THE INFLUENCE OF THE METHODOLOGY FOR SLOPES FORMING IN OPEN PIT MINES ON THEIR STABILITY

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Abstract. Open pit mines are frequently accumulating significant amounts of material in the form of dumping grounds, landfills or forming land for reclamation. Often the form of emerging dumping grounds is determined by stability analysis of their slopes at the design stage. During the operation of the mining site and the collection of material on the pile, only the geometry of the slope is a subject of control. In many cases, after making slopes of a dozen or so meters height or even up to several tens of meters, and after a certain time has elapsed since their formation, deformation of the escarpments can be observed. At this stage, the only option is to change the geometry, i.e. inclination of a slope or, in the worst case, rebuilding of the dump. In the paper the analysis of the impact of the method of forming slopes and material quality on stability of formed slopes and their safe exploitation has been presented. It also presents a proposal to normalize the methodology of design and construction of slopes in a manner ensuring stability and taking into account the variability of the material parameters from which the slope is to be formed.

1. Introduction
Open pit mines design dumps in such a way that after the storage process, the resulting forms fit into a designed model of reclamation. The slope design takes into account the type and properties of the material being stored, the variability of its physical and mechanical parameters and the assumed geometry of the site (including the height of slopes, safety shelves, land accessibility, etc.). Slides of the slopes of the dumping grounds negatively affect the final form of the terrain, while at the same time causing a large problem in securing the slopes, and ensuring the safety of current mining operations [1]. In order to ensure the final terrain shape, it is necessary in the event of a landslide, taking remedial measures by applying additional safeguards, doing partial or complete reconstruction of the earlier formed slope. This also entails the necessity of incurring additional, high costs of earthworks. For this reason, it is important to identify the causes of landslides in the formed slopes, which supposed to be safe, underwent however a loss of stability.

Pursuant to the definition included in the Act on Environmental Protection Law, ground mass movements are natural, or as a result of human activity, landslides, yielding or removal of surface layers of rock, rock-mantle and soil.

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The factors causing the occurrence of slope deformation or the emergence of landslides in mining opencast facilities include, among others [2, 3]:
– the presence of tectonic faults in the bedrock or in the soil of the overburden,
– cracks and relaxation cracks in the ground rocks and in the soil of the overburden,
– leakage of water from lenses and sandy or gravel-stony interbeddings, causing changes in the consistency of cohesive soils,
– large inclination of lithological strata, especially in the edge parts of the deposit in which the slopes and hillside of the excavation pit are located,
– influence of geodynamic processes (vibrations, oscillations, loads from devices working in the area of the open pit, etc.).

The causes of landslides can be natural or anthropogenic. Natural causes of landslides are the effects of natural forces, such as undercutting of slopes by watercourses, marine abrasion, changes of slope load by sediments (eg growing of rock-mantle covers, silting-up or washing of sediments, aeolian accumulation, etc.), changes in hydrogeological conditions, development of cracks and crevices in the result of the activities of plants and animals, the development of suffusion in the scarp, etc.

Anthropogenic causes of landslides include, above all, undercutting slopes and hillside, changes in terrain shaping, loading or unloading slopes, dynamic impacts (shocks), changes in land use (deforestation, sodding) or changes in water conditions [5]. The impact of human activity can directly or indirectly lead to the emergence of landslides. The direct impact on the formation of a landslide may have slope undercutting or slope overloading with embankments or building structures [4].

In the case of open pit mines, the most dangerous threats include landslides, especially multi-slope landslides, especially if they occur unexpectedly and in an uncontrolled manner. The emergence of an uncontrolled landslide causes, on the one hand, a threat to people and equipment, and on the other, the need to incur additional expenses to eliminate the effects of its occurrence [4].

For the purpose of analysing the causes of loss of stability in the existing dumping grounds (long-lasting), analysis was conducted on selected three case studies where landslide processes were observed or progressed.

2. Case studies
For the purpose of identifying reasons for the formation of landslides in the slopes of the opencast mine heaps, three cases of slopes of dumps constructed of various materials have been analysed. The analysed slopes are located in one of the excavations of the opencast facility extracting crushed aggregates using blasting works in Upper Silesia region. For the needs of the analysis, the slopes have been marked as slopes A, B and C, and samples of rock material was taken from them for analysis of physical and mechanical properties.

The escarpments are mainly made of material collected from the overburden of the deposit and material produced in the production of crushed aggregate, i.e. clayey sandstone with large amount of coarse rock crumbs (initial unsorted material on slopes A and B) and well sorted material generated in the processing (post-production waste - slope C). On the slopes marked as A and B, material of a similar nature was stored, which did not differ much macroscopically, but came from various stages of the extraction process – from the deposit overburden and from the process of preliminary sorting of spoil [5].

2.1 Case study – slopes A and B
Slopes A and B are made of identical material and with similar technology. There are slopes up to 30 m high, with a safety shelf of 5 meters in the middle of the escarpment (on about 15 meters). They are built from mixed material coming from the overburden of the deposit, mainly clays of various types in the hard-plastic state and material with a similar granulometric composition but originating from the preliminary sorting of the spoil and containing significant admixtures of coarse rock crumbs. On the scarp, the symptoms of mass movement have been noted in the form of slipping off a part of the material and cracks in the ground level in a distance of approx. 5 - 10 m from the edge (figure 1 and 2).
There were also identified places at the foot of the escarpment, in which point outflows of waters with a capacity of several to several dozen litters per minute were visible (figure 3).

**Figure 1.** Slides of a part of the material being stored (photo by T. Mzyk).

**Figure 2.** Cracks in the ground level of the slope (photo by T. Mzyk).

**Figure 3.** Visible water outflows on a scarp of significant intensity (photo by T. Mzyk).
From the scarps A and B samples of the material has been collected for laboratory tests. The samples taken for analysis came from: the foot of the lower scarp (sample A1), the top of the lower scarp (sample A2), from the foot of the upper scarp (at the height of the safety shelf - sample A3) and from the top of the upper scarp (sample A4). In first place, the granulometric composition has been determined (figure 4) and the consistency of the material, then the tests of internal friction angle, cohesion and bulk density have been carried out. The results of the conducted analysis are presented in table 1 and on the graph in figure 4.

![Grain-size distribution curve](image)

**Figure 4.** Grain-size distribution curves of analysed samples taken from the slope A.

**Table 1.** Results of laboratory tests of analyzed samples taken from the slope A.

| Sample | A1   | A2   | A3   | A4   |
|--------|------|------|------|------|
| **Content of fraction (%):** |      |      |      |      |
| Stone  | 8.17 | 0.00 | 2.29 | 0.00 |
| Gravel | 30.99| 9.89 | 38.04| 7.19 |
| Sand   | 29.55| 24.20| 29.82| 20.26|
| Dust   | 9.52 | 49.06| 15.52| 51.59|
| Clay   | 21.77| 16.85| 14.33| 20.96|
| **Internal friction angle (°)** | 14.1 | 16.3 | 14.6 | 16.2 |
| **Cohesion (kPa)** | 15.31| 19.38| 16.29| 18.94|
| **Specific gravity (kN/m^3)** | 20.36| 19.74| 20.51| 19.58|
| **Degree of plasticity (-)** | 0.24 | 0.12 | 0.22 | 0.13 |

The conducted analysis exhibited that the material collected on the slope shows great diversity both in terms of grain-size and variability of physical and mechanical parameters. It can be seen that there is a certain regularity in the parameter change. It was found that the material occurring in the lower part of the escarpment is characterized by an increased content of stony and gravel fraction. The consistency of this material also decreases, i.e. the material increases its plasticity. The identified relationships were tried to be associated with the time duration and technology of slope formation. On this basis, it was found that there is a relationship between slope formation technology and graining.
The increase in the content of coarse fractions in the lower part of the escarpments is due to the fact that the material stored on the pile was transported by trucks and formed by bulldozing it towards the slope [6]. Such technology caused that thick rock crumbs rolled to the foot and formed a layer with a coarser grain size. Such a layer was characterized by the presence of an increased amount of empty voids, which created favourable conditions for the accumulation of precipitation water. Hence the identified outflows of waters with a relatively high flow intensity at the bottom of the escarpment. The accumulation within the lower part of the escarpment, in the layers forming the slope of precipitation water and the presence of voids promotes infiltration of rainwater (probably of considerable range) and influences the accumulated material gradually plasticizing it. Such a situation may in the future cause the intensification of landslide phenomena reasoned by the decrease of physical and mechanical properties of material collected on the slope and within the dumping ground [5].

2.2. Case study – slope C
Slope C is made of well sorted material coming from preparation processes, practically free of fraction with a diameter greater than 20 mm and with a reduced content of clay fraction. This material in dry condition corresponds to loose soils, exhobots little consistency. Slope C is formed to a height of about 30 m, originally with a safety shelf of 5 meters in the middle of the escarpment (at about 15 meters), but in the current state virtually the entire width of the shelf is occupied by slided or rinsed material. On the scarp, the symptoms of mass movement in the form of fissures, cracks, falling off of material, and thresholds in the slope foot as well as large erosive e dilutions (figures 5, 6 and 7) were noticed.

![Figure 5. Cracks in the slope foot (photo T. Mzyk).](image)

![Figure 6. Thresholds indicating the landslide of the material accumulated on the slope (photo by T. Mzyk).](image)
Due to the diversified humidity and permeability of the material collected on the slope C, samples were taken from places of poorly permeable nature (visible stagnant precipitation water basins) and material with good permeability. The samples taken for analysis came from: the foot of the lower escarpment (sample C1), the top of the of the lower escarpment (sample C2), from the foot of the upper slope (at the height of the safety shelf - sample C3) and from the top of the upper escarpment (sample C4). First, the granulometric composition was determined (figure 8) and the consistency of the material, then the tests of internal friction angle, cohesion and bulk density have been carried out. The results of the conducted analysis are presented in table 2 and on the graph in figure 8.

**Figure 7.** Visible deep erosive dilutions on the slope (photo by T. Mzyk).

**Figure 8.** Grain-size distribution curves of analysed samples taken from the slope C.
Table 2. Results of laboratory tests of analyzed samples taken from the slope C.

| Sample | A1  | A2  | A3  | A4  |
|--------|-----|-----|-----|-----|
| Content of fraction (%):
| Stone  | 0.00| 0.00| 0.00| 0.00|
| Gravel | 35.73| 20.09| 33.55| 2.62|
| Sand   | 64.27| 60.54| 50.35| 54.90|
| Dust   | 0.00| 19.37| 16.11| 42.48|
| Clay   | 0.00| 0.00| 0.00| 0.00|
| Internal friction angle (°) | 37.4| 36.8| 38.1| 35.4|
| Cohesion (kPa) | 6.12| 0.00| 3.41| 0.00|
| Specific gravity (kN/m³) | 22.74| 21.98| 22.37| 21.63|

The conducted analysis showed that the material collected on the slope exhibits little differentiation in terms of grain-size distribution and variability of physical and mechanical parameters. It can be seen that there is a certain regularity in the parameter change. It was found that the material occurring in the lower part of the slope is characterized by slightly higher specific gravity values, a slightly higher value of the internal friction angle, and shows minimal consistency values. This material can be classified as non-cohesive one. The identified relationships were tried to be associated with the time duration and technology of slope formation. On this basis, it was found that there is a relationship between slope formation technology and graining. The material accumulated at the edge of the slope is much less densely compressed and easier to rinse. In particular, at the edges of the escarpment, precipitation water runoff involves leaching significant amounts of material and accumulating them in the lower parts of the escarpment, hence virtually the disappearance of the security shelf, buried by the rinsed material from the above-mentioned parts of the escarpment. The same situation takes place in the lower part of the escarpment where it also accumulates leached material. In general, this reduces the slope angle [5].

3. Analysis of slope stability

One of the three calculation approaches introduced by PN-EN 1997-1 was used to assess stability. In Poland, in accordance with the national annex, approach No. 3 is used for stability assessment. Partial coefficients have been divided into three groups and take into account the coefficients used for interactions or their effects (A), coefficients used for ground parameters (M) and coefficients used for resistances occurring on the slip surface (R) [7, 8].

In the DA3 approach, for the analysis of slopes stability and overall stability of the impact on the ground foundation (structures impacts, traffic load) is considered as a geotechnical impact and a set of A2 load coefficients is applied, i.e. factors are taken into account for variable impacts. The DA3 also includes coefficients for strength parameters [7, 8].

On the basis of determination of actual parameters obtained from laboratory tests of samples of the material dumped on scarps, a slope stability analysis was conducted to answer the question: whether the formed slopes are stable and possibly what additional factors may influence initiation of a landslide. Stability analysis was carried out using the Fellenius, Bishop and Morgenstern Price method in the Geo Slope 1.12XE program. An automatic determination of the center of rotation of the critical slip plane was adopted. Next, attempts have been made to find a slip surface with the characteristics (course, range) identical as observed on the escarpment [5].

4. Identification of the causes of a landslide on the analysed slopes

According to the requirements of EUROKOD 7 [7, 8] for slopes loaded in the foot and endangered by mass movements, the minimum values of the stability index should be increased in the range from 1.5 to 2.0.
The slopes in the analysed excavation were and still are subjected to shocks and vibrations resulting from the used method of mining operations. For this reason, the values of the stability index above 2.0 obtained from modelling - stability analysis, allow to recognize such slopes as safe – stable. Smaller values indicate that the slope of designed geometry made of a specific material has been designed incorrectly.

On the basis of the results of the slope analysis, it was found that the minimum value of the stability index FS for slope A is above 2.35 and for slope B is 3.17. The obtained values indicate that the escarpments should be stable and the causes of landslides within them belong to other factors, not considered in the process of designing. Previously mentioned, highly probable factors related to the separation of material during its dumping on the escarpment and leaving the voids in the ground, in which the fine material is probably currently being washed in, causes the formation of depressions and zones with significantly reduced physical and mechanical properties. In the case when these zones are located in the area of the slope, it is in these areas that the material tends to slip. In addition, the dynamic impacts contribute the phenomenon of thixotropy causing even temporary plasticization of the material within the escarpment [5].

The FS stability factor value for slope C is 1.27. The potential slip plane with the lowest values obtained from calculations, covers the part of the slope without giving rise to the deformations observed in the actual slopes. The values of the obtained stability factors indicate that the A and B slopes are stable. On the other hand, taking into account the low value of the stability factor C, it should be recognized that the cause of the formation of a landslide within it, is a design error, not taking into account the characteristics of the material built into it. This is confirmed by erosive dilution and successive covering of material on the embankment [5].

5. Summary and Conclusions

The conducted analysis made it possible to assess the slope stability at an open pit mine facility and to identify the causes of the formation of landslides within the slopes of the dumping grounds of this plant. It was found that in one case the loss of slope stability results from its incorrect design. In the other two cases, the cause of the formation of a landslide in the slope formation technology was identified. It was also determined that the effects of the method of forming slopes will be significantly extended over time and in the future may cause the landslide process to intensify.

Conclusions for the practice resulting directly from the conducted analysis can be formulated as follows: in determining the safe inclination of slopes one should take into consideration:

- the type of land in which the slope will be made, - the controlled process, soil or material collected should be properly formed or modified to the designed parameters,
- in particular, the size of expected loads, vibrations, impacts in the vicinity of the slope, the possibility of changing parameters as a result of irrigation of collected material and as a result of dynamic impacts should be taken into account,
- it is necessary to precisely determine the expected lifetime of slopes and their durability - scars that are the final slopes have to take into account the manner of the final use of the area,
- effects of a possible loss of slope stability, the possibility of securing, remodelling, changing the way of use, should be included in the method of shaping, including taking into account the possibility of changing the properties of the material (modification of its properties),
- at the design stage, possible ways of strengthening, securing the slope should be taken into account (perform reverse filters on a regular basis, apply geosynthetics, anti-vibration barriers).

Scarps made in open pit mining plants should be designed and executed as building objects with strict adherence to technology and monitoring principles at each stage of their execution. Abandoning such an approach results in very expensive works related to the transfer of significant quantities of material or the use of expensive technologies to protect landslides.
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