

KONTROLA KVALITETE PRI GRADNJI NASIPOV IZ JALOVINE

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Izvleček

Rudarska industrija dnevno proizvaja velike količine rudarske jalovine. Pri izkoriščanju bakrove rude na Poljskem ostanki po flotaciji predstavljajo 95 % izkopane hribine, vsi ti ostanki so deponirani na odlagališča, ki so podprta z zunanjimi jezovi. Trajnost in stabilnost teh zemljinskih objektov je odločilno za varno delovanje celotnega objekta. Izbira ustrezne kakovosti zemljin za gradnjo jezov predstavlja ključni dejavnik za omejevanje tveganja njegove potencialne porušitve. Zelo veliki depoji zahtevajo zadostno velike količine zemljine za gradnjo nasipov. Alternativa temu klasičnemu pristopu predstavlja uporaba odložene jalovine. Pri tej rešitvi se zniža količina rudniških odpadkov, ki so shranjeni v depojih jalovine, ni treba izkoriščati nahajališča naravnih zemljin in poveča se potencialna kapaciteta predvidenih depojev. Prispevek prikazuje principe tehnologije gradnje jezov za akumuliranje vode; kriterije za izbiro primerne granulacije zemljin in fizikalnih parametrov sedimentov za uporabo v gradnji jezov; principe kontrole kvalitete za zemeljska dela; in metodologijo geotehničnih kontrolnih preizkusov. Prav tako so razloženi učinki uporabljene tehnologije na stanje naravnega okolja.

Ključne besede

flotacijski sedimenti, jezovi iz jalovine, geotehnični kontrolni preizkusi

QUALITY CONTROL FOR THE CONSTRUCTION OF A TAILINGS DAM

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Keywords

post-flotation sediments; tailings dams; geotechnical control tests

Abstract

Every day the mining industry produces large amounts of mine tailings. In the case of copper ores exploited in Poland, the post-flotation tailings constitute 95% of the excavated rock and all the tailings are deposited in dumps, which are supported by outer dams. The durability and stability of these earth structures determine the safe operation of the entire object. The selection of adequate-quality soils for the construction of the dams is a crucial factor limiting the risk of its potential failure. Very large depositories require sufficiently large amounts of soil for the construction of the dams. An alternative to this classic approach is the use of the deposited tailings. In this solution the amount of mine wastes stored in the depository is reduced, there is no need to exploit the deposits of natural soils and the potential capacity of the depository increases. This paper presents the principles of the construction technology for hydraulically filled dams; the criteria for the selection of proper soil gradation and the physical properties of the sediments to be used in the construction of the dams; the principles of quality control for earth works; and the methodology of the geotechnical control tests. The effects of the applied technology on the condition of the natural environment are also discussed.

1 INTRODUCTION

Competent waste management in accordance with legal regulations at the site of their deposition is a priority for properly managed and exploited waste depositories. This problem becomes particularly significant when deposited waste products can be economically re-used. Such a situation occurs, e.g., in the case of wastes classified as neutral to the environment. The category of such wastes frequently includes mining wastes, distinguished by two indicators: varied composition, dependent on the site and technology of the produced tailings, and their considerable volume. In open-pit mines it is most typically overburden soil removed from the layers over the deposit, while in deep mines it is the output coming from the construction of the mine and the exploitation of the deposit. Thus, formally the suitability of this output as engineering construction material should be similar to that of natural soils. However, in practice the material after its processing differs from the material deposited into the dump with regard to its strength. A key element of this change results from the fact that the rock material of the continuous structure changes after crushing into granular three-phase material. A very good example of such material is provided by post-flotation tailings from copper ore processing. The utilization of post-flotation tailings as a construction material suitable for earth

structures on the one hand requires a determination of its index and strength properties, and on the other the identification of the type, purpose and parameters of the structure, where the material is to be used.

The aim of this paper is to define the physical criteria for evaluating the quality of tailings used to construct dams based on strength criteria. As a result a new approach for the quality assessment is proposed in terms of a relationship between the relative density and compaction index for the tailings [3].

1 THE OBJECT

Poland is a world-leading producer of copper and silver, exploiting non-ferrous metal ores located in the south-western part of the country, where the entire copper-ore mining and processing industry is found. The output from all the deep mines is subjected first to mechanical treatment and next to the flotation processes, the product of which is copper concentrate and post-flotation wastes, which need to be properly managed. On the global scale post-flotation tailings constitute approximately 95% of the excavated deposit, which due to the volume of production results in the need to manage approximately 25 million Mg waste annually. Starting from 1997 all post-flotation tailings are transported to a single depository, which has recently been officially named the Żelazny Most Mining Tailings Storage Facility (OUOW Żelazny Most). The amount of wastes deposited over the years of the facility's operation has resulted in the construction of a hydro-engineering mega-structure, the second (after the Chinese Great Wall) engineering structure seen from space.

The size of the object is indicated by its parameters: the amount of deposited tailings – over 500 million m^3 ; storage area – 14 km^2 ; the capacity of the tailings pond - 7 million m^3 ; the length of the dams surrounding the depository – 14.3 km; and the height of the highest dams – over 60 m (Fig. 1). Post-flotation tailings are transported to the depository by the hydraulic method, first under pressure and then by gravity, in the form of a soil-water mixture with a density of 1.11–1.15 Mg/m^3 . The wastes mixture is discharged into the depository from pipelines located on the crests of the external dams surrounding the depository (Fig. 2). After the discharge the coarse particles settle on the beach, whereas the finer ones flow with water towards the pond located in the central part of the depository. Due to sedimentation of the finer material in the pond the cleaned water is captured by intake towers and transported back to the mines to the secondary technological cycle. Guidelines



Figure 1. General view of the OUOW Żelazny Most [KGHM Polska Miedz S.A.].



Figure 2. Spigotting of post-flotation tailings at the Żelazny Most depository.

for the safe operation of the depository require the maintenance of the water line at a minimum distance of 200 m from the dam crest, which determines the beach slope, naturally oscillating around 1%.

Tailings are always discharged into the depository beach within one of the 26 separated alluvial fan sections from outlet pipes of 20 cm in diameter, located 20 m from one another (Fig. 2). As was shown in practice, such a spacing of discharge pipes ensures a uniform coverage of the beach with the discharged tailings.

The development of the depository is based on the upstream method, constructing the higher embankments on the spigotted beaches. The new embankments are formed using tailings deposited on the beaches near the dams [11]. The height of the embankments amounts to 2.5 m and it is adapted to the re-arrangement of the spigotting pipelines. The annual increase of the dam height is on average 1.3 m [3].

2 CHARACTERISTICS OF THE DEPOSITED TAILINGS

Post-flotation tailings produced from ores genetically connected with dolomites and copper shales are characterized by a considerable grain angularity, while those from sandstones have a finer morphology or even a preserved original grain shape in deposits with a weaker binder. The basic component of the fraction of less than 0.06 mm comprises chips of carbonate rocks, while in the coarser fraction of quartz is the dominant material, occurring mostly in the fraction of 0.25–0.1 mm. The shale content decreases with a reduction of the grain diameter. The characteristics of the tailings connected with their original geomorphology determine the mechanical properties of the material to be used in the construction of earth dams.

The tailings that are gravitationally spigotted on the beach undergo the natural process of sedimentation segregation, as a result of which coarser fractions are deposited in the vicinity of the tailing-discharge sites, while finer fractions flow with water over the surface of the beach towards the pond. The finest tailings (carbonate-clay tailings) are excluded from the spigotting

process, as material that cannot be used for the construction of the embankments. These wastes are discharged directly inside the depository to seal the bottom of the pond. The spigotting of the tailings is a cyclic process, in which a fragment of the beach is elevated by several dozen centimetres at a time. Then the beach undergoes a drying stage, lasting up to 2 months, followed by another spigotting process. The technology of the hydraulic transport of the tailings to the depository, spigotting of the beach, the process of drainage, drying and beach formation cause significant effects, i.e., the spatial heterogeneity of the tailings' compaction and specific macrostructure characterized by horizontal laminations. The number and thickness of the laminations with the finest grains increase with the distance from the dams, limiting the range of the sedimentation zone for deposits suitable for the rise of the dams. Sediments deposited in that zone have to meet specific compactibility criteria, and as a consequence, also the bearing capacity, since they additionally form the subsoil for new embankments constructed by the upstream method [2]. A diagram for the depository section with an arbitrary division into zones and grading envelopes for the Želazny Most depository is presented in Figs. 3 and 4.

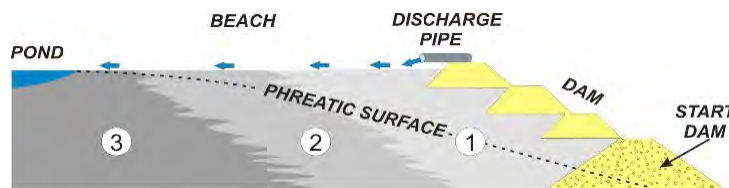


Figure 3. Diagram of a section of a depository fragment divided into tailings-sedimentation zones differing in grain size (zone 1 – coarse tailings, zone 2 – mixed sand-silty deposits, zone 3 – fine tailings and slimes).

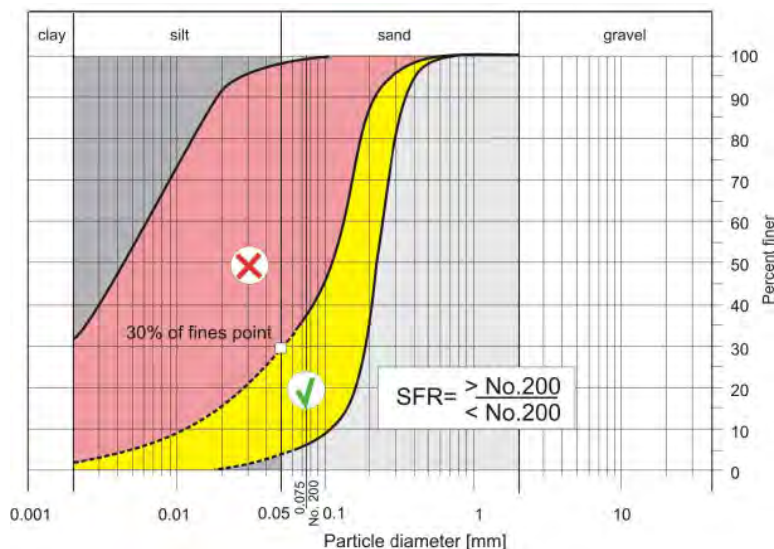


Figure 4. Areas of particle size variation in deposited tailings divided into suitable waste ($d_{30} > 0.05$ mm) and inadequate waste ($d_{30} < 0.05$ mm) for dam construction.

3 CRITERIA FOR THE SELECTION OF MATERIAL FOR THE DAM CONSTRUCTION

Due to the necessity to continuously increase the depository capacity, the processes of engineering design, tailings deposition and dam construction are realized in parallel. The adopted method of upstream development results in a situation when only the starter dams made from natural soils are founded on the subsoil. Successive stages of the development are realized from drained sediments deposited on beaches. The design of the depository development requires the geotechnical identification of the deposited sediments. The geotechnical parameters of the sediments change with the distance from the dams, while they also depend on the type of rock from which they originate, the applied processing, the disposal technology, the seepage and the consolidation processes. Only some of the deposited sediments can be used as a construction material for new higher embankments. Extremely fine silty deposits exhibit the properties of a plastic material with limited shear strength [2]. Sandy deposits have the characteristics of a non-cohesive material with much greater rigidity and shear strength. Such materials can be well described by compactibility indexes. Assuming the strength criterion as the starting point for the determination of the suitability of deposits for construction purposes, a series of tests was performed in a direct shear apparatus at a sediment compaction corresponding to the maximum dry density from the Proctor test, Fig. 5. Samples of sediments were differentiated in terms of their grain

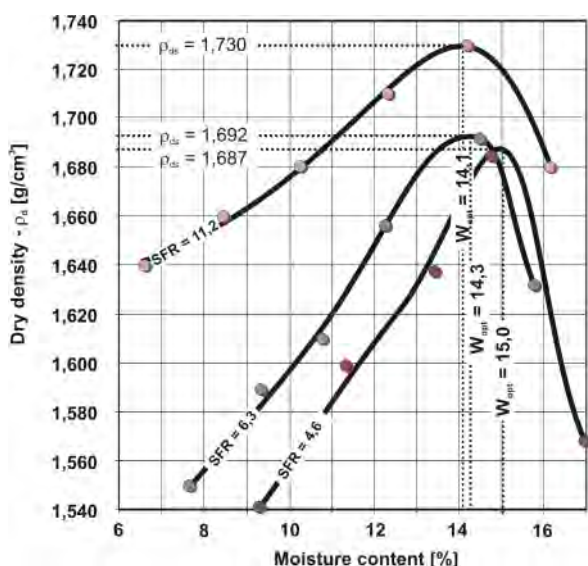


Figure 5. Example curves of the compactibility for post-flotation tailings from the Proctor test (ρ_{ds} - maximum dry density, w_{opt} - optimum moisture content).

size distribution, identified by the *SFR* (ratio of sand to fines < 0.074mm), according to the ASTM standard [4]. The correlation was identified on the basis of model tests between the internal friction angle, determined in a direct shear apparatus, and the grain size parameter *SFR* used in the determination of the physical criterion of sediment suitability, Fig. 6.

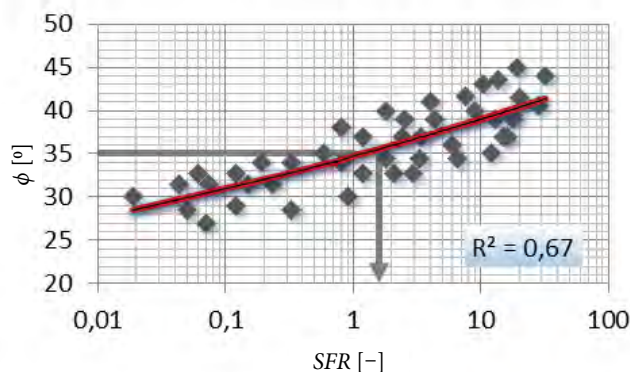


Figure 6. Correlation between the internal friction angle (ϕ) and the *SFR* coefficient for compacted tailings at a natural moisture content equal $\pm 5\%$ of the optimum moisture content.

Samples of post-flotation tailings were compacted at a moisture content similar to the optimal moisture content (typically slightly lower) and as was shown in this analysis, this factor had no significant effect on the low value of the coefficient of determination of equation 1. Factors having a significant effect on the values of the internal friction angle of the deposits with a specific grain size expressed by the *SFR* value are other grain size parameters, e.g., the coefficient of uniformity and the genesis of the deposits.

This dependence can be presented using the following equation (1).

$$\phi = 34.71 \cdot SFR^{0.05} \quad (1)$$

Relatively high values of the internal friction angles result from the high angularity of the sediment grains. On the basis of the stability analysis it can be assumed that in order to meet the strength criterion ($\phi > 35^\circ$) at the required compaction, the sediments embedded in the dams should have $SFR > 2$, which corresponds to a limitation of the silt content in the sediments up to 30%.

The area of grain size variability in sediments classified as suitable for dam construction is presented in Fig. 4.

The identification of the distribution and the potential prediction of changes in sediment grain size in the beach profile and cross-section is the basic information for the

selection of the sediment for the construction of dams and a determination of the geotechnical parameters for an analysis of object stability. The process of sediment deposition results in a situation when the hydraulically filled beach is a heterogeneous medium of random character. Identification of the grain size of the sediments, being a function of the location in space, can be considered as a deterministic problem for a heterogeneous medium [7]. The probability of the occurrence of sediments with varying grain size at a specific distance from the dam can be investigated by clustering sediments into groups with a similar grain size or by the so-called continuous distribution method for one of the adopted measures of the grain size distribution curve, Fig. 7, [6], [1], [7] and [8]. It results from the analysis of Fig. 7 that the previously determined gradation criterion (sand content > 70%) is met by sediments deposited in the zone of the beach adjacent to the dam at a distance of up to 200 m (the yellow zone in Fig. 7). Thus, it was this zone of the beach that was designated as a potential zone for earth works, from which the sediments may be used for dam construction. An advantage of the earth

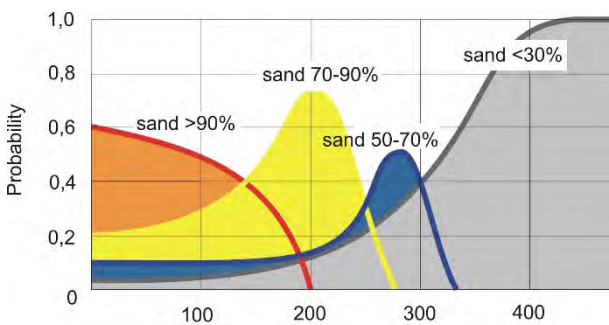


Figure 7. Probability of grain size distribution of tailings deposited on the depository beach depending on the distance from the discharge location.

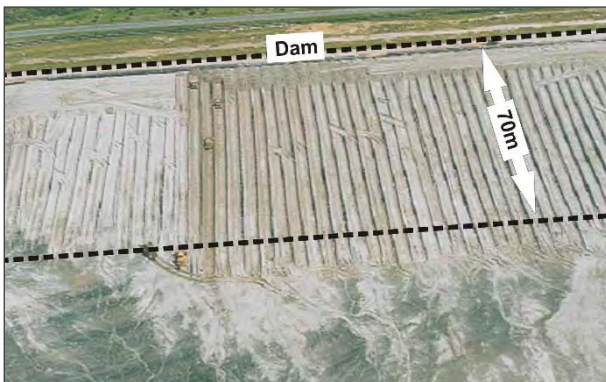


Figure 8. A fragment of the formed beach with the separated zone of deposits suitable for embedding in the dam. The view of the zone of tailings used for dam construction.

work in the identified zone of the beach is the mixing of sediments with different grain sizes, together with the elimination of laminations of cohesive deposits formed in the course of hydraulic filling and compaction of the subsoil for future embankments.

The conditions specified above for the construction of dams from the material deposited in the depository constituted the basis for the development of a procedure defining the manner and sequence of operations:

- Spigotting of a specified fragment of the beach with post-flotation tailings,
- Drainage and drying of deposited sediments in the beach to a moisture content corresponding to the optimal moisture content,
- Collection of hydraulically deposited sediments from a beach section of 70 m in width by bulldozers (at this stage the beach is further compacted for the successive stages of the dam's construction), (Fig. 8).
- Formation of a 0.5-m-thick layer of a new embankment,
- Compaction of the formed layer using a vibrating roll until the required compaction criterion is met,
- Quality control of the performed earth work,
- A repetition of the entire cycle until the complete module of the 2.5-m-high embankment is obtained, together with the final geotechnical acceptance test.

4 QUALITY CONTROL OF PERFORMED EARTH WORKS

The structures of high, hydraulically filled dams from post-flotation tailings surrounding the object require a strict observation of the technological regime and particularly careful quality-control tests of the performed earth work.

Meeting the criteria of the grain size distribution and compaction of the material built in the dam is a necessary pre-condition for the safe operation of the object, guaranteeing its stability and durability. Within the framework of control tests, testing is performed on an on-going basis by the surface method after the formation and compaction of a successive layer of 0.5 m in thickness and the final verification tests by the penetration test after the completion of the construction stage of the 2.5-m-high embankment. The surface tests are based on standard methods, i.e., isotope and volumetric tests [10]. In the isotope method the moisture content and the density of sediments in the controlled layer are determined and, as a consequence, its relative compaction index – R (dry density – ρ_d to maximum dry density – ρ_{ds}), (Fig. 5). In the latter method laboratory

analyses of the physical parameters are performed on the collected sediment samples, and together with the Proctor test results (Fig. 5) they enable a determination of the relative compaction and additionally a verification of the grain size criterion. An original solution in this respect is provided by the cone-penetration test CPT, [5] and [7]. In this method the penetration characteristics are recorded, i.e., the cone resistance - q_c and the friction ratio - R_f , which are indicators for the assessment of the relative density - D_r and the grain size in sediments over the entire analysed profile. The sediments embedded in the dams meet the compaction criterion, when the condition described by equation 2 is met, which can also be clearly seen on the q_c plot (parts of the q_c profile in Fig. 9, above the red line, representing equation (2)).

for $D_r > 70\%$:

$$q_c > \exp\left(\left(36.81 \cdot \ln(\sigma_{v0}) + 733\right) / \left(17 \cdot \sigma_{v0}^{0.0876}\right)\right) \quad (2)$$

where: q_c – cone resistance and σ_{v0} – total vertical stress.

To verify the measures of sediment compaction it is possible to evaluate the relative compaction index - R by the relative density - D_r on the basis of a correlation dependence expressed by equation (3), [9].

$$R = 0.769 + 0.231 \cdot D_r \quad (3)$$

where: R – relative compaction index and D_r – relative density.

The required criterion for the sediment grain size distribution (silt content < 30%) expressed by the CPT parameters is determined by the condition $R_f < 1.3\%$, [5] and [7]. In contrast, the area limited by the criterion

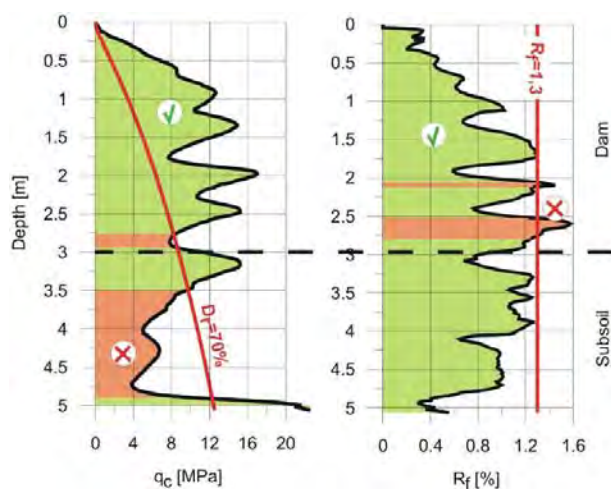


Figure 9. CPT results at the background of the quality criterion.

$R_f < 1.3\%$ meets the grain size distribution criteria (below the red line in the parts of the R_f diagram).

An example of the interpretation of the CPT results in order to identify the grain size distribution and the relative density of sediments in the profile of the new embankment is presented in Fig. 9.

It should be noted that the application of the commonly used CPT soil-behaviour charts to the quality control of the dam construction does not yield the expected results due to the specific grain size distribution and the mineral composition of the tested sediments, [7].

5 THE IMPACT OF THE DAM-DEVELOPMENT TECHNOLOGY ON THE NATURAL ENVIRONMENT

From the point of view of the environmentally safe operation of the Želazny Most Mining Tailings Storage Facility the following important problems should be addressed [11], [2]:

- Assurance of the object’s stability,
- Limitation of the migration of contaminated saline waters from the depository to the ground waters,
- Limitation of dusting.

In the case of the first two problems the applied technology of a gradual rise of the dams by the construction of higher embankments from post-flotation tailings previously deposited in the depository does not generally differ from the conventional methods of dam construction. In the case of a risk of stability loss, in the threatened sections of the dam, the loading berms are constructed. The migration of saline waters from the depository to the subsoil is reduced thanks to the construction of a comprehensive drainage system consisting of multi-floor circumferential drainage, drainage of the starter dam, drainage ditches at the dam toe and finally the barrier of deep-drainage wells at the close forefield. In contrast to the previous aspects, the hazard connected with dusting is a specific characteristic of the Želazny Most facility. Post-flotation tailings deposited on the beach and used in the dam construction are characterized by the capacity to dry rapidly. Dry sediments, free of the binding force, are exposed to the action of wind and are easily transported outside the depository area, forming fine dust that is suspended in the air. The impact of dust on the environment is so intense that as a counter-measure the surfaces of the beach and the dams are covered with an air-sprayed bituminous emulsion supplemented by water curtains activated during strong winds.

6 CONCLUDING REMARKS

The presented technology of a gradual stage construction of the dams from post-flotation tailings deposited with wet disposal technology has at least one spectacular economic advantage. The use of wastes for the formation of dams on one hand reduces the amount of wastes stored in the depository, while on the other hand it eliminates the need to exploit deposits of natural soils and transport them to the crest of the highest embankments. In the case of a huge facility such as Żelazny Most, in which the annual dam development requires approximately 300,000 m³ of soil, savings connected with the applied technology cover two basic cost components, i.e., the elimination of fees for the disposal of sediments built in the dams and no need to extract and transport natural soils for the dam's construction. It is also worth mentioning that due to crushing of the mine output the post-flotation tailings have the characteristics of fine-grained broken aggregates, easy to compact and having favourable shear-strength parameters, provided that the strict technological regime of the dam's construction is maintained. This regime has to be carefully controlled by different specific geotechnical control tests. A certain disadvantage of the described technology can be connected with the environmental impact due to periodic intensive dusting of the dried sediments embedded in the dams. However, this can be solved by the application of appropriate counter-measures reducing dust emissions to areas adjacent to the depository.

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