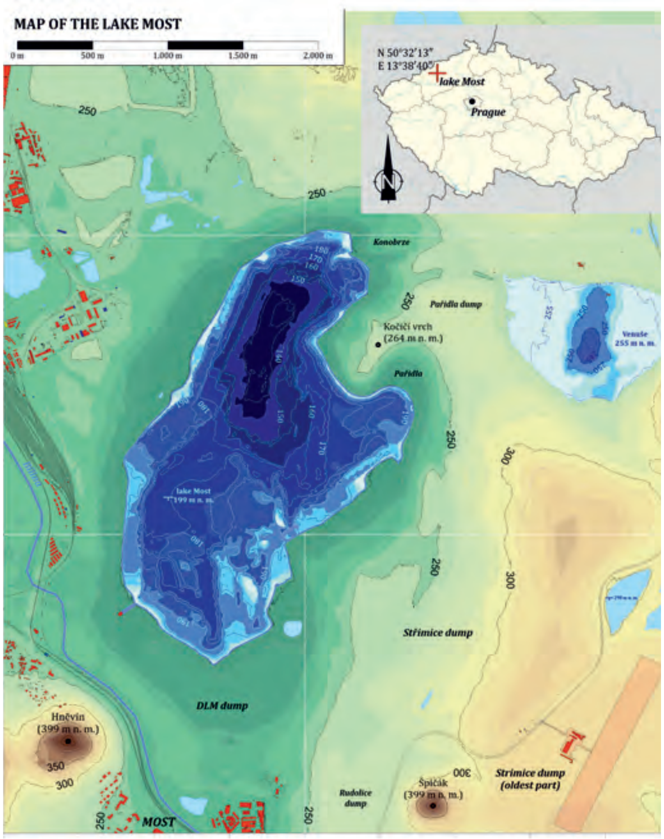


Fig. 1. Localization of Lake Most – Czech Republic
Rys. 1. Lokalizacja jeziora Most – Czechy

open pit mine and the dumps. The flooding began in October 2008 and finished in September 2014 (surface =309 ha, volume = 70 hm^3 [3]).

Geometric and geologic data

3D numerical model is time consuming, however the study area must, at least, integrate the areas of ground movement already identified and must consider the heights of geometric anomalies (valleys or hills). The maximum depth of the lake being 75 m, the highest hill in the immediate vicinity of the lake having a height of 70 m, the boundaries of the 3D model were positioned at more than 6 times 70+75 m from the shores of Lake Most. Additionally, a large LiDAR campaign was carried out in August 2019. The final data point cloud was used to create the digital terrain model to build the 3D volumetric mesh.

To avoid too many meshes and therefore prohibitive calculation, a finer mesh corresponding to 5 m, was adopted, based on 2D calculation for the area of interest whose horizontal perimeter includes all records and observed of ground movements in the Most Lake slopes. The elements at the boundaries are cubes of 50 m edge. The 3D geometric model thus designed has 11,826,069 elements. 14 non-tabular geologic formations are identified, and faults are present. The geology of the site is based on thousands of boreholes (carried out between 1867 and 2018) that have been used to build DMT of the interfaces of the different formations. But since the spatial distribution of these boreholes is not homogeneous and does not always extend to the limits of the model, it was necessary to interpolate the position of these interfaces. The analysis of the numerous data from this campaign has helped to determine both the position of these interfaces as well as the values of the geomechanical parameters. Figure 2 represents the different geologic units used for building the 3D numerical model.

Geotechnical data

The geotechnical data are based on 2 groups: the data relating to geological formations and the data characterizing the dump units (Žižka and Burda, 2021). The first group concerns all the units described in Figure 2 except NS-TV1 and TV2 anthropogenic units. Among these geological units, the 3 least resistant units (quaternary gravel, JIL1=plastic soft clays and PJIL=sandy clays: 52 kPa<σc<143 kPa) will play a role in the calculation of slope stability, especially in areas where these units are near the topographic surface. The second group of data is very rich in geotechnical information due to a recent measurement campaign (CPT). There are 9538 CPT measures available, including pore pressure (u2), sleeve friction (fs), depth, cone resistance (qc), corrected cone resistance (qt), soil weight (γ), density (ρ), pore water pressure (u), total stress (σv)

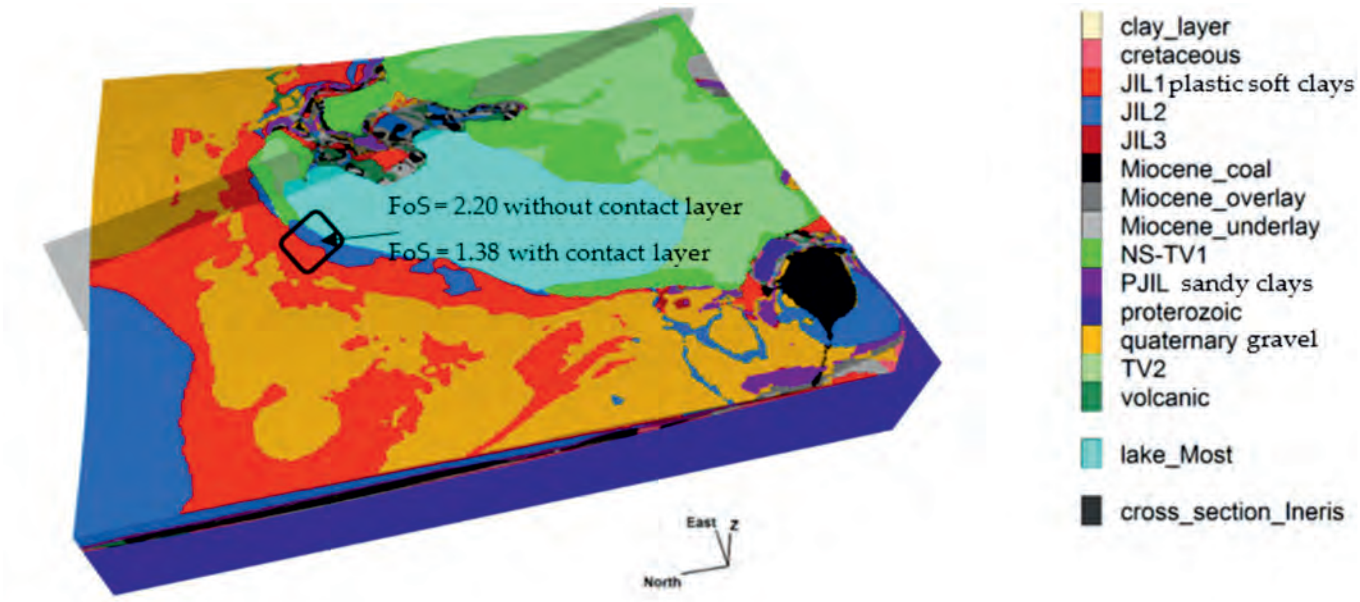


Fig. 2. 3D geological model of lake Most (11 826 069 elements); rectangular limit: area where the FoS is minimal.
Rys. 2. Model geologiczny 3D jeziora Most (11 826 069 elementów); ograniczenie prostokątne: obszar, w którym FoS jest minimalny.

and Young's modulus (E). The last 6 parameters are classically calculated from the data recorded every 10 cm and parameters characterizing the used cone (net area ratio: a= 0.8 and penetrometer diameter B = 0.0357 m). As materials are assumed to have a Mohr-Coulomb elastoplastic constitutive model, the cohesion (C) and the friction angle (ϕ) were calculated from these data. The CPT data interpretation theory manual gives 3 empirical relationships (Mayne, 2006) for assessing ϕ. The disadvantage is that these relationships do not give assess to cohesion and that their validity is limited to sands or to fine-grained soils. Therefore, we prefer to use the system of 2 equations proposed by Motaghedi & Eslami, (2014) which gives access to C and ϕ after numerical resolution.

The parameters of the CPT campaign were recorded for 23 exploitable penetrometer profiles whose depth of investigation varies between 10 m and 101 m. This depth was calibrated to the estimated thickness of the mining deposits. These 23 profiles have been statistically analysed with an automated method based on the evolution of the coefficient of determination (between depth and cohesion). The position of the interface between different dump units is obtained by analysing the cohesion profiles (Fig. 3). This completes the determination of the geological model shown in Figure 1 with a homogeneous structured mesh. To gain accuracy in the areas of interest, this mesh will be replaced by a heterogeneous unstructured mesh. In addition, an assumption was made concerning a contact layer. This layer was not detected in the CPT campaign measurements. This layer may play a main role on slope stability and in situ observations.

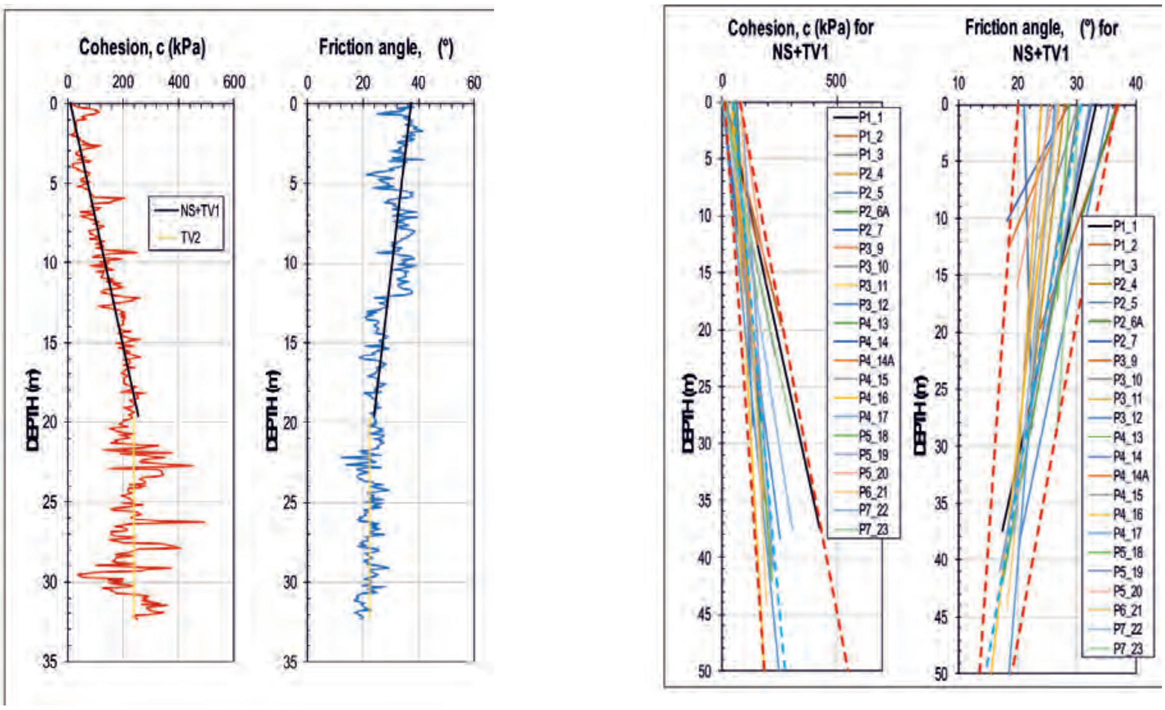
Two calculation scenarios have been built from the average values and the minimum bounds of C, ϕ, ρ and E. A third scenario is possible by modelling the properties with the most representative distribution of the measurements. For the TV2 unit (properties not very sensitive to depth), we considered all the data attributed to this unit (2843 measurements) to find the best distribution. To account for the variation of the statistical parameters with the depth in the NS-TV1 unit, we gathered the measurements at 2 m depth. The measurements are numerous enough for this unit (population = 6629) to have enough individuals to analyse. The criterion for selecting the best distribution is a minimization of the square of the difference of the theoretical and measured frequencies. As one of the aims of the RAFF project is to develop an operational methodology, we have chosen, for modelling, only the easily implementable distributions: normal distribution, lognormal and Birnbaum-Saunders. The results of this statistical analysis are reported in Table 3. Note that the lognormal distribution is the one that best represents variations in cohesions and Young's modulus. The same is true for the friction angle except for the TV2 unit, which correlates better with a Birnbaum-Saunders distribution. The normal distribution is the best fit for spatial distribution of the density masses in the 23 CPT profiles. The probability density function of the Birnbaum-Saunders distribution is shown on Figure 3.

Hydraulic data

Typically, the position of the water table is poorly known, and it is often determined by a few points where the pore pressure is known, by the hydromechanical properties of the studied layers (permeability, porosity, Biot coefficient, dynamic viscosity) and by boundary conditions (null fluid flux, prescribed pore pressure field, inflow, outflow, leak-age). Fortunately, the Lake Most site is very well instrumented: the piezometric heights of the water table have been recorded for 93 wells since 2014. The water table DMT has been built from 93 piezometric water levels and lake surface. For slope stability calculations, the position of the water table has been used to calculate the pore pressure and effective stress fields.

Results

The use of the strength reduction method produces one global minimum stability state per simulation. This method is applied with the Mohr-Coulomb failure criterion (Zienkiewicz et al., 1975) by progressively reducing the shear strength of the material to bring the slope to a state of limiting equilibrium. However, along a complex slope profile (as the profile of the NNW-SSE cross section: Fig. 3), it is interesting to be able to compute multiple minimum states. Instead of excluding diffe-



a)

b)

Fig. 3 (a) Cohesion and friction angle computed for profile P1_2. (b) Linear variation of cohesion and friction angle for all CPT profiles for NS-TV1 unit; minimum and maximum limits in red and mean value in cyan

Rys. 3. (a) Kohezja i kąt tarcia obliczony dla profilu P1_2. (b) Liniowa zmienność kohezji i kąta tarcia dla wszystkich profili CPT dla jednostki NS-TV1; limity minimalne i maksymalne zaznaczono na czerwono, a średnią wartość - na niebiesko

Tab. 3. Statistical properties of dump units. N, LN & BS dist: Normal, Log-normal and Birnbaum-Saunders distributions; d: depth

Tab. 3. Właściwości statystyczne jednostek zwałowiska. N, LN i BS dist: rozkłady normalne, log-normalne i Birnbauma-Saundersa; d: głębokość

dump unit / *Property*	NS + TV1	TV2	Contact Layer
cohesion: C (kPa)	mean : 4.59 d+46.15 min : 3.5 d+10 LN dist ∫ [0.6 , 650]: μLN=0.0324 d+4.034 σLN=-0.0063 d+0.598	mean : 247.4 min : 4 d-60 LN dist ∫ [6 , 1098]: μLN=5.31 & σLN=0.626	6.0
friction: ϕ (°)	mean : -0.323 d+30.69 min : -0.13 d+20 LN dist ∫ [7 , 44]: μLN=-0.241 d+28.73 σLN=-0.071 d+6.074	mean : 22.7 min : 16.8 BS dist ∫ [8.2 , 38.6]: β=22.019 & γ=0.244	6.0
Young's modulus: E (MPa)	mean : 3.67 d+18.51 min : 2.96 d+5 LN dist ∫ [1 , 354]: μLN=0.037 d+3.577 σLN=-0.004 d+0.377	mean : 193.9 min : 3.6 d-52 LN dist ∫ [29.6 , 636.5]: μLN=3.855 d+32.046 σLN=0.6195 d+28.295	7.0
saturated density: r (t/m^3)	mean : 0.0124 d+1.739 (d≤12.5 m) 0.0035 d+1.869 (d>12.5 m) min : 0.0035 d+2.0 N dist ∫ [1.3 , 2.2]: μ=0.0053 d+1.813 σ=-0.0008 d+0.0919	mean : 2.023min : 0.0017 d+2.079 N dist ∫ [1.55 , 2.285]: μ=2.023 & σ=0.098	2.0

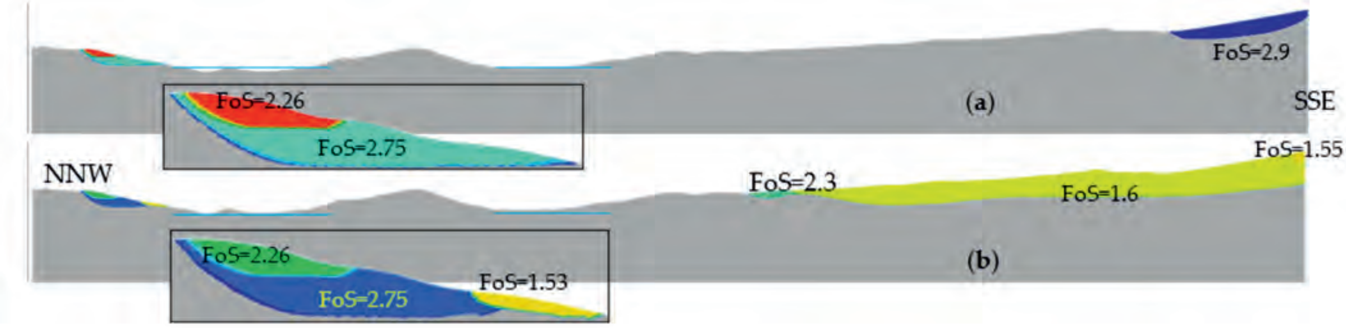


Fig. 4 FoS contours for the 4629 m length NNW-SSE cross section the dump units (a) without contact layer, (b) with contact layer
Rys. 4. Kontury FoS dla przekroju NNW-SSE o długości 4629 m dla jednostek zwałowiska a) bez warstwy kontaktowej, (b) z warstwą kontaktową

rent regions of the slope when performing the strength reduction calculation, we have used the ability of Flac3D (Itasca, 2019) to compute multiple local stability surfaces in a single simulation.

Six calculations were made to estimate the safety factor of the Most site in its current (short-term) situation. The 6 calculations were established from the scenarios of geomechanical properties of dump units (mean values, minimum bounds or statistical distribution) and the presence or not of the contact layer at the bottom of the dump bodies. The contact layer is characterized by very low geomechanical parameters (C = 6 kPa and $\phi = 6\ °$). Some results of these scenarios are shown in Figure 4. First, the 3 scenarios without contact layer produce the same iso-values of FoS because these 6 scenarios differ only in the properties of the dump units and because dump units are not the weakest geologic units. On the other hand, the 3 scenarios including the contact layer change the stability of all dump units (NS-TV1, TV2 and contact layer). This is explained by the very low proper-ties of the contact layer. Areas with FoS of 2.75 (NNW) and 2.9 (SSE) without contact layer have a safety factor of between 1.14 and 1.53 at NNW and between 1.5 and 1.6 at SSE when a contact layer is present. The 3D calculations give results compatible with this 2D cross section: FoS = 2.2 and 1.38 without or with a contact layer respectively. The global 3D FoS is located on the north bank of lake Most (Fig. 4) at the location where most slope failure stabilization operations took place in the past. In those zones earth and stabilisation works were carried out to insure long-term stability.

Conclusions

The paper presented the main mining hazards which may affect mine lakes in former open pit mines. The main mining hazards in the context of the creation of a post-mining lake according to our analysis are ground movement, fire and pollution. The ground movements should be analysed taking into account the morphology, the geology and hydrogeology of the site. The slope stability (shallow and deep landslide) is one of the main identified hazards in the context of mine lakes.

In order to establish a reliable methodology for assessing the long-term stability of flooded open pit mines, a large-scale numerical model of lake Most was carried out with Flac3D. The model integrated the complex geology of the mine and the dumps as well as the surface of the water table interpolated from 93 piezometric levels. The results of the 2D and 3D numerical modelling were analysed as large scale by calculating global and local safety factors. The results highlighted the reliability of the methodology to combine the geometric, geological and hydraulic models to create a large-scale numerical model, and to identify local potentially instable zones. The hypothesis of the presence of a very weak contact layer (at the bottom of dump bodies) is therefore a strong hypothesis, capable of questioning the stability of the slopes of the site (Most Lake). It should be noted that the contact layer was not detected from the CPT campaign measurements. But neither the absence nor the presence of the contact layer can be confirmed because only 2 profiles are deeper than the dump units on an area to be investigated of more than 8 km^2.The most realistic hypothesis is probably to consider a partial presence of the contact layer. These new calculations could show whether the reality lies between the minorant (with contact layer) and majorant (without contact layer) scenarios. In this case, the Lake Most site could then be concluded to be stable in the short to medium term.

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Post-coal mining Lake Most, Czech Republic