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# A slope stability analysis of an open-pit mine to evaluate its suitability as a site for the intersection of the S-7 and S-52 expressways

# Analiza stateczności kopalni odkrywkowej w oszacowaniu przydatności pod planowaną budowę trasy S-7 i północnej obwodnicy Krakowa trasy S-52

**Abstract**

This paper presents a comprehensive approach to the numerical modelling of the geotechnical issues related to the stability of the slopes of a former open-pit mine. The mine is located within short distance of the planned S-7 expressway route and the northern bypass of Krakow; therefore, there is a need of opinion as the project might have a significant impact on the surrounding area including structures planned nearby, as well as stability of slopes of former open-pit mine. The finite element method (FEM) was applied to the numerical analysis with the specific aim of assessing the risk of the movement of soil mass as far as the slopes of the Zesławice open-pit mine are concerned [4]. Field work and numerical analysis were conducted in reference to land reclamation plans of former Miocene clay mine located in the Carpathian Foredeep. The numerical modelling includes zoning plans. The numerical modelling was conducted with a terrestrial laser scanner application [12]. In addition, spatial distribution and the identification of the parameters of the subsoil layers was performed. A numerical soil model, based on Mohr–Coulomb theory, was also taken into consideration. shear reduction method (SRM) was applied to determine the slope stability; the areas at risk of mass movement were then identified on the basis of the slope stability ratio.

**Keywords:** numerical modelling, failure surface, slope stability, terrestrial laser scanning

**Streszczenie**

W artykule przedstawiono kompleksowe podejście do modelowania numerycznego zagadnień geotechnicznych, które dotyczą stateczności skarp dawnej kopalni odkrywkowej. Kopalnia zlokalizowana jest w pewnej odległości od planowanego przebiegu trasy S-7 i północnej obwodnicy Krakowa, konieczne jest zatem przeanalizowanie, czy projekt może mieć znaczący wpływ na otaczający obszar, planowane i istniejące obiekty budowlane oraz stateczność stoków byłej kopalni odkrywkowej. Metoda elementów skończonych (MES) została zastosowana do analizy numerycznej, przede wszystkim w celu dokonania oceny ryzyka ruchów masowych gruntów stoków nieczynnej kopalni odkrywkowej. Prace terenowe i analizy numeryczne zostały przeprowadzone w odniesieniu do planów rekultywacji obszaru kopalni odkrywkowej iłów mioceńskich zapadliska przedkarpackiego. Modelowanie numeryczne uwzględniło planowany obszar. Jest on wyznaczony na podstawie naziemnego skanera laserowego. Wykonany został również przestrzenny rozkład i identyfikacja parametrów warstw gruntów. Model numeryczny gruntu, bazujący na teorii Coulomba–Mohra, został również uwzględniony w analizie. Metoda redukcji wytrzymałości gruntu na ścinanie (SRM) została zastosowana w celu określenia stateczności skarp. Obszary zagrożone ruchami masowymi zidentyfikowano na podstawie współczynnika stateczności.

**Słowa kluczowe:** modelowanie numeryczne, powierzchnia zniszczenia, stateczność zboczy, naziemny skaning laserowy

## 1. Introduction

*Zesławice* clay mine is one of the oldest open-pit mines near Krakow see above note (District XVII – Krzesławickie Hills), minerals were exploited here from 1952. A brickyard was also located at the site of the mine, this supplied the inhabitants of Nowa Huta and the Tadeusz Sendzimir Steelworks with building materials. According to the zoning plan, a significant part of the mine area has been assigned for housing development (single family dwellings), while the other part has been assigned for the site of the intersection of the S-7 and S-52 expressways. The intersection of the S7 expressway and the northern bypass of Krakow – Expressway S7 as well as gen. Okulicki Street will undeniably be one of the routes around Krakow that carry the highest volumes of traffic. The investment plan to be completed according to [1], and it will be possible to use this route to travel between Krakow and Warsaw around the year 2021. Afterwards, the northern part of Krakow will be ready for further development. As a result, the intersection of Krakow – Mistrzejowice (former: Nowohucki) will be the next route where traffic congestion will increase. Moreover, it might have a negative influence on the surrounding area, in particular, the condition of subsoil.

Fig. 1. Exposed parts of Miocene clay in an open-pit mine

## 2. Open-pit clay mine characteristics

Zesławice clay mine has an area of 45 ha and covers a section of the geomorphological unit known as the Carpathian Foredeep, where Miocene clay deposits (Fig. 1) can be found. Clay, which is the base material for the building industry, is no longer extracted there due to the fact that a section of the S-7 expressway is to run through it. Moreover, the intersection of the S-7 and S-52 expressways will also run through it because, as stated in the zoning plan, there is no better location for this intersection – the decision to build it at this location is thus justified. However, the mine site remains home to some active landslides which have brought this place to ruin, and consequently, have brought operations to a halt. It is therefore important to conduct an analysis on how the new investment will affect the mine site and its surroundings, taking into consideration the Miocene clay deposits and the fact that this area is at risk of landslides. The route plan shown in Figure 2.

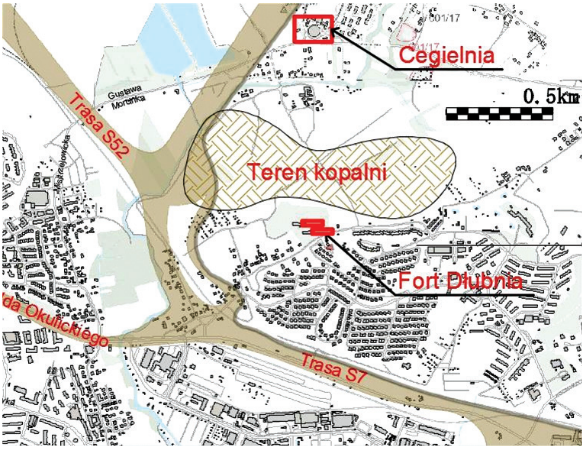

Fig. 2. Route plan of the S-7 and S-52 intersection on the former open-pit mine area in Zesławice

The other reason for the investment to be analysed is the presence of two historical structures which are in the proximity of the investment site. The first is the abovementioned brickyard, which is made of reinforced concrete frames and was built in 1952. The brickyard, abundant in raw materials like clay deposits and built alongside the clay, served as a source of building materials for nearby construction sites, e.g. property development and the Tadeusz Sendzimir Steelworks. The second structure is Dłubnia Fortification 49a, built from brick and stone and dating back to the nineteenth century. The historical significance of this fortification was one of the reasons for the open-pit mine to be shut down. The altered shape of the mine site due to earthworks, the susceptibility of clay to earthflows, the risk of landslides, accessible mine highwalls and floor and considerable sums of money spent to secure the site were among the other reasons for its closure.

It is crucial to analyse every stage of the investment project and its impact on the existing housing estates and relicts of the past. The study included four stages:

- analysis of the sensitivity of the slope to triggering mechanisms and the stability of the slope of the former Zesławice open-pit mine;
- assessment of soil consolidation and soil subsidence due to covering the basin of the work with anthropogenic soil parts;
- impact of housing development on the subsidence of anthropogenic soils on lands which underwent reclamation;
- analysis of the impact of the planned intersection on slope stability within the area of the mine, including analysis of the impact of traffic vibrations on the housing development that is close to Dłubnia Fortification.

## 3. Calculation assumptions

### 3.1. Slope stability evaluation

In evaluating the stability of road embankments, hillsides, and mine terraces, the standard methods of ground-stability evaluation based on the theory of limit equilibrium and the assumption of cylindrical slip surfaces (eg. Fellenius, Bishop, Janbu method) are utilised. However, nowadays there are engineering issues in which discrete methods based on the finite element method (FEM) or finite difference method (FDM) are more functional. The slope stability method is based on modified shear strength reduction (SRM). The SRM algorithm consists of reduction strength parameters of the soil (friction angle and cohesion) in each iteration step. The process of iteration is considered complete when the body reaches instability. The ratio of the output parameters resulting from the iterative procedure allows to determine the safety factor defined as:

$$\tau = \frac{\tau_f}{\tau} = \frac{\tan\varphi}{F}\sigma_n + \frac{c}{F} \tag{1}$$

Limit equilibrium methods are successfully used for homogeneous soil conditions for which it is founded flat cylindrical slip surface, which corresponds to the actual behavior of the soil medium. However, in most cases, the arrangement of geotechnical layers is more elaborated. In such cases, the use of numerical methods to evaluate the stability of the analysed medium is reasonable. This causes the shape and the surface not provided with failure in this case is limited to cylindrical and may have various forms of stability loss.

Engineering practice is dominated by an approach based on the designation of the slope stability under consideration in the plane state of deformations. In the case of linear infrastructure, railway and road embankments where the geological layers do not change the length of structure. This approach is justified. However, in particular situations, the designer should adjust the range of the computational model to the prevailing soil conditions. This determines that the designer needs to take into account the different models that are built on the basis of a greater amount of field tests, allowing the nature of the soil to be more accurately determined. Analysis of the plane state of deformations only allows the obtaining of information regarding the local safety factor and shape in range of the designated failure surface. Obtaining more accurate results, including the location and range of the actual slip surface, demands three-dimensional modelling and analysis [10].

### 3.2. Geotechnical parameters

Since 2010, the soil-structure of Cracow University of Technology has been continuously conducting research on the former clay mine in Zesławice. This work is related to determining the strength parameters of the Miocene clays under various loads. Over the years, a number of field studies and laboratory tests have been performed. Examples of these tests include: static CPT and CPTU tests using the Pagani mobile device; light and heavy probing with

SLVT and DPL, DPH and DPSH devices outdoor and several laboratory works including oedometric tests, and shear box tests, and triaxial stress tests The test procedures are consistent with European standards and guidelines [3, 16].

This paper attempts to assess the stability of slope terraces located in the south-eastern part of the discussed open-pit mine. A spatial arrangement of geotechnical layers is matched with the three-dimensional terrain of the mine. As a result of the 2010-15 field tests, the geotechnical profile of analysed area of the mine has been identified.

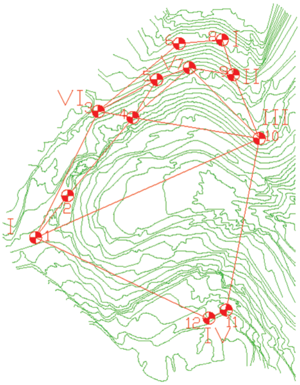

Fig. 3. Geotechnical profiles on the contour line map of the south-eastern section of the mine

The geotechnical prospection is performed in six different planes (Fig. 3). This enables the creation of a 3-D model of the subsoil, assuming that the change of the geotechnical layers occurs linearly along the identified profiles. Field studies have shown that a layer of silts (Si) with a thin layer of silty sands (siSa) are located immediately below the ground level (Fig. 4). The tertiary Miocene clays are located below the layer of sands.

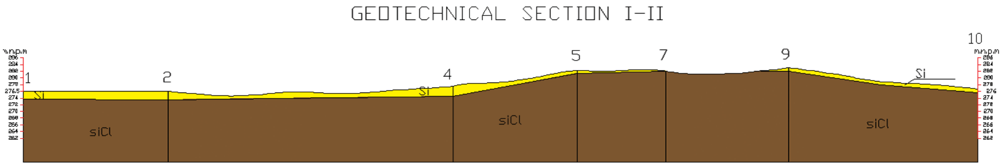


Fig. 4. Geotechnical intersection within I-II

Table 1 presents the parameters of identified there. The values of the internal friction angle ϕ and cohesion *c*, as well as volume weight γ, plasticity index $I_L$, Young modulus of the deformation *E*, and Poisson's ratio *ν* are obtained from the tests.

Table 1. Characteristic values of the geotechnical parameters for the layers included in the analysis

| **Soil name** | **Φ [o]** | ***c* [kPa]** | **γ [kN/m³]** | ***E0* [MPa]** | ***ν* [-]** | **$I_L$ [-]** |
|---|---|---|---|---|---|---|
| saSi | 30.0 | 25.0 | 19.56 | 74 | 0.3 | 0.12 |
| Cl | 16.0 | 40.0 | 21.49 | 197 | 0.3 | 0 |

### 3.3. Spatial modelling

Elaborated numerical modelling includes the spatial character of the land surface in addition to the spatial distribution of the geotechnical layers. It is important in the slope stability analysis to accurately reflect the slope of the hill, affecting the general stability of massive ground. In the stability analysis for post-mining excavations with terraces comprising many slopes, accurate surface representation with slopes is obtained using a terrain model derived from terrestrial laser scanning.

The measurements campaign is made with precise the Riegl VZ-400 terrestrial laser scanner in 11 measuring points, enabling a comprehensive survey of the area of the south-eastern part of the open-cast mine. The measuring device is characterised by a scan range of 400 to 500 m, with a precision of 5 mm (Fig. 5). The process of laser scanning [9, 12] is based on the automatic measurement of existing buildings or land through the use of a high frequency sampling rate (i.e. $f$ = 122 kHz). Due to connecting frame and linear scanning in the device from an analogue signal to the digital one tens of thousands of points per second are processed in real time.

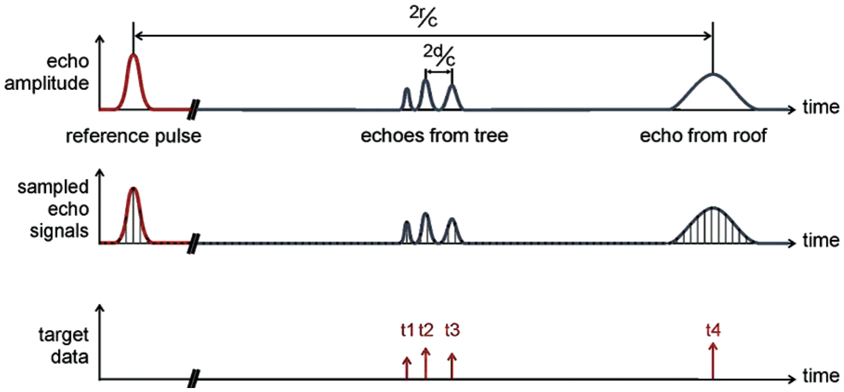


Fig. 5. Collecting data reflected by the measuring device [12]

During the measurements, terrestrial laser scanner generated a point cloud area. As a result of the signal processing by removing unnecessary objects in the measured area (i.e. plants, trees, buildings, etc.), a spatial hypsometric map is generated (Fig. 6) and is then approximated with a cloud of points in a triangular finite elements mesh.

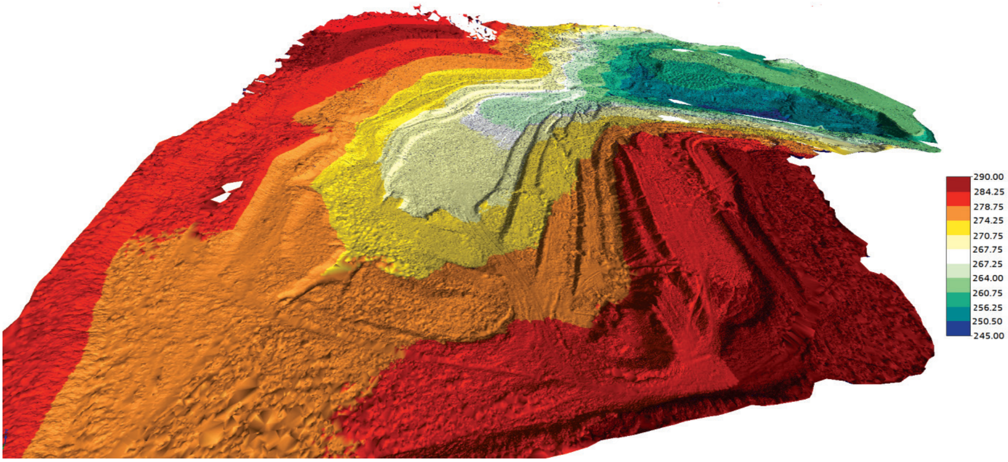


Fig. 6. Hypsometric map of the area of the spatial model

### 3.4. Numerical model

The modelling procedure of the analysed open-pit mine used information from literature [2, 14]. The analysed area is a three-dimensional medium and takes into account the spatial stress and strain distribution. In the modelling of the soil, the Mohr–Coulomb hypothesis was applied – this is widely used in geotechnical engineering; it provides sufficiently reliable results of the overall analysis of nonlinear soil behaviour (Fig. 7).

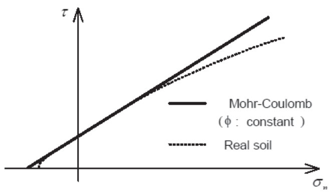

Fig. 7. Comparison of the Mohr–Coulomb hypothesis and the real behaviour of the soil [4]

The Mohr–Coulomb criterion can be written in the form of principal stress as:

$$\frac{\sigma_1 - \sigma_3}{2} = -\frac{\sigma_1 + \sigma_3}{2} \sin\varphi + c\cos\phi \tag{2}$$

For the purposes of the numerical model, Mohr–Coulomb presented in the form of the equation of invariants of the stress tensor $I_1$, $J_2$ and Lode angle θ [4].

$$\begin{aligned} f(I_1, J_2, \Theta) &= -\frac{1}{3} I_1 \sin\varphi + \sqrt{J_2}\left(\cos\Theta + \frac{1}{\sqrt{3}} \sin\Theta \sin\varphi\right) - c\cos\varphi = 0 \\ g(I_1, J_2, \Theta) &= -\frac{1}{3} I_1 \sin\psi + \sqrt{J_2}\left(\cos\Theta + \frac{1}{\sqrt{3}} \sin\Theta \sin\psi\right) - c\cos\psi = 0 \end{aligned} \tag{3}$$

The Mohr–Coulomb criterion is an irregular hexagonal pyramid with a line indicating the point of stress stress as shown in Figure 8. The shape of the deviator plane π $(\sigma_1 + \sigma_2 + \sigma_3 = 0)$ takes the form of an irregular hexahedron.

The analysis assumed a perfectly elastic-plastic model of the Mohr–Coulomb linear plasticity condition.

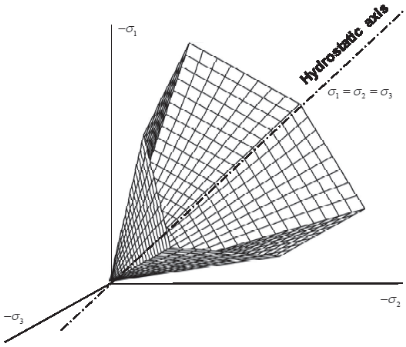

Fig. 8. Mohr–Coulomba criterion in the deviatoric space along the hydrostatic axis [4]

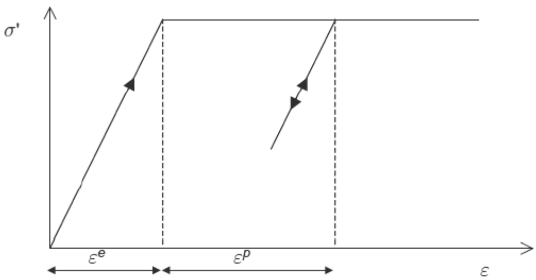

Fig. 9. Graph of the stress from the deformation of elastic-plastic model M-C [4]

A limitation of the Mohr–Coulomb model is the linear nature of the destruction. The friction angle does not change with pressure-limiting (hydrostatic pressure). In addition, the linear nature of the destruction of the soil causes beyond the shear strength of formed permanent plastic deformation and the soil does not transfer stresses (Fig. 9). Figure 10 presents the hexahedral finite element used for the discretisation of digitised terrain.

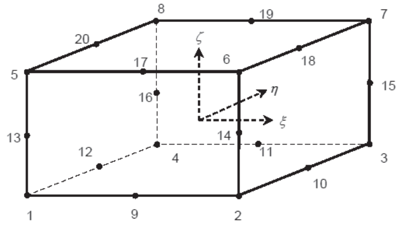


Fig. 10. Hexahedral element used for the discretisation model

## 4. Numerical analysis model

Numerical analysis is used to determine the spatial distribution of the stability factor of the analysed area and determine the location of the largest shear strains in the soil. The model is discretised with 297,000 finite elements of a higher-order hexahedral type. Boundary conditions are applied in the form of a sliding pivot about a vertical axis, preventing movement in the horizontal direction in two perpendicular directions along the x and y axes. The lower edge of the model is blocked in all three directions through the use of non-slip joints. Soil parameters used in computations are taken from Table 1. Figure 11 presents the digitised 3-D model. The computations are performed using a modified shear strength reduction method (SRM) for the dead weight loading.

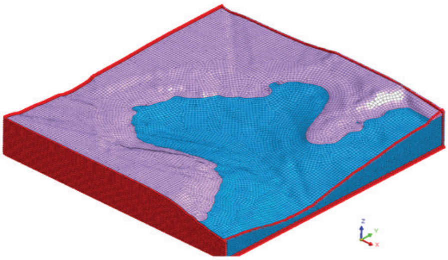

Fig. 11. Digitised three-dimensional model of the analysed area

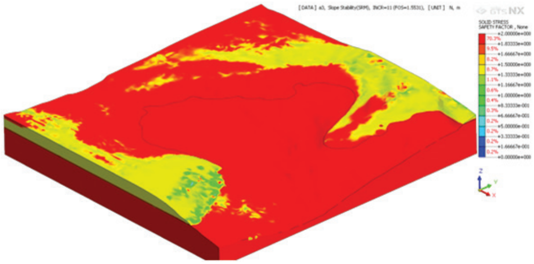

Fig. 12. Distribution of the spatial slope stability factor

Figure 12 shows the spatial distribution of the stability factor of the analysed area. The stability of the analysed area is characterised by a factor in the range 1.10 to 2.00. It mostly consists of areas with a stability factor equal to 2.00. The smallest values are in the range 1.1-1.3 (green and yellow) and occur in the western and eastern parts of the valley. The slopes and terraces of mine are quite stable. The first form of loss of stability may occur in the upper layers of the terraces and will be related to the loss of stability of the Quaternary layers of silts.

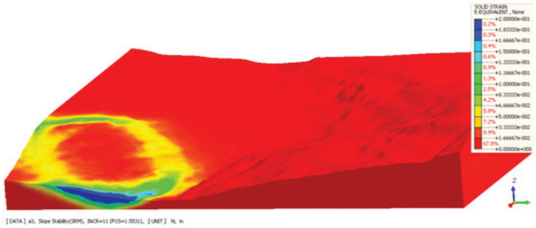

Fig. 13. Exhibits the form of stability loss of the western slope of the terrace of the mine. The soil slip surface covers the entire height of the cliff of the mine

## 5. Final remarks

The paper focuses on the slope stability analysis of an open-pit mine in the context of the gradual development of prospective S-7 and S-52 intersection. The issue raised in this article is based on the first stage of mine reclamation. The area definitely needs to be restored to an acceptable standard of use since the new investment plan for the site includes the development of housing and infrastructure. A modified shear strength reduction method was used in order to determine the spatial slope stability of the area of a former open-pit mine in Zesławice. The analysis results have been used to determine the actual slope stability of the high walls of the mine. Numerical analysis of the area revealed that slopes are formed of silt that is prone to mass movement. In the case of tertiary clay deposits, which are stable if the shear strength parameters decrease, the slope stability factor may significantly drop. The on-site investigation revealed minor landslide activity of slopes in the southern part of the mine due to water activity in the silt layer.

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