This project is co-funded by

the Research Fund for Coal and Steel of the European Union

MiDSafe

Advancing Post-Mining Waste Dump Safety and Sustainability

Grant Agreement Project No 101157379 — MiDSafe

Work Package 2

Deliverable related No D2.1.

Report on archival data, designs, past failures, guidelines and regulations on mining dumps and in- situ surveys of chosen dumps

Authors:

Teams of:
POLT (Task leader)
GIG
NTUA
TUC
UP
CEO
VUHU
LIA

December 2025

TABLE OF CONTENTS:

LIST OF FIGURES:

LIST OF TABLES:

1 Introduction

The aim of the Deliverable D2.1 is description of post mining dumps, comparison of the past data gathered from archives and actual state of the mining dumps as well as investigation the main characteristics of dumps and their behaviour based on existing data.

This deliverable will serve as a base for WP3, WP4 and WP5 as numerical, environmental, and risk analysis should consider the lessons learnt from previous experience in these fields and respect global guidelines and engineering practice.

2 Dump characterisation

2.1 Poland

The main Polish site is located in Konin Lignite Basin where exploitation of lignite started in the 1940s. Up to the date several final pits have been completed and flooded, two more are during flooding and one more is planned to be flooded after completion of lignite excavation. In October 2020 ZE PAK (operator of the Konin Lignite Mine) published a new strategy, radically changing the directions of its development. It declared, among other things, to abandon the construction of new lignite open pits and to gradually close the existing ones, and to close coal-fired power plants by 2030. Thus, Konin area is coal phasing out, and it is preparing for Just Transition Plan.

Additionally, it should be noted that in this area there are dozens of dumps of varying ages, reflecting the long history of lignite mining and reclamation activities. These dumps differ in their stages of development and restoration, contributing to the diversity of landscape features and environmental conditions observed across the region.

The second of the areas covered by the study is located in Upper Silesia. Research in this area will focus on the possibilities of creating new geopolymers using residues found in post-coal heaps. Particular emphasis will be placed on the analysis of the physicochemical properties of these materials and the assessment of their suitability as raw materials for the synthesis of innovative, sustainable mineral binders. Such an approach can contribute to reducing the negative impact of heaps on the environment and create new directions for the management of industrial waste in the region.

Fig. 1 Polish study areas (EURACOAL AISBL European Association for Coal and Lignite, 2021)

-

2.1.1 Jóźwin dump

The "Jóźwin" dump is located near Konin in the Wielkopolska Voivodeship. It is part of the infrastructure of the "Konin" Lignite Mine. The dump is associated with the exploitation of the Jóźwin I, Jóźwin IIA and Jóźwin IIB open-pit mines, which began in 1971 and ended in June 2023. mining. The external dump of Jóźwin is characterized by a significant elevation above the surrounding area, reaching a height of about 30 meters in places.

Fig. 2 Jóźwin external dump (Google Earth)

Slope inclination

The slope of the Jóźwin dump slope changed over time and depended on the stage of mining work and geotechnical conditions. During the storage of the overburden, the slopes were formed at the angle of the natural chute, which for a mixture of sand and clay was usually from 25° to 32° (approx. 1:1.5 to 1:2). Finally, in the process of reclamation, the formation of slopes for forest management with a slope not exceeding 1:3.3 and for agricultural management of 1:10 was adopted.

Substratum

The Jóźwin dump is located within the Mogileńsko-Łódzkie basin, which is characterized by a relatively shallow deposit of Mesozoic sediments. The direct substrate of the dump is a layer of Quaternary sediments: order clays, fluvioglacial sands and gravels, as well as locally peat and silt. Tertiary (Neogene) sediments are represented by Poznań clays, lignite seams and quartzite sands. Beneath the Neogene deposits, there are Oligocene glauconite sands. The Mesozoic substrate (Upper Cretaceous) consists of marls and chalk limestones. The total thickness of the Cretaceous formations is estimated at 800 - 3000 m.

Deposited material

The material deposited in the dump is an overburden removed from the coal seam, which is represented by Quaternary sediments - mainly sandy loams, clay sands, silty sands and locally sandy dusts and Neogene clay deposits - mainly sandy clays, clays and clays with lignite inserts. In general, cohesive soils originally constituted 2/3 of the entire overburden volume.

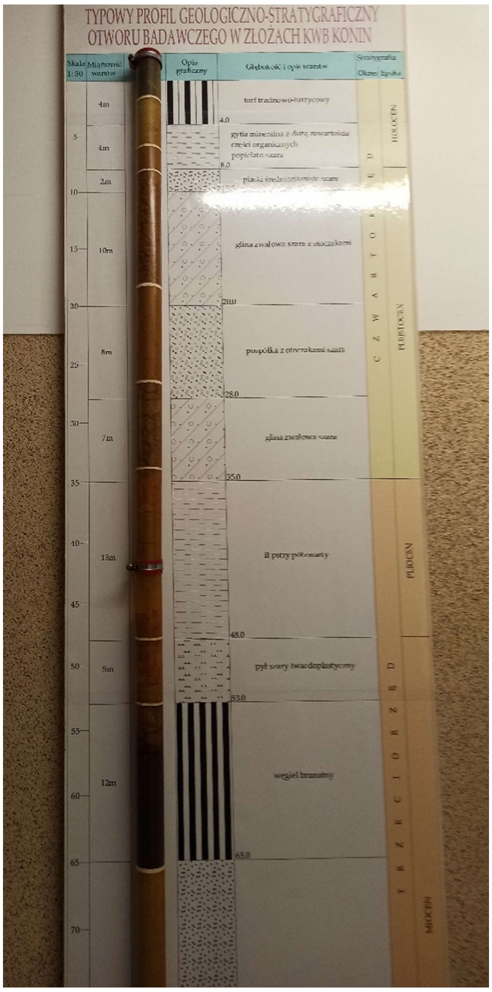


Fig. 3 Typical profile of overburden in Konin area

Critical properties

The studies showed variability in the physico-mechanical parameters of sandy clays and clay sands in terms of natural moisture (from 10.5-15.4 %) and the degree of plasticity. The tests found soil conditions ranging from compact (IL= -0.19) to soft-plastic (IL=0.74). The volume density of the tested samples ranged from 1.96-2.12 Mg/m3.

Studies of sandy clays and clay sands (with a semi-compact to plastic consistency) showed cohesion in the range of 26.54-43.82 kPa and an angle of internal friction of 6.48-10.47°, which would indicate low-strength soils. For sandy clays and clay sands, the obtained test results showed a significant reduction in the value of the angle of internal friction compared to the archival and standard results for this type of clay. Archival research results showed a semi-compact and hard-plastic consistency of these soils at an angle of internal friction in the range of variability of 17-31°, on average 28°. In the case of Poznań clays, the results obtained are within the angle values for this type of soils in their native state. Archival results of clay tests showed values in the range of variability of 6-32°, on average 16°, while the results obtained on the basis of current studies are within the range of 19.95°.

The study of the edometric compressibility modulus testifies to the high compressibility of the tested soils, and thus to their susceptibility to the phenomenon of subsidence. The range of variability of the results for the primary modules of the tested samples of sandy clays and clay sands ranges from 11.30 to 21.50 MPa with the values of secondary modules in the range of 42.60-69.20 MPa. In the case of the Poznań clays studied, the study showed a primary modulus value of 8.6 MPa with a secondary modulus value of 17.10 MPa. The results obtained indicate a decrease in the deformation parameters of the studied soils in relation to their natural properties.

Hydraulic properties

Hydrogeological conditions are characterized by four aquifers, two above and two below the lignite seam. The first aquifer with a free water table occurs in Quaternary sands and gravels. The second level occurs in sandy lenses in clays, the third in sands lying below the coal seam, and the fourth in cracked chalk marls. The main hydrogeological factor of the Jóźwin dump is the depression funnel, which lowered the groundwater level in a wide radius around the excavation. This caused a change in the natural flow of water. The depression funnel around the outcrops in the Quaternary aquifer is very irregular and depends on the thickness of the aquifer and the geological structure. It varies from 1 to 2 km. The groundwater depression funnel in the Neogene and Cretaceous aquifers has a more regular shape and ranges from 4 to 9 km. As a result of the drainage of the mine, the original elevation of the water level in the lakes has decreased by several meters. Monitoring of the water level around the Jóźwin dump is carried out on an ongoing basis with the help of a network of observation holes (piezometers). After the end of coal mining, the mine switched off the bottom pumps and the excavation is currently flooded with water (Bajcar, 2021; Bajcar, 2022), which leads to a spontaneous rise in the water level.

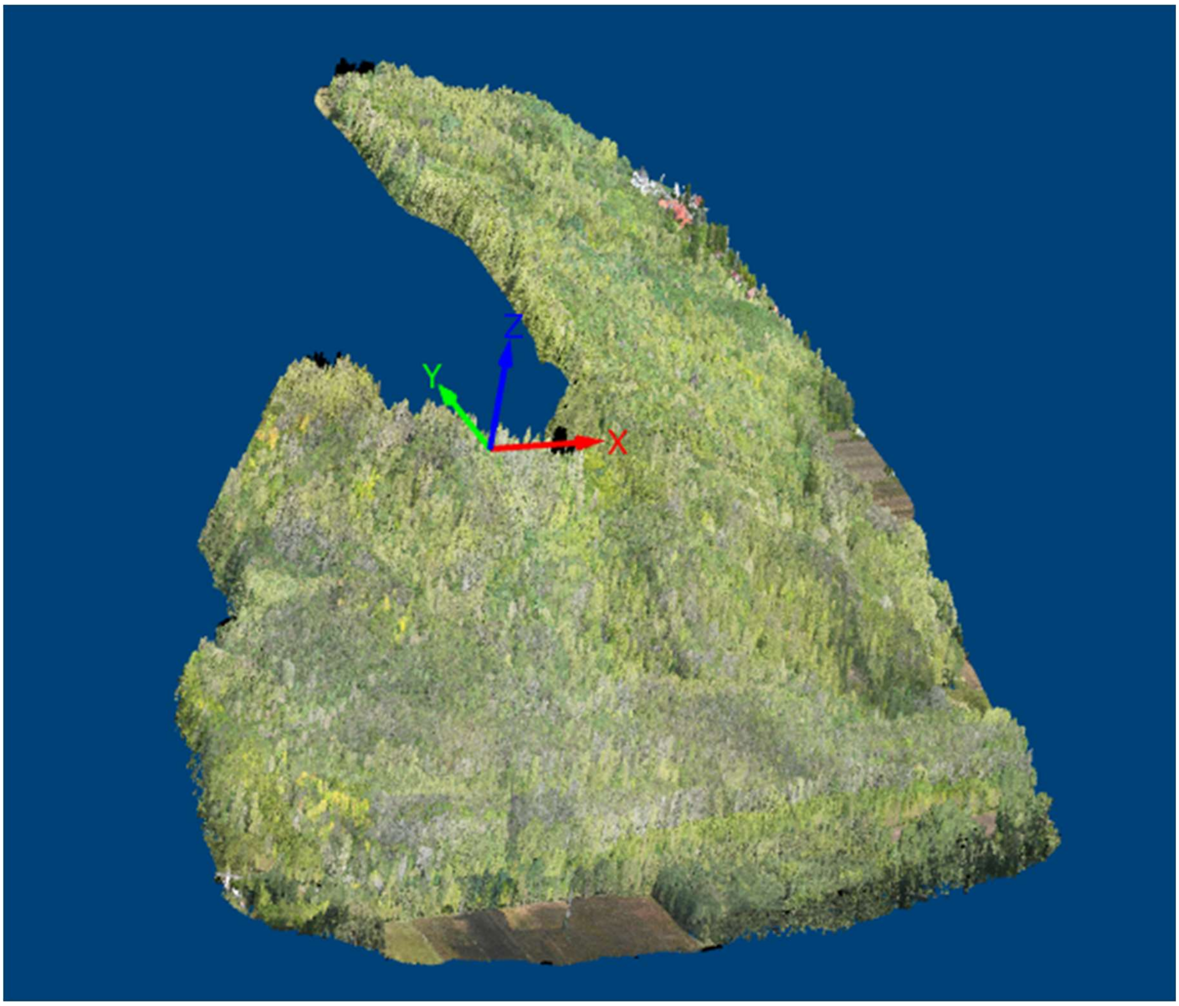
It should be emphasised that external dumps do not contain aquifer levels. Surface water flow within these areas is regulated primarily by surface drainage systems.

Consolidation & stability

As part of the reclamation, the largest water reservoir in Wielkopolska with an area of approx. 1300 ha is being built in the area of the former Jóźwin IIB open-pit. The filling of the reservoir is underway, the process is supported by a system of pipelines and water transfers (m.in. from the Warta River and the Ślesiński Canal). The aim of the action is to eliminate the depression funnel and restore water resources. The external dump, on the other hand, has already been largely reclaimed. Slopes and dump areas are forested, protecting the soil from erosion and giving the opportunity to create new ecosystems. The placement of order clays in the top created better conditions for the root systems of trees in forest complexes. Part of the dump area was handed over for agricultural crops.

Survey overwiev

During the formation of the Jóźwin external dump stability failures in the form of landslides have occurred. This was particularly visible on the eastern and southern slopes of the dump. In order to analyse the potential threat in this area, which may threaten the nearby village, scans were carried out with the use of a drone equipped with LIDAR.



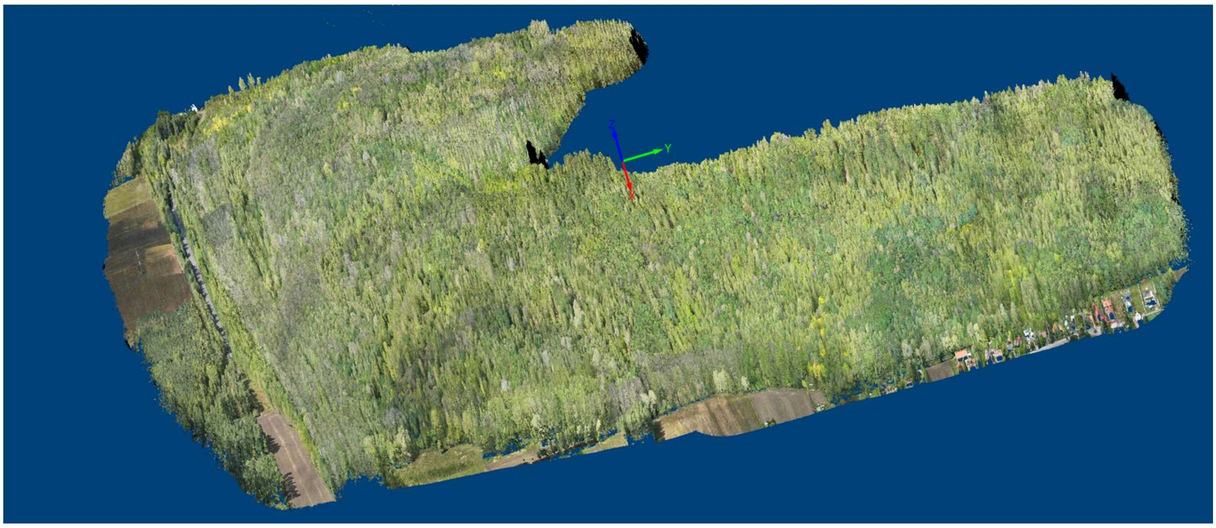


Fig. 4 3D model of the Jóźwin dump

2.1.2 Lubstów dump

The Lubstów dump was created as an external dump for the Lubstów open-pit, which functioned in the years 1982–2009. The area covered by the dump is in the range of 220–250 hectares. The object rises to a height of about 60–70 meters above the surrounding area. About 100-110 million m³ of overburden was deposited on the external dump, which in terms of average volume density of the soil gives us 180-220 million tons of material. The entire overburden removed during the exploitation during the years of operation of the open pit was much larger, but a significant part of it ended up in the internal dump (excavation).

Fig. 5 Lubstów pit lake and external dump (Google Earth)

Slope inclination

The slopes of the dump had a slope of 1:2 to 1:3 (from approx. 18° to 26°). In places particularly exposed to erosion or at higher levels of collapse, the slope was gentler (up to 1:5). Finally, in the process of reclamation, the formation of slopes for forest management with a slope not exceeding 1:3.3, and for agricultural development of 1:10 was adopted.

Substratum

The bedrock is made up of Quaternary (Pleistocean) order clays and fluvioglacial sands and gravels underpinning them. Below the Quaternary, peat deposits, gytias and Poznań clays (Neogene) are found in a small amount. It was on these deposits at a depth of 70-100 m that lignite deposits of the Poznań series were formed. It was the thickest seam in the Konin Basin, reaching up to 90 m thick in places. Under the coal seam there are still Neogene quartzite sands. Beneath the Neogene deposits, there are Oligocene glauconite sands. The Mesozoic substrate (Upper Cretaceous) consists of marls and chalk limestones.

Deposited material

The material deposited at the dump is Quaternary order clays, sands, fluvioglacial gravels, peat and lake sediments such as gytia, lake silts and clays (Eemian age) and Tertiary Poznań clays. The material at the Lubstów dump has a block-clump structure. In the process of stacking, Poznań clays form large blocks ("lumps"), between which there are looser sands, which promotes the processes of settling during water saturation (e.g. during the filling of the final reservoir present there).

Hydraulic properties

Deep mining drainage associated with the Lubstów open-pit and the functioning Tomisławice open-pit caused the formation of a depression funnel, which led to a decrease in the level of surface and groundwater in the zone covered by its range. As a result of the drying up of large areas of the upper Noteć catchment, this river became a periodic watercourse, the wetlands associated with its valley ceased to function, and significant decreases in the water table were recorded in the nearby lakes.

As part of repair and reclamation activities, the final excavation of the Lubstów open-pit is flooded, resulting in the creation of a large water reservoir. Ultimately, the reservoir is to reach an area of 480 ha and a capacity of 137 million m^3. This process aims to accelerate the restoration of surface and groundwater resources in the region.

The external dump does not have aquifers.

Consolidation & stability

On the western slope of the Lubstów outer dump, there were landslides of overburden masses. The main reason for this was the failure to sufficiently take into account the specificity of the works building the dump. As a result of non-selective storage of overburden, they are a mixture of various materials and are characterized by different geotechnical conditions. This can cause impaired stability of slopes, leading to the initiation of landslide processes.

As part of the reclamation of the dump, millions of trees were planted on the surface, and part of the adjacent areas was restored to agricultural production using Quaternary overburden clays. Due to the high height of the dump, advanced engineering techniques were introduced, such as: dense tree planting of slopes in the terrace system, which stopped erosion and prevented the formation of grooves on the slopes, and in order to accelerate the soil-forming process, organic fertilization and sowing of mixtures of grasses and nitrogen-fixing plants in the soil were used. In 2026, the key element of reclamation will be the connection of the Lubstów external dump with the water reservoir being built in the place of the internal dump.

Fig. 6 View of the Lubstów pit lake from internal dump

2.1.3 Kazimierz dump

Coal mining at the Kazimierz open-pit mine lasted from 1965 to 2011. 131 million tons of raw material were extracted from the open-pit mine, with 641.3 million m3 of overburden displaced. The exploitation area was divided into two fields: Kazimierz Południe, where mining was terminated in 1997, and Kazimierz Północ, which operated until 2011. The total area occupied by the excavation and dump was about 2600 ha. The external dump itself (formed before the start of internal dumping) covers an area of about 450 ha. The Kazimierz dump rises to a height of 50-60 m above ground level.

Fig. 7 Kazimierz external dump (Google Earth)

Slope inclination

The slope of the slopes changed as a result of reclamation processes. Immediately after forming, the slopes were quite steep and required later shaping. The slopes have been formed at an angle that ensures stability, usually from 1:3 to 1:5. Finally, in the process of reclamation, the formation of slopes for forest management with a slope not exceeding 1:3.3, and for agricultural development of 1:10 was adopted.

Substratum

The substrate of the dump is made up of Quaternary sediments: it is dominated by order clays (originating from glaciations, mainly from Central Poland), water-glacial sands and gravels, river sediments (muds, terrace sands), peat and lake sediments such as gytia, lake silts and clays (Eemian age). Directly under the Quaternary there are Poznań clays (Neogene), below which there is the main seam of lignite, the exploitation of which forced the creation of a dump. Under the coal seam there are sands and silts. The lowest unit is the Mesozoic rocks (mainly marls and Upper Cretaceous limestones), which form a structural substrate for younger sediments. Their ceiling is strongly morphologically diverse due to paleotectonic and erosion processes.

Deposited material

The material deposited at the dump is Quaternary order clays, fluvioglacial sands and gravels, river sediments (mads), peat and lake sediments such as gytia, lake silts and clays, and Tertiary Poznań clays. This material is inconsistent, with a block-clump structure, which can lead to local subsidence or landslide phenomena in the coastal zones.

Critical properties

Studies indicate a high variability of parameters due to the presence of gytia and peat lenses in the substrate and overburden, which lowers the local consistency to values close to zero and can lead to landslides. The angle of internal friction for sandy soils is in the range of 28° - 32°, while the cohesion is between 0 and 5 kPa. For order clays, the friction angle is in the range of 16-22°, while the cohesion is 15-35 kPa. Order clays are characterized by high sensitivity to water. In case of excessive humidity (e.g. near the Kazimierz Północ reservoir), the angle of internal friction may drop below 15°.

Hydraulic properties

The top layer of the dump is made up of order. They are highly consolidated, poorly permeable and are characterized by high compressibility, viscosity and plasticity, which limits water infiltration into deeper layers and makes it difficult to supply precipitation. In the area of the Kazimierz dump, there are two levels of groundwater – the near-surface-quaternary level, in which it is possible to distinguish: the level in sands within the order clays, the level in near-surface sands, and – the Cretaceous-Tertiary (deeper) level occurring in sub-coal and super-coal sands. This is the level of greatest importance for exploitation, as these waters exert pressure on the bottom of the coal seam. The exploitation of the Kazimierz open-pit mine required lowering the water table by several dozen meters. Long-term pumping of water through a system of deep wells and drainage resulted in the formation of an extensive depression funnel.

External dump does not have any aquifer.

Consolidation & stability

The processes of consolidation and stabilization of the Kazimierz dump due to the presence of weak-bearing soils (clays and gytia) are of a long-term nature. This consolidation consists in gradually reducing the volume of pores in the embankment under the influence of its own weight and removing water and air from them. Stabilization of slopes and slopes is necessary to prevent landslides. As a standard, the slopes of the dump are formed with a slope of 1:3 to 1:5, and in underwater zones (below the designed water table) even more gently to ensure the stability factor. Finally, in the process of reclamation, the formation of slopes for forest management with a slope not exceeding 1:3.3, and for agricultural development of 1:10 was adopted.

The use of a drainage ditch system on the top of the dump prevents uncontrolled infiltration of rainwater, which could lead to liquefaction of sandy soils (suffocation). The use of biological reclamation is also of great importance - the root systems of the planted vegetation bind the top layer of the soil, protecting it from erosion. The use of selective stacking, as a result of which the top layer of the dump consists mainly of order clays, allows to use their properties to achieve adequate productivity of newly created soils in post-mining areas.

Fig. 8 Konin Aeroklub airstrips located on Kazimierz external dump (from Aeroklub Koniński)

2.1.4 Tomisławice dump

The youngest open-pit mine of the Konin Basin is the Tomisławice open-pit. The industrial resources of the deposit were estimated at 41 million tons. The removal of the overburden and the filling of the external dump started in May 2010, the exploitation of coal has been carried out since September 2011, while the completion of the dumping on the external dump took place in March 2013. The planned complete shutdown of coal mining from the Tomisławice open-pit will take place in 2026. The Tomisławice external dump covers an area of 46.3 hectares, about 30 million m^3 of earth masses have been deposited there. It was formed with an elevation of up to 30 m in relation to the surrounding terrain.

Fig. 9 Tomisławice open pit and external dump (Google Earth)

Slope inclination

In the process of forming the external dump of the Tomisławice open-pit, the slope of the slopes changed with the transition from the exploitation phase to the reclamation phase. During the active storage of the overburden, the slopes were poured at the angle of the natural chute, which for the mixture of sands and clays was usually from 25° to 32° (approx. 1:1.5 to 1:2). Eventually, the formation of slopes for forest management with a slope not exceeding 1:3.3 and for agricultural development of 1:10 was adopted. However, observations show that such shaping of slopes does not provide them with stability.

Substratum

The direct substrate of the dump is about 40 m of a layer of Quaternary sediments: order clays, fluvioglacial sands and gravels, and limnoglacial silts. Tertiary sediments (Neogene): Poznań clays, lignite seam (about 7 m thick) occurring at a depth of 38-47 m, and quartzite sands with an admixture of dust, silt and muscovite.

In the depressions of the Cretaceous ceiling, under the Neogene sediments, there are Oligocene glauconite sands.

The Mesozoic substrate (Upper Cretaceous) is marls.

The Tomisławice open-pit is an excellent facility where you can distinguish layers or lenses of lignite differing from each other in textural and structural features, i.e. the so-called lithotypes.

Deposited material

The earth masses accumulated in the external dump are a mixture of formations found in the overburden, i.e. order clays, clays of the Poznań Formation, fluvioglacial sands and gravels, and siltstones.

Hydraulic properties

The Tomisławice lignite deposit is located in the Kujawy Lake District at the junction of the Oder and Vistula basins, in a depression of the terrain built of cracked marls of the Upper Cretaceous. The key geological element is the Gopło tectonic trench, which limits the impact of mine drainage to the west, and chalk marls are the basic aquifer. Above the Cretaceous there are glauconite sea sands, quartzite sands (Miocene) and clays of the Poznań Formation, which form a natural seal over the main coal seam. The mine's drainage system had to take into account four water levels: 2 Quaternary, Neogene and Cretaceous, with tectonic faults and clay layers acting as natural barriers, protecting Lake Gopło from runoff. The depression funnel of the Tomisławice open-pit mine has an irregular, elongated shape and range, covering an area within a radius of several kilometres from the mine. It affects all groundwater levels, reaching towards the Noteć River and Lake Gopło.

Consolidation & stability

The first works as part of technical reclamation on the external dump began in 2019. The area was prepared for planting trees and shrubs, the slopes and the top of the dump were profiled so that rainwater could flow freely to the outskirts, without creating stagnation on the slopes and crown. The leading direction of reclamation on the external dump is the forest direction, the completion of which is scheduled for 2026. The forested area will be about 110 hectares. The technical stage of the internal dump reclamation process, in which it is crucial to ensure the stability of underwater and overwater slopes, is to be completed in mid-2026. The biological stage and preparation for flooding is to last until 2027, and the filling of the reservoir itself is to begin after 2027. The resulting water reservoir is to have an area of nearly 200 ha.

Tomisławice external dump was chosen as a case study for the future development research within the MiDSafe project.

2.1.5 Niesłusz dump

The Niesłusz open-pit was the first and at the same time the oldest open-pit mine of the Konin Lignite Mine. It operated in the years 1953 – 1961, during which time 4 million tons of coal were extracted from it. The open-pit was created after the drying of Lake Niesłusz, because the coal partially remained under its bottom. The lignite deposits exploited belonged to lenticular deposits occupying from several to several dozen ha. The coal was deposited at a depth of 14.5 to 18.7 m, and its thickness was from 8.3 to 9.5 m. The amount of overburden was estimated at 78 million m3. The internal dump of the open-pit mine occupies about 80 ha, while the external dump covers 43 ha. The height of the external dump is from 10 to 12 m above the surface of the site.

Fig. 10 Niesłusz pit lake and external dump (Google Earth)

Slope inclination

The slope for the Niesłusz dump was about 30°. Their shape was strongly influenced by the technology of stacking and forming the dump, water erosion and geodynamic processes. On the dumps there are numerous steepnesses, depressions, faults and landslides. As part of the technical reclamation, which took place in Niesłusz in the 60s and 70s of the twentieth century, efforts were made to significantly soften the relief of the terrain in order to enable its agricultural, forestry, and later construction use.

Substratum

The bedrock consists of Quaternary formations, including order clays, postglacial sands and gravels, and stagnant silt. Directly below them lie Tertiary Poznań clays (Neogene), often with an admixture of organic matter. It was in these layers (the formation of Central Polish lignite deposits) that the exploited coal seam occurred. Under the coal seam there are quartzite sands with an admixture of dust and silt.

Beneath the Neogene sediments, there are Oligocene glauconite sands and below them Upper Cretaceous marls, which constitute the Mesozoic bedrock.

Deposited material

The non-selective management of overburden material used by open-pit mining resulted in the material placed on the dumps being a conglomerate of all the formations present in the overburden. Mixing and random arrangement of material with different properties in the order mass causes its heterogeneity, manifested by high variability of its properties. In the overburden of coal there were Quaternary formations – order clays, postglacial sands and gravels, as well as Tertiary rocks – Poznań clays. The dominant soils in the overburden were different types of clays.

Hydraulic properties

Prior to the reclamation of the Niesłusz dump, hydrogeological conditions were dominated by active mining activities and loose material storage processes. The entire area was within the range of a strong depression funnel caused by the open-pit drainage system. This caused a lowering of the groundwater table in the natural aquifers surrounding the excavation and the dump. Rainwater infiltrated vertically through loose sands and gravels, stopping locally on the lenses of impermeable Poznań clays, creating the so-called suspended waters. The order, before it underwent natural concentration (consolidation), was characterized by a very high porosity and filtration coefficient, which facilitated the rapid seepage of rainwater into the dump. Only the process of reclamation (landscaping, afforestation) and the cessation of drainage led to the stabilization of water conditions that we observe today.

Consolidation & stability

The reclamation of the Niesłusz dump is a completed process that has transformed this area into an urbanized and forest area. Currently, this area is fully integrated with the urban infrastructure. After the end of coal exploitation, a water reservoir with orderly and profiled, shrubby slopes was created at the site of the internal excavation - Lake Zatorze. The depth of this reservoir is 27 m, and the area is 18.5 ha. The surroundings of the lake have been interestingly developed – walking alleys, bicycle paths and playgrounds have been created there. At the beginning of the 21st century, the "By the Lake" shopping mall was built at Lake Zator. A part of the internal dump was used for this purpose. Most of the outer dump was afforested using pioneer tree species to protect the slopes from erosion and create a new layer of soil. On parts of the former mine area there are housing estates, sports facilities and service areas. The area is considered to be geotechnically stabilized. The subsidence processes typical of dumps were completed decades ago thanks to the natural consolidation of the material.

Fig. 11 Niesłusz pit lake (kwbkonin.pl)

2.2 Czech Republic

In this chapter, a catalogue of Czech spoil heaps potentially available for use in the project is presented.

Below is an illustration showing the location of the aforementioned spoil heaps in the Czech Republic.

Fig. 12 Czech study areas (EURACOAL AISBL European Association for Coal and Lignite, 2021)

2.2.1 Velebudická dump

This is an external dump of the Jan Šverma Mine, which was constructed between 1955 and 1995. It covers an area of approximately 790 ha and has formed an elongated earth embankment (length 4.5 km in the NW–SE direction, width 1.5–2.2 km) rising about 50–75 m above the surrounding terrain (the top of the dump reaches 330 m a.s.l.). Deposition took place in two phases: during 1955–1982 the lower benches were created (105 million m³) and by 1995 the upper benches were laid (127 million m³). In total, about 242 million m³ of overburden soil was deposited in the dump (including older bulldozed dumps).

Slope inclination

The external slopes were designed with a gentle overall inclination of 1:5.5–1:9.0 (in unstable sections up to 1:12). Individual benches 30–75 m high were shaped into broad plateaus during operation.

Substratum

The original ground was a flat floodplain of the Luční Potok stream with wetlands. The substratum is composed of Neogene volcanic and sedimentary deposits (sandy-clayey Quaternary clays and gravelly sands, with local coal seams).

Deposited material

The majority of the fill consisted of clayey overburden from the Jan Šverma surface mine. These Tertiary clays contain fine-grained sand in places and have unfavourable properties – they lose strength when wet. A smaller portion comprised hard claystones and siltstones (the so-called "porcelanites") from the overburden, as well as imported topsoil or loess for reclamation purposes.

Critical properties

Laboratory tests on the dump's clayey soils showed cohesion c in the range of 13–25 kPa (typically around 13 kPa) and an internal friction angle ϕ of about 5° in the upper parts and 14° in deeper parts. This corresponds to low shear strength – in practice the outer slopes had to be graded to about 1:8–1:10 instead of the originally planned 1:5.5.

Hydraulic properties

The western part of the dump was deposited on undrained wetlands, so water accumulated in places at the toe of the slopes. This triggered landslides – the largest landslide occurred on the northern edge in areas of waterlogged foundation sediments. Gradually, the base of the dump was drained: a protective drainage ditch was built along the toe of the northern slope.

Consolidation & stability

The surface of the dump was already technically reclaimed during its operation, and by 1995 it had been afforested or grassed (74 ha of agricultural reclamation and 334 ha of forestry reclamation). To ensure stability, problematic slopes were flattened to 1:12 and strengthened with technical measures (removal of liquefied soils, coverage with sealing clay at the site of the former municipal waste landfill). Thanks to these measures and thorough monitoring the Velebudice dump is now stabilised.

2.2.2 Radovesická dump

This is the external dump of the Bílina opencast mine, covering roughly 1500 ha, deposited between 1969 and 2003 in the former valley of the Lukovský Potok stream. The dump rises from 250 m a.s.l. at the northwestern edge up to 424 m a.s.l. in the east, where it seamlessly adjoins the massif of the České Středohoří. It is about 170 m in height (the highest deposited bench is divided by a central valley-oriented E–W). The dump's footprint measures about 3.2 km by 2.7 km, and the volume of deposited material exceeds 680 million m^3.

Slope inclination

Given the low strength of the fill material, the final landform was designed with very gentle slopes – the general inclination of the outer slopes is 1:8 or flatter. The highest bench is additionally divided by a broad central valley, which helped stabilise the surface.

Substratum

The substratum is crystalline bedrock (muscovite–biotite gneiss) outcropping in the Lukovský Potok valley, locally overlain by Cretaceous marls and limestones. On these sediments lies a thin brown coal seam and layers of volcanic tuff. The entire area was highly waterlogged before the dump was established (the Lukovský Potok drained a catchment of 23 km²).

Deposited material

All the material came from the Bílina open pit mine. It consisted predominantly of fine-grained clays and clayey sands from the upper overburden cuts (II–IV), with up to 90% of the fill comprising silty to sandy clays and fine sands.

Critical properties

From a geotechnical perspective, these soils range from conditionally suitable to unsuitable, as they have high plasticity (WL 52–92%, plasticity index Ip 31) and very low shear strength in drained conditions ($\phi' \approx 8$–$12°$, $c' \approx 10$ kPa). Laboratory-determined residual parameters after consolidation confirm the low shear resistance: ϕr ~7–9°, cr ~0–6 kPa. In addition, the dump contains ~5–12% of unstable loose sands (sterile, acidic, with pyrite) and a minor amount of stiff clays of the so-called Libkovice layers.

Hydraulic properties

The dump was constructed without prior dewatering of the foundation, which led to serious issues. In front of the advancing dump, water from the Lukovský Potok catchment and adjacent slopes accumulated – in 1980–1981 a water lagoon up to 14 ha in area and 400,000 m³ in volume formed at the dump's toe. Water partially infiltrated into unconsolidated clays at the base of the dump and saturated the lower benches, reducing their strength. In the early 1980s, a drainage adit beneath the dump was proposed. This adit, 3.3 km long, was driven between 1982 and 1987 roughly along the course of the buried Lukovský Potok, mostly within stable gneiss bedrock. Drainage systems were connected to the 2.8 m diameter adit: in front of the dump's toe, gravel drain branches were built. After the adit and drains were put into operation, the groundwater level within the dump dropped by tens of metres and surface water accumulations disappeared.

Consolidation & stability

The dewatering significantly increased stability – the massive landslides of the initial period have not reoccurred. However, during extreme rainfall, surface slide can still occur. In 1994 a large landslide (an "earth flow" type) affected the southwest slope, damaging the conveyor and the reclaimed surface. The cause was oversaturation of some permeable layers of the dump. Remediation was carried out in 1996–1997 – removal of the mobile soils, regrading and reinforcement of the slope. In subsequent years, stabilising stone drains were built at critical spots and deep inclinometers installed to monitor movements. Since then, the Radovesice dump has been in a stabilised condition. The surface is 90% reclaimed – predominantly forestry reclamation (~830 ha) alongside other reclamation, including experimental succession plots. Groundwater levels are maintained below critical thresholds by the system of the drainage adit, wells, and the dump is continuously monitored.

2.2.3 Pokrok dump

This is an external dump of the Bílina open cast mine, constructed between 1981 and 2010. It covers roughly 900 ha, with a length of 4.7 km and a width of 2.2 km (N–S). The dump partially filled the remaining pits of the former Pokrok and Julius Fučík mines and was partly deposited on undisturbed original terrain. The thickness of the dump is about 110–120 m. The dump's surface reaches 280–285 m a.s.l. The total volume of material placed is estimated at 250 million m³.

Slope Inclination

The final slopes were shaped to an inclination of ~1:7 (locally even gentler), and the highest parts are plateau-like.

Substratum

The foundation ground of the dump consists partly of the floor of mined-out pits (covered by remnants of coal seams and clayey overburden sediments) and partly of intact terrain. The northern edge lies on Quaternary gravel-sands and clays in the Lodina stream floodplain; the eastern part lies on hard Neogene volcanic rocks (basalt, tuffs) and Tertiary claystones. The western part of the dump has a more complex base – it transitions into the slopes of the Krušné hory (Ore Mountains) and connects to older dump under which coal seams and waterlogged sediments are present.

Deposited Material

Exclusively overburden from the Bílina mine was deposited here. From 1981 until 2003, Pokrok was filled first with higher-quality, denser soils. Starting in 2003, less suitable clayey soils and after 2010 even the most problematic clay was deposited.

Critical Properties

The dump is dominated by silty clays and sands of the regolith (weathered) zone, which have similarly unfavourable parameters as those in Radovesice – high moisture content (natural 25–45%), a plasticity index of ~32, and low strength (effective ϕ' ~8–10°, c' ~10–15 kPa). Over the years, water-saturated horizons have developed in the dump – shallow groundwater accumulates at the interfaces between permeable and impermeable layers of the dump and, especially in the lowest quarter of the dump's thickness, forms a continuous saturated zone. Shear tests confirmed the residual strength parameters of the fill: ϕr only ~5–7°, and cohesion nearly zero. Therefore, the slopes had to be designed very gently, and thorough drainage had to be ensured.

Hydraulic Properties

Prior to construction, the Lodina stream was diverted and surface ditches were built in the foreland. Despite this, in the 1980s the toe of the heap became saturated – springs and marshy areas appeared on the northwest and southeast sides, which had to be continuously pumped. To permanently reduce waterlogging of both the base and the dump, systems of drainage wells and drains were installed. By the 1990s a geotechnical monitoring system was in place: a network of piezometers and inclinometers recorded rising water levels in certain parts of the fill in the early 2000s. Therefore, additional measures were taken – on the northern slopes, where local slides occurred (2004–2006), stabilisation berms and stone drains were constructed.

Consolidation & Stability

Thanks to these interventions, conditions improved significantly – the major potential shear surfaces were secured and movements slowed or stopped (as confirmed by long-term measurements). The Pokrok dump is largely reclaimed (farmland, forests and wetlands over 200 ha in total) and was evaluated in 2018 as stable with sufficient safety reserves.

2.2.4 Slatinická dump

The Slatinice dump was constructed from 1972 to 1999 as a continuation of the Čepirožská dump, filling the residual pit of the former Slatinice opencast mine. It covers an area of approximately 420 ha and has a volume of about 220 million m³. The dump body has an elongated shape (3 km long and 1.7 km wide) and only slightly rises above the surrounding terrain.

Slope Inclination

The slope inclination of the Slatinice dump gradually increased over time – originally the general slope was about 1:14, but after the introduction of high-capacity stackers and elevated dumping, it steepened to around 1:10. This steeper slope, together with unsuitable soils and insufficient drainage, greatly contributed to the dump's instability.

Substratum

The substratum consists of Tertiary clays (often tuffaceous), Quaternary sediments (colluvial clays, gravels, sands), and in some parts "baked" (thermally altered) clays. A pronounced dip of the base strata (up to 15° in the upper sections) also contributed to instability.

Deposited Material

Markedly heterogeneous soils were deposited, predominantly clays and claystones with silty and sandy admixtures. There are also sands of various grain sizes and, in places, coal-bearing clays. The parameters of the clayey soils given here are derived from the results of geomechanical tests on Slatinice dump soils from 2013 to 2021.

Critical Properties

Effective shear strength parameters: ϕ' ~12–16°, c' ~15–40 kPa. Over the years, waterlogged horizons have formed within the dump and groundwater accumulates at the boundaries between permeable and impermeable fill layers. Shear tests also confirmed the residual strength parameters of the fill: ϕr ~3–5°, cohesion c′ ~0–10 kPa, i.e. cohesion can be almost zero.

Hydraulic Properties

The dump was built on an undrained base, which led to water accumulation and stability problems. In 1983 a large-scale slide of soils occurred, affecting most of the dump and displacing about 30 million m^3 of material. The primary cause was the combination of the inclined, un-dewatered foundation, the low shear strength of the soils, and the high groundwater levels. At present, drainage is managed by a system of open ditches and pumping wells that channel water into a retention basin and then into the Slatinice stream.

Consolidation & Stability

Reclamation has been underway since 1999, and the majority of the area has been reclaimed (by 2012 about 354 ha; an additional 97 ha since 2013 are in progress). Notably, a so-called "Slatinice Educational Reclamation Area" (90 ha) serves as a forest park and protective greenery. An important rerouting of infrastructure services (the Hořany Corridor) also passes through the dump. For this reason, extensive hydrogeological and geotechnical monitoring is in place (dozens of hydrogeological boreholes, inclinometer boreholes, penetration probes, geodetic survey points, and tensometers).

2.2.5 Dump Obránci míru

The area of interest is located in the central part of the Most Basin in the northwestern part of the Czech Republic. The dump was created by filling the residual pit of the Obránci míru open-cast mine and is connected to the soil foundation of the adjacent ČSA open-cast mine. Today, the OM dump body represents an extensive anthropogenic accumulation relief with an area of approximately 850 ha, integrated into the area of relocated watercourses, reclaimed areas, and technical infrastructure associated with mining.

The OM was built in stages in line with the mining procedures of the mine. After initial filling in the 1920s–1950s, systematic levels were created by stackers from the mid-1950s onwards. The first loader levels (I.a, I.b) were created between 1955 and 1983, the balancing level II between 1962 and 1985, and other levels (III.a, III.b) between 1963 and 1985. After the closure of the Obránci míru mine (formally in 1982), the internal dump was further used to store soil from the neighboring ČSA mine – the so-called final levels were filled with material from the ČSA mine between 1984 and 2004. In total, the dump held approximately 593 million m^3 of overburden. The general slopes were designed to be gentle – the projected slope was 1:7.7 (≈13°) and the actual slopes achieved were around 1:8 to 1:10 – with a total slope height of 112–160 m. The drainage of the dump is provided by a system of pumping and collection structures, which are connected to a blind arm of the Bílina River. As part of the reclamation, 252 ha of the dump had been reclaimed by 2010; further work was carried out on 326 ha (by 2022) and reclamation of an area of 866.6 ha will begin in 2015–2025. Reclamation measures are thus gradually integrating the dump into the landscape – the target use mainly includes forestry and agricultural areas, with the remaining part of the area to be used for a planned lake in the residual pit of the ČSA mine.

The Obránci míru dump was chosen as a subject of interest due to its strategic importance in the context of the planned flooding of the residual pit of the ČSA mine, where its slopes will form the shoreline of the future lake. For this reason, it is necessary to pay increased attention to the issue of slope stability. Although the body of the dump has been examined in detail using penetration methods, other monitoring techniques, such as GNSS monitoring of reference points or geophysical surveys, have not yet been applied here. Currently, additional dumping of soil is taking place at the foot of the slope, and these areas are already being affected by the rising water level of the emerging lake (Fig. 5). It is also necessary to take into account the fact that older parts of the dump have been affected by landslides of varying extent in the past (the most significant one is captured in the geotechnical profile in Fig. 1), which underlines the importance of continuous monitoring of the overall stability of the dump body.

The use of unmanned aerial vehicles (UAVs) appears to be a promising tool for monitoring the stability of newly formed slope structures connected to older and more consolidated layers. These technologies enable effective and repeated monitoring of morphological changes in the terrain. In combination with already available penetration data, the information obtained in this way could provide valuable input for further analyses carried out within the project, particularly in work packages WP4 and WP5.

Geological characteristics

The body of the dump is mainly composed of soils from the Most Basin stratigraphy – i.e., Tertiary clays and clayey rocks overlying the coal seam, mixed in places with gravel and sand of Quaternary origin. Clayey soils predominate (Fig. 1) with a high content of clay minerals (illitic-kaolinitic clays forming 60–85 % of the mass) and an admixture of carbonates (mainly siderite around 10 %). These soils are relatively stiff and firm when compacted, but when in prolonged contact with water, they swell, become plastic, and are prone to slumping. Engineering geological tests have confirmed that the upper layers of the dump show residual shear parameters with zero cohesion – these are poorly consolidated clays, disturbed by weathering and climatic influences. Due to high moisture content (40–60% water content in places, approaching fluidity), the immediate bearing capacity of the surface was also often low during operational piling. These unfavourable material properties posed the main geotechnical challenge during the construction of the dump.

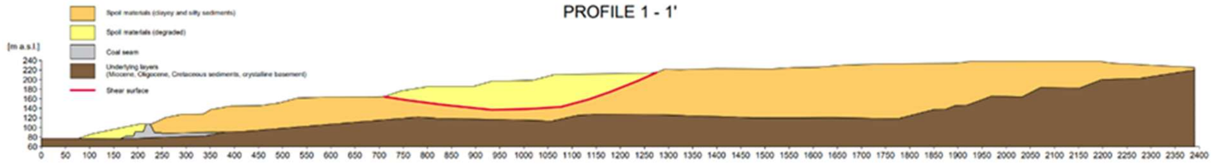


Fig. 13 Geotechnical profile – OM dump

To ensure slope stability, it was necessary to maintain gentle slopes and suitable terrace geometry. Wide platforms and low terraces were created – the heights of the individual terraces were generally between 15 and 18 m to prevent excessive loads and landslides on the slopes. Even so, minor landslides occurred initially, requiring further caution when shaping the slopes. The least suitable soils (highly plastic, water-saturated clays) were partially deposited outside the main body. Gradual monitoring and calculations (regression analysis of shear parameters) verified the resulting stable shape of the slopes.

The general slope of ~1:8 proved to be sustainable in the long term, provided that important conditions relating to the water regime of the body are met.

Survey overview

The OM dump has been thoroughly surveyed geotechnically. In recent years, an extensive penetration survey campaign has been carried out here, during which a total of 19 penetration tests (Fig. 2) were performed using the static penetration (CPT) method, with a total length of almost 990 meters. The surveys provided detailed information on the geological structure of the dump, identified various types of dump soils (including granular layers, the dump body, and zones with residual strength), and made it possible to determine shear strength parameters, deformation modules, and pore pressures. The results indicate considerable heterogeneity of the dump body, with layers of high shear strength and zones with lower strength characteristics being recorded. These data form a reliable basis for addressing stability issues and numerical modelling.

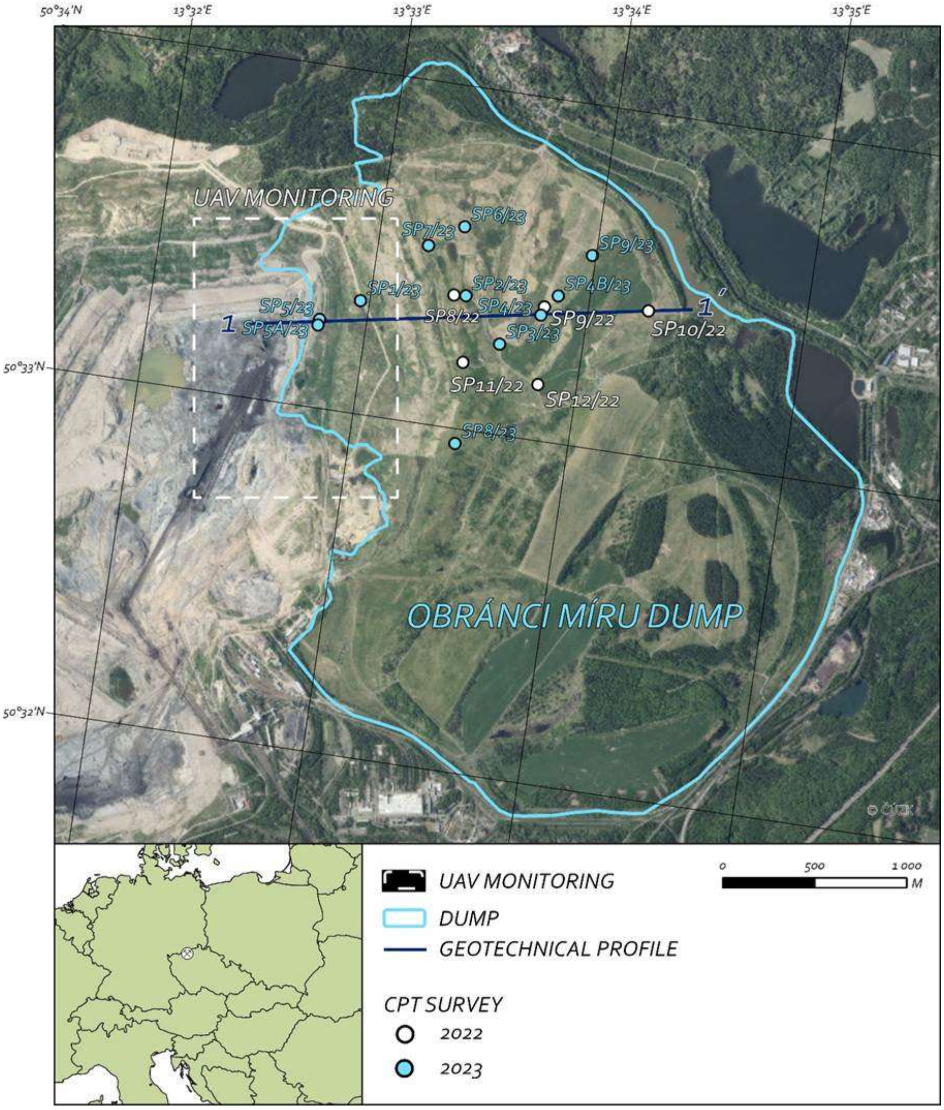


Fig. 14 OM dump with delineation of areas where CPT survey and UAV monitoring were performed

DJI Matrice 350 RTK unmanned aerial vehicle was used for aerial surveying and subsequent analysis of the area of interest (Fig. 3). The Matrice 350 RTK is a modern industrial UAV platform with high payload capacity, stability, and the ability to integrate advanced sensors. Zenmuse L2 laser scanner was used on the platform to collect geodata. It integrates a LiDAR sensor, RGB camera, and IMU unit, using the drone's integrated RTK module for accurate positioning. This system allows for the collection of dense point clouds with high accuracy, even in areas with dense vegetation or difficult-to-access terrain. Zenmuse L2 can achieve an accuracy of up to 4 cm horizontally and 4 cm vertically (under ideal conditions and using PPK corrections). The maximum LiDAR measurement range is up to 450 meters at 80% reflectivity and a frequency of up to 240,000 points per second. The integrated RGB camera with a 20 MP CMOS sensor allows for colour texturing of the point cloud and better data interpretation. The data is processed in DJI Terra software, where it is converted into the commonly used las format. The data is further processed and analysed in a GIS environment, where a final digital terrain model (DTM) and digital surface model (DSM) are generated (Fig. 15). The resulting accuracy depends, among other things, on the scanning density, flight altitude, RTK/PPK mode used, and the quality of the correction data. The reason for choosing LiDAR technology is its ability to be used effectively even in poor visual conditions (compared to conventional photogrammetry), especially in fog, which is typical for large open-cast mines and often persists for much of the day. Another significant advantage of this technology is the ability to accurately map terrain under vegetation cover, which greatly facilitates the separation of vegetation and mining objects from the terrain itself. Another advantage of LiDAR is the high speed of data collection, processing, and evaluation compared to photogrammetry, both in the aerial imaging phase and in the subsequent analysis of the acquired data.

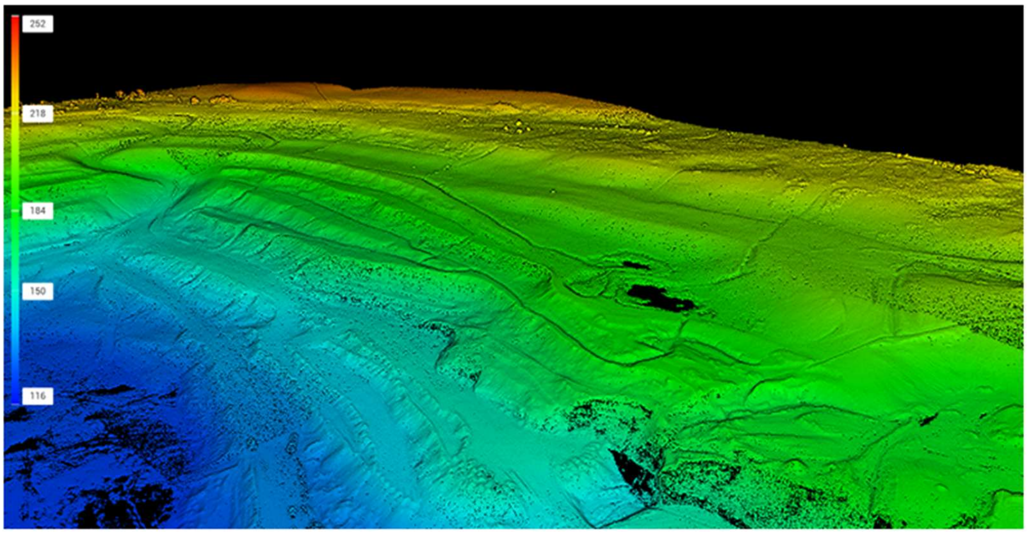


Fig. 15 Point cloud obtained based on LiDAR scanning

Full Reflectivity mode was selected for the settings, which allows for maximum accuracy of outputs in conditions of heterogeneous surface and vegetation. RGB colorization was activated for visualization and colour assignment of points in the cloud, which greatly facilitates their interpretation. Due to the characteristics of the LiDAR sensor used, which provides higher point coverage density than standard photogrammetry, the flight path overlap was set to 70%. This parameter ensures sufficient data redundancy and minimizes the occurrence of shadow zones or gaps in the resulting point cloud. The total flight time was 26 minutes, covering an area of 1.55 km2. The accuracy of the measurements is verified using five control points, which are evenly distributed throughout the monitored area.

UAV survey was performed in the area of OM dump, as mentioned above. The main objective was to monitor the stability of newly deposited material at the foot of the slope, which is in contact with the water table of the lake formed after mining. Due to the intensive movement of mining equipment, it is not yet possible to perform standard GNSS point measurements in this location. For this reason, the UAV method appears to be a suitable complementary tool for monitoring the condition of the area. Measurements were started at fourteen-day intervals, always depending on the current weather conditions. During this period, no significant changes in the terrain were recorded that were not related to the deposition of new soil at the foot of the dump (Fig. 16). The interval was therefore extended to a monthly frequency. During this period, slope movements developed (Fig. 16) in the area where soil was deposited in the previous phase of foundation work (2021–2024).

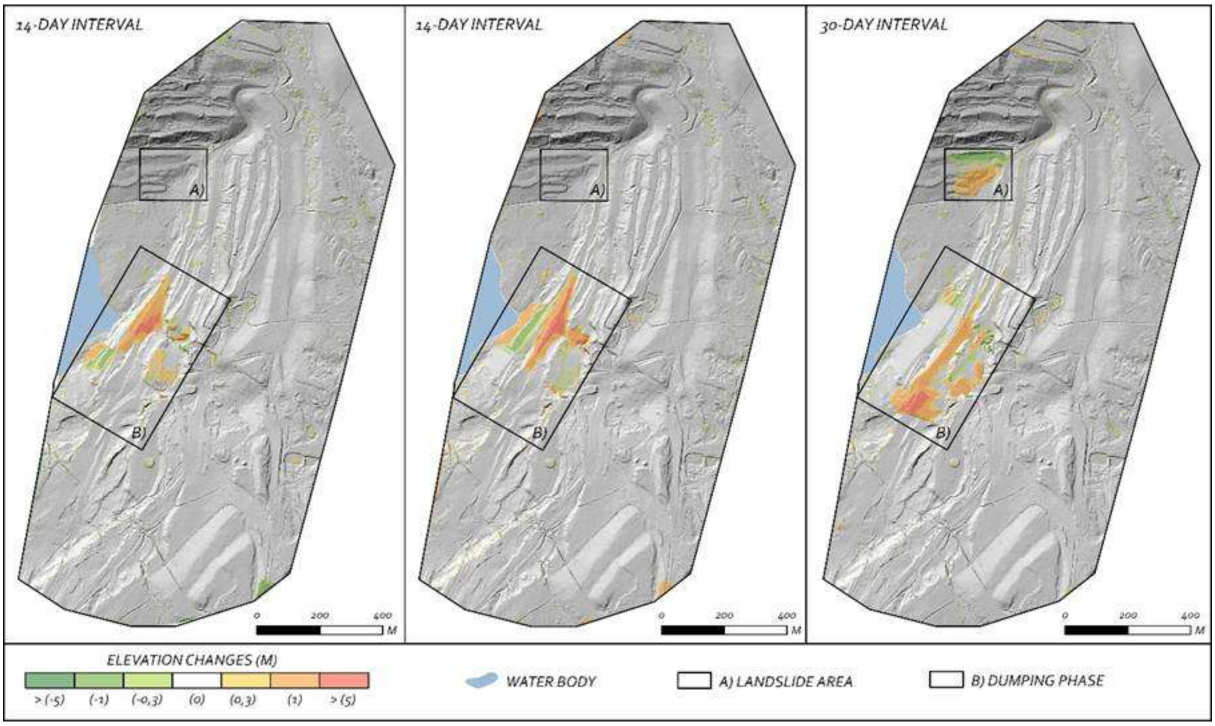


Fig. 16 Monitoring of selected parts of the OM dump, A) Landslide area, B) Dump foundation area

A frontal landslide measuring approximately 190 m in width and 140 m in length was detected (Fig. 17), with a main scarp approximately 6 m high. The total volume of landslide material is approximately 12,000 m³. Based on a digital terrain model, it is possible to interpret the probable direction of movement of the material, identify the causes, and propose appropriate remediation measures. Thanks to the high operability of UAVs, it is possible to continuously monitor whether further deformations are occurring outside the existing contour of the landslide. The use of UAVs also shows its advantages in winter, when access to the site is significantly limited by adverse terrain conditions.

Fig. 17 Frontal landslide recorded during the last UAV monitoring campaign

2.3 Romania

The waste rock stored in the dumps comes from the overburden and from the interburden between the lignite layers, being a heterogeneous and non-homogeneous material directly dependent on the area and the excavation level. This non homogeneity is manifested along the dump steps in their direction as well as in the structure of each step.

Five waste dumps were considered for this project:

- Pesteana Nord, interior waste dump – active;
- Valea Negomir, exterior waste dump – in conservation;
- Pinoasa, interior waste dump – active;
- Rosia de Jiu, interior waste dump – active;
- Tismana, interior waste dump – active.

These are the last active waste dumps within Rovinari mining basin (m.b). Although Valea Negomir is considered to be in conservation, the dump was sporadically used to deposit waste rocks from Pinoasa open pit when there were problems with the transportation circuit of the interior waste dump.

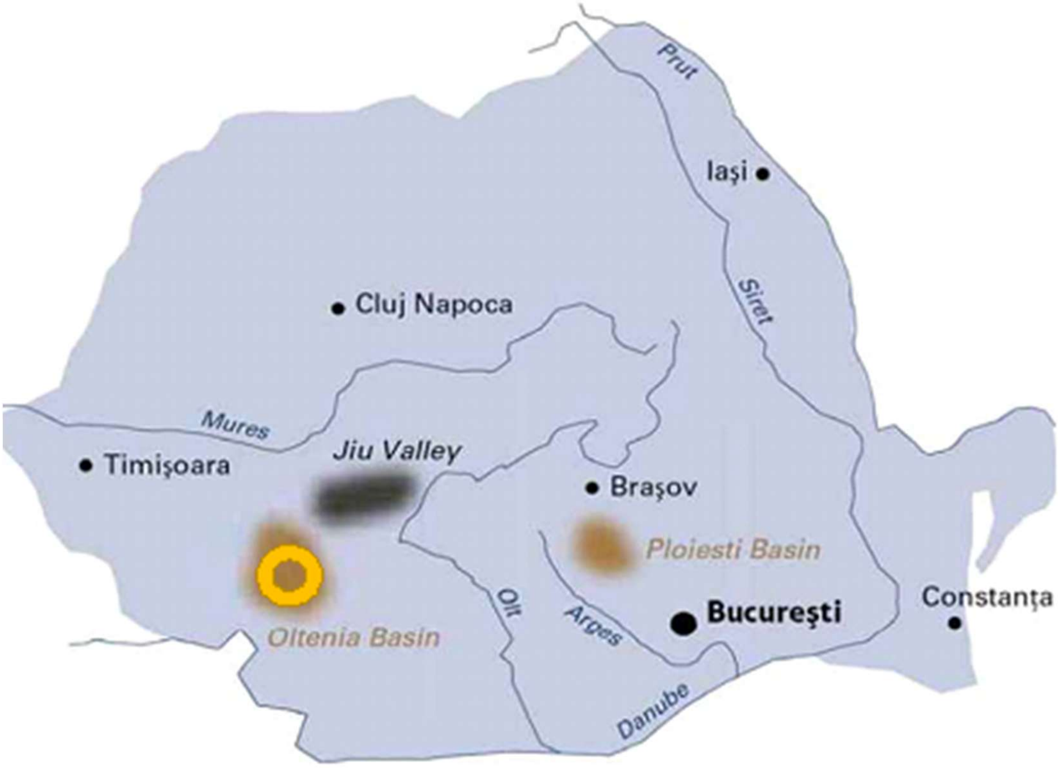


Fig. 18 Romanian study area

Table 1 Designed surface to be occupied by waste dumps (Apostu et al., 2024, 2025; CEO, 2022-2025)

Rovinari m.b.	**Surface [ha]**
Pesteana Nord (interior w.d.)	Approx. 500
Valea Negomir (exterior w.d.)	197
Pinoasa (interior w.d.)	387
Roşia de Jiu (interior w.d.)	779.5
Tismana (interior w.d.)	1452.5

Table 2 Construction parameters (as designed) of waste dumps in the Rovinari mining basin (CEO, 2022-2025)

Waste dump	**Number of steps**	**Working berms [m]**	**Total height [m]**	**Height of individual steps [m]**	**General slope angle [°]**	**Slope angle of individual steps [°]**
Pesteana Nord (int.)	4	100	105	10-15	9	18-27
Valea Negomir (ext.)	8	120	95	10-15	4-5	26
Pinoasa (int.)	5	130	70	10-15	4-5	20-28
Roşia de Jiu (int.)	10	100	107	10-15	3	26
Tismana (int.)	4	100-150	60-65	10-15	3	20-28

Due to the instability phenomena manifested over time in the waste dumps from Rovinari m.b., special attention must be paid in the design phase, but especially in the construction phase, as it is necessary to take constructive measures to avoid the occurrence of such negative geo-mining phenomena.

The material is deposited in the dump in several ways, the deposition variants being shown in Fig. 19 (Apostu, 2019).

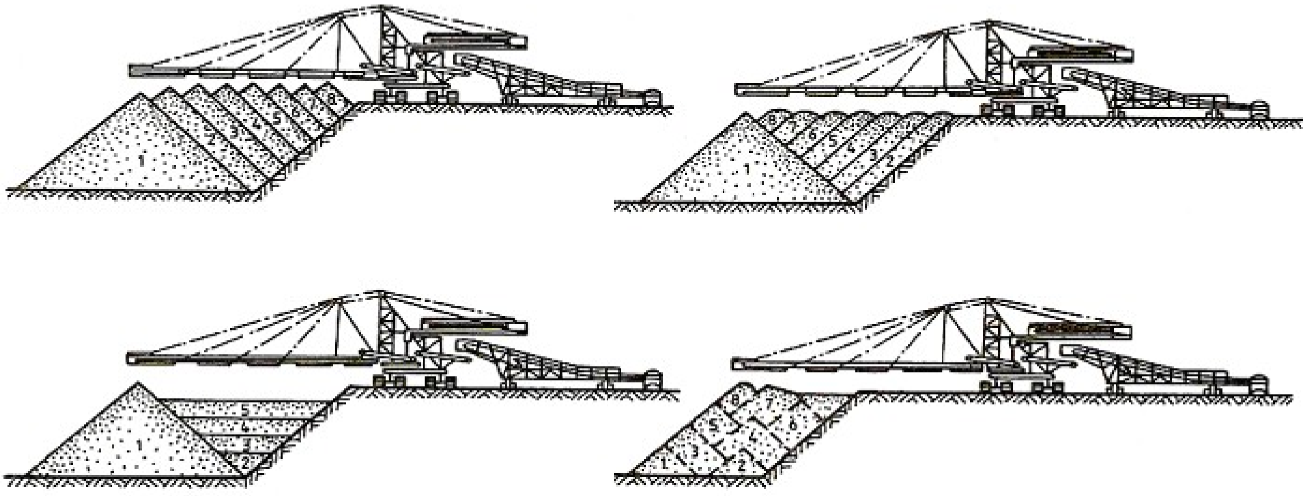


Fig. 19. Construction of dumps using dumping machines (spreaders) 1,2,3.- order of material deposition (Apostu, 2019)

2.3.1 Physical and mechanical characteristics of the waste rocks

The data obtained from recent laboratory analyses were combined with other values determined over time and were statistically processed in order to obtain average values and eliminate errors for each rock type that was identified (Table 3).

Table 3 Physical-mechanical properties of rocks from the Rovinari m.b. (CEO, 2022-2025)

Rock type	**Volumetric weight γ_a [kN/m^3]**	**Cohesion c [kN/m^2]**	**Internal friction angle ϕ [°]**
Clay	17.0 ÷ 21.0	24.0 ÷ 48.0	16 ÷ 23
Carbonaceous clay	15.6 ÷ 19.2	50.0 ÷ 70.0	32 ÷ 34
Greasy clay	18.8 ÷ 20.1	40.0 ÷ 65.0	22 ÷ 27
Sandy clay	18.8 ÷ 20.5	14.0 ÷ 32.0	15 ÷ 22
Dusty clay	19.9 ÷ 20.4	20.0 ÷ 40.0	13 ÷ 21
Marl	18.7 ÷ 19.4	30.0 ÷ 70.0	18 ÷ 25
Sandy marl	18.0 ÷ 19.2	24.0 ÷ 52.0	23 ÷ 27
Clayey dust	17.0 ÷ 20.7	16.0 ÷ 22.0	10 ÷ 17
Clayey dusty sand	18.4 ÷ 19.9	12.0 ÷ 20.0	17 ÷ 19
Clayey sand	17.0 ÷ 20.0	5.0 ÷ 16.0	24 ÷ 27
Dusty sand	15.7 ÷ 16.9	4.0 ÷ 12.0	22 ÷ 26
Sand	19.5 ÷ 19.3	-	30 ÷ 35

The physical and mechanical characteristics of the deposited material depend essentially on the proportion of these rocks found in the dumped mixture, and on the moisture (Table 4).

Table 4 Physical-mechanical properties of the dumped rock mixture (CEO, 2022-2025)

Waste dump	Volumetric weight γ_a [kN/m^3]	Cohesion c [kN/m^2]	Internal friction angle φ [°]	Moisture w [%]
Pesteana Nord (int. w.d.)	15.3 ÷ 24.0	3 ÷ 36	3 ÷ 32	17,8 ÷ 34.0
Valea Negomir (ext. w.d.)	19.5 ÷ 20.2	5 ÷ 25	12 ÷ 21	23.5 ÷ 33.2
Pinoasa (int. w.d.)	19.5 ÷ 20.2	5 ÷ 25	12 ÷ 21	23.5 ÷ 33.2
Roşia de Jiu (int. w.d.)	14.6 ÷ 24.0	15 ÷ 24	14 ÷ 26	23.2 ÷ 29.5
Tismana (int. w.d.)	13.4 ÷ 18.0	9 ÷ 28	10 ÷ 18	20.3 ÷ 35.0

Of course, the values of the physical and mechanical characteristics of the dumped rocks depend on a series of factors, the most important of which is the climatic factor, which in turn conditions the moisture of the rocks.

2.3.2 Technical conditions of the waste dumps and negative geotechnical phenomena

It must be stated from the beginning that in the past 5 years no important landslide affected any of the 5 waste dumps considered.

From the field observations regarding the technical condition of the dumps, a number of aspects can be listed, as follows:

- During periods of excessive rainfall or after snowmelt, as a result of increased moisture, superficial landslides of the individual steps occur, without affecting the overall stability of the dumps. These superficial landslides are small in size and are usually remedied as the dumping front advances;
- Also, during periods of excessive rainfall or after snowmelt, thixotropy phenomena (if clayey rocks predominate) and liquefaction (if sandy rocks predominate) were observed. These phenomena lead to increased instability of the dumped rocks by reducing shear resistance, thus favoring the occurrence of the superficial landslides mentioned above (Apostu et al., 2020, 2021);
- On slopes with an inclination greater than 30°, gullies and ravines (Fig. 20), formed as a result of the superficial runoff of precipitation, can be observed. In the absence of measures to stop these phenomena, over time, they will act as factors favoring the triggering of landslides;

Fig. 20 Erosion phenomena

- Another problem observed is the presence on all the studied dumps of areas affected by uneven settlements (in areas where rocks with a higher degree of loosening are deposited). These areas allow in a first phase the accumulation of precipitation water, and then their infiltration into the body of the dumps, which leads to a change in the state of consistency or in the worst case to the formation of aquifer areas;
- Especially on the berms of the last step of the dump, tension cracks (Fig. 21) can be observed (these are a warning factor and also a factor favoring the occurrence of landslides) and their monitoring is required. It must, however, be taken into account that recent years have been characterized by a severe deficit of precipitation and taking into account the large proportion of clay rocks in the composition of the waste dumps, these cracks may not be caused by the tensions in the dump body but by the drastic decrease in the moisture of the dumped rocks;

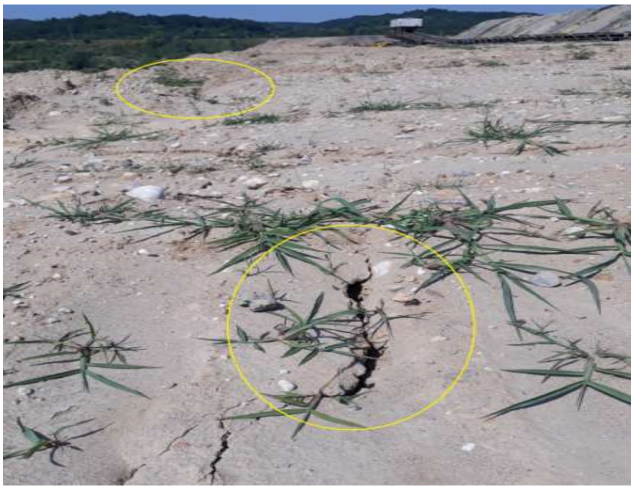


Fig. 21 Cracks on the upper part of the deposition steps

- In previous years, when, on the contrary, there were periods of excess precipitation, relatively small areas were observed where swelling phenomena occurred (both of the rocks in the foundation of the dumps and of the dumped rocks). This phenomenon is also due to the presence of clays, which have a high-water storage capacity, and by increasing in volume can lead to the destabilization of the dumps.
- Another important observation is that the tailings deposit in the advancing stage is not done uniformly (Fig. 22), this aspect favoring the accumulation of precipitation water at the base of the dump and its subsequent infiltration into the body of the dump, thus increasing the risk of landslides;

Fig. 22 Uneven depositions

- In some situations, the height and slope angle of the steps of the waste dumps exceed the designed ones. These deviations from the designed geometry may favor the emergence of instability phenomena or the reactivation of some older ones;
- In the case of the external dump (Valea Negomir) no works were carried out to remove the topsoil cover and to remove water from the base of the valley. In this case, there is a risk of landslides at the contact surface between the dump and its foundation;
- In general, reclamation works on dump surfaces that have reached the designed geometry and are free from technological loads are carried out according to the projects contained in the documentation on the basis of which the exploitation licenses were obtained (progressive reclamation);
- For the reclaimed areas of Rovinari m.b. it can be stated that the forest plantations have developed normally thus being achieved an additional stabilization of the lands important in areas prone to landslides).

2.3.3 Pesteana Nord internal dump

The sterile rocks from the Peșteana Nord open pit are dumped in the interior dump of the same name, using 3 dumping machines (Fig. 23).

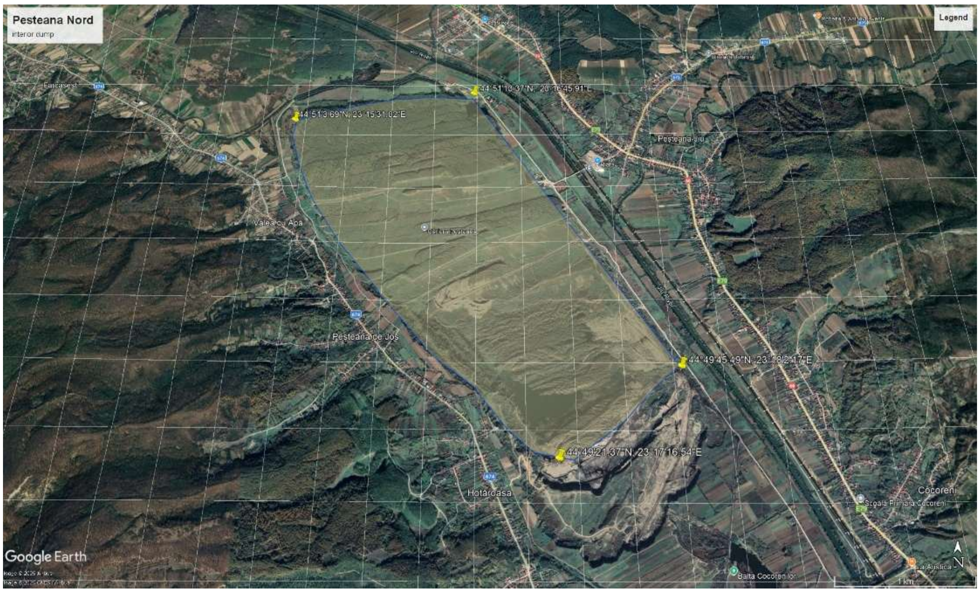


Fig. 23 Pesteana Nord open pit and interior dump (Google Earth Pro)

The open pit base has a 2° slope, from the interior dump towards the final steps of the pit.

The interior dump extends from north to south with the advancement of the working fronts and covers the base of the open pit.

The foundation line shows major variations as a result of the geological conditions and the exploitation project.

In 2018, as a result of the worsening exploitation conditions in the mining perimeter, as well as the hydrogeological conditions as a result of the lowering of the bed elevation of the V lignite layer, the exploitation of the V lignite layer was abandoned. The deposit of tailings by transshipment was also abandoned (CEO, 2022-2025).

According to the geological profile, the foundation of the dump is made up of marls, clays and sands (sands significantly predominate). At the same time, between these layers there are lignite "films", as well as lignite layer IV, a layer that is not exploited due to very difficult hydrogeological conditions and inefficiency from a technical and economic point of view.

Based on the geological profile, it can be stated that the dump comes into direct contact with the layers of marly and clayey rocks on approx. 75-80% of the foundation surface, the rest of the surface having contact with sandy rock layers, especially in the area of the former open pit steps. The thickness of the marly and clayey layers varies greatly, from a few meters to a few tens of meters, beneath them being layers of sandy rocks, with thicknesses of the order of tens of meters (CEO, 2022-2025).

Considering the fact that the sands are aquiferous rocks and the water inflow coefficient registers a high value in the Peșteana Nord perimeter, their contact with the dump involves a series of risks as a result of the rise in the groundwater level. In general, the aquifers in the foundation of the dump meet these areas through which they drain. In the same area there is also an aquifer with water under pressure, having an impermeable layer with variable thickness in the roof, which in some places is only 3 - 4 m. In such case, the high-water pressure can cause the impermeable layer to break. However, the height of the dump and the specific weight of the dumped material significantly reduce or even eliminate this risk.

The waste rock layers in the Peșteana Nord perimeter are mainly composed of a succession of clayey rocks (28.36%), marly (12.72%) and sandy (47.91%) rocks, to which are added the gravel and boulders from the terrace (9.82%) and the topsoil (1.19%).

The nature of the dumped material highlighted the same types of rocks, so it was considered that the waste material in the inner dump is a non-homogeneous mixture of soft rocks (sand, clay, marl, topsoil), in which fragments of harder rocks (boulders, gravel, pieces of lignite) are incorporated. Therefore, the dumped material is somehow similar, the differences that endanger stability being the degree of loosening, the reduction of mechanical resistance characteristics following excavation and transport, the location area, the shape and inclination of the base terrain, the geometric shape of the dump, the presence of water, etc.

2.3.4 Valea Negomir external dump

Valea Negomir dump was designed to store part of the waste rocks from the Pinoasa open pit. It is located in the Negomir Valley, south of the Pinoasa open pit (Fig. 24).

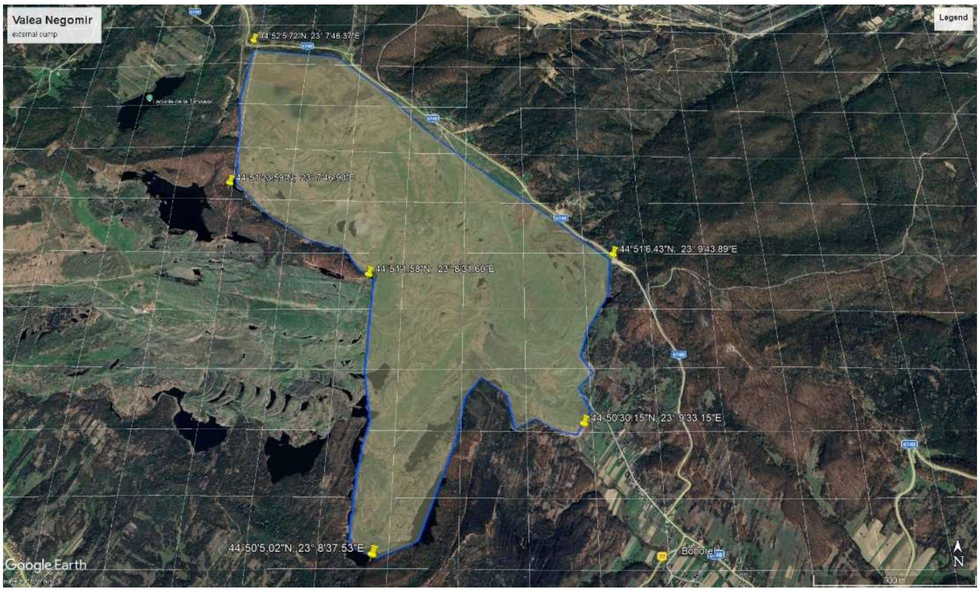


Fig. 24 Valea Negomir waste dump (Google Earth Pro)

Waste rocks have been deposited since 1987. The depositing works with the help of dumping machines have stagnated since 2015, being resumed for short periods of time in 2025. Currently, Valea Negomir dump is under conservation, being proposed for closure and for the construction of a photovoltaic park (CEO, 2022-2025).

The location area falls within the terrace area of the Oltenia Subcarpathians, with a relief resulting from erosion phenomena. In the depression areas of this microrelief, precipitation water accumulates in the form of puddles, which are mostly seasonal.

Waste rocks were deposited in this dump on an undeveloped bed without water drainage works.

The works to remove the vegetation layer were carried out sporadically and without continuity.

Valea Negomir dump presents the most favorable instability conditions, which required a rethinking of the dumping technology, namely lowering the dumping machine and reducing the height of the forward step to a maximum of 10-12 m and creating an appropriate gap between the first step and the next two working steps.

The final designed capacity of the Valea Negomir dump is 270 million m3. The area planned to be occupied by the Valea Negomir dump is 197 ha. The tailings were deposited in steps with heights of 15 m, the step slope angle was 26º, the general slope angle was 4º30' and the berms were 120 m wide (CEO, 2022-2025).

The general angle of the step system made between the 225-335 m elevations is 3 - 4°, the dump presenting local instability phenomena, mainly due to the non-twinning of the dump with the side slopes, the depression areas where water accumulates during heavy rainfall or in spring from melting snow. Since water is one of the main causes that determine the landslides of mining dumps, its proper drainage together with the reprofiling works represent the main measures to ensure and increase stability for the following design phases.

The tailings deposit activity was carried out with three A2Rs 6500x90 type dumping machines, both through low deposit and high-step deposit in 15 m steps (CEO, 2022-2025).

2.3.5 Pinoasa internal waste dump

Pinoasa interior waste dump was also designed to store part of the waste rocks from the Pinoasa open pit (Fig. 25).

Fig. 25 Pinoasa open pit and internal waste dump (Google Earth Pro)

The deposition of waste rocks was carried out in the space resulting from the exploitation of lignite in the Pinoasa open pit starting with 2007 and will continue until at least 2027.

The open pit base was established at the bed of layer V, taking into account ensuring optimal hydrogeological conditions for carrying out excavation works.

In the "Technical documentation regarding the internal dumping technology at the Pinoasa quarry", elaborated in 2018, the following general stability conditions for the internal dump were established (CEO, 2022-2025):

- total height of the dump - 70 m;
- height of the dump steps - 15 m;
- working berm - min 130 m;
- general slope angle of 4-5º;
- designed total surface of the internal dump - 387.00 ha.

The dumping of the waste rocks from the excavation steps is carried out in the internal dump with 4 A2RsB 6500.90 type dumping machines (CEO, 2022-2025).

2.3.6 Roşia de Jiu internal dump

Roşia de Jiu interior dump is located south of the opening trench of the Roşia de Jiu open pit and consists of 10 steps, the deposition in the exterior dump having long been completed (Fig. 26).

Fig. 26 Roşia de Jiu open pit and internal waste dump (Google Earth Pro)

Waste rocks have been deposited since 1995 (CEO, 2022-2025).

The open pit base was established at the bed of layer V, taking into account ensuring optimal hydrogeological conditions for carrying out excavation works.

The location of the interior dump was established on the open pit base (layer V bed) in the area freed from technological loads.

In order to drain the interior waste dump, drainage works were planned, represented by a system of drains made under the dump (ballast-filled drains, with the possibility of water circulation), respectively guard channels made along the entire contour of the dump.

The total area designed to be occupied by the Roşia de Jiu interior dump is 779.78 ha (CEO, 2022-2025).

Based on the granulometric analyses, the plasticity index, the cohesion consistency index and the mineralogical composition, the formations from the over and interburden of Roşia de Jiu open pit can be grouped into three main categories:

- non-cohesive rocks (sands, gravels);
- weakly cohesive rocks (clay dust, clay-sandy dust, clay sand);
- cohesive rocks (dusty clay, greasy clay, marly clay).

These rocks are mostly made up of clay minerals (15-90%) and minerals from the quartz-feldspar group (12-55%), and subordinately minerals from the group of micas (0.5-6%), carbonaceous substances (0.5-10%) and carbonates (1-5%).

The instability phenomenon manifested at this dump in the past years led to the resizing of the deposition steps and at the same time to the enlargement of the dump surface on the southern side, reducing the general slope angle below 6º.

The dumping of the waste rocks from the excavation steps is carried out in the internal dump with 5 dumping machines, of which: 1 MH 4400.170 type cantilever arm transfer truck, two A2RsB 12500.95 type dumping machines, one A2RsB 6500.90 type dumping machine and one A2RsB 6300.95 type dumping machine (CEO, 2022-2025).

2.3.7 Tismana internal dump

Initially, in Rovinari m.b. two open pits were designed with the name Tismana, respectively Tismana I and II, and two related internal dumps.

Although in some documentation these are still addressed separately, in reality they are united, which is why they will be treated as such (Fig. 27).

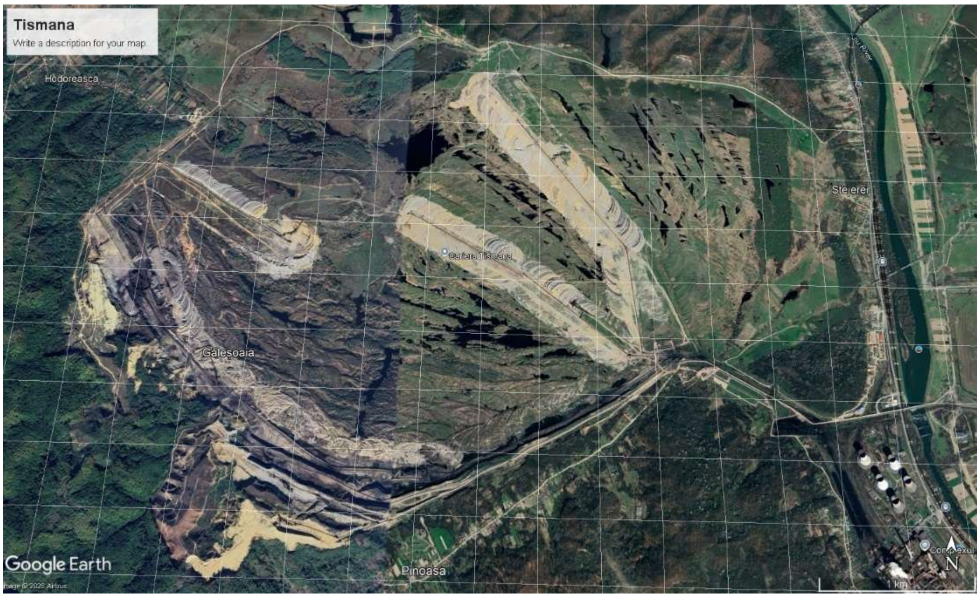


Fig. 27 Tismana open pit and internal waste dump (Google Earth Pro)

Waste rocks have been deposited since 1995 (CEO, 2022-2025).

When designing the technological flow of dumping, the conditions and configuration of the space remaining free after the extraction of the over and interburden and useful mineral substance from the Tismana River floodplain area were taken into account.

The open pit base was established at the bed of layer V, taking into account ensuring optimal hydrogeological conditions for carrying out excavation works.

The location of the interior dump was established on the open pit base (layer V bed) in the area freed from technological loads.

Currently, the deposition is carried out with five dumping machines, three A2Rs 6500.90 type, one A2Rs 6300 x95 type, respectively two direct dumping machines of the MH4400x170 type (CEO, 2022-2025).

According to the provisions of the technical documentation developed, the total area occupied by the interior dump is TI 823.4 + TII 629.1 = 1452.5 million ha (CEO, 2022-2025).

2.3.8 Survey overview

During the last half of November 2025, the team from UP (with the support of our partners from CEO) conducted a surveying campaign for two of the waste dumps, namely Pesteana Nord interior w.d. and Valea Negomir exterior w.d, initially considered within the MiDSafe Project.

This campaign was carried out by means of UAV and Lidar equipment and the raw data is still under processing.

The processed data will be used to obtain different cross sections, which, in turn will be necessary for the stability analyses and the design of the innovative monitoring system.

However, at this point, we can present a few 3D images of the two waste dumps (Fig. 28-Fig. 33).

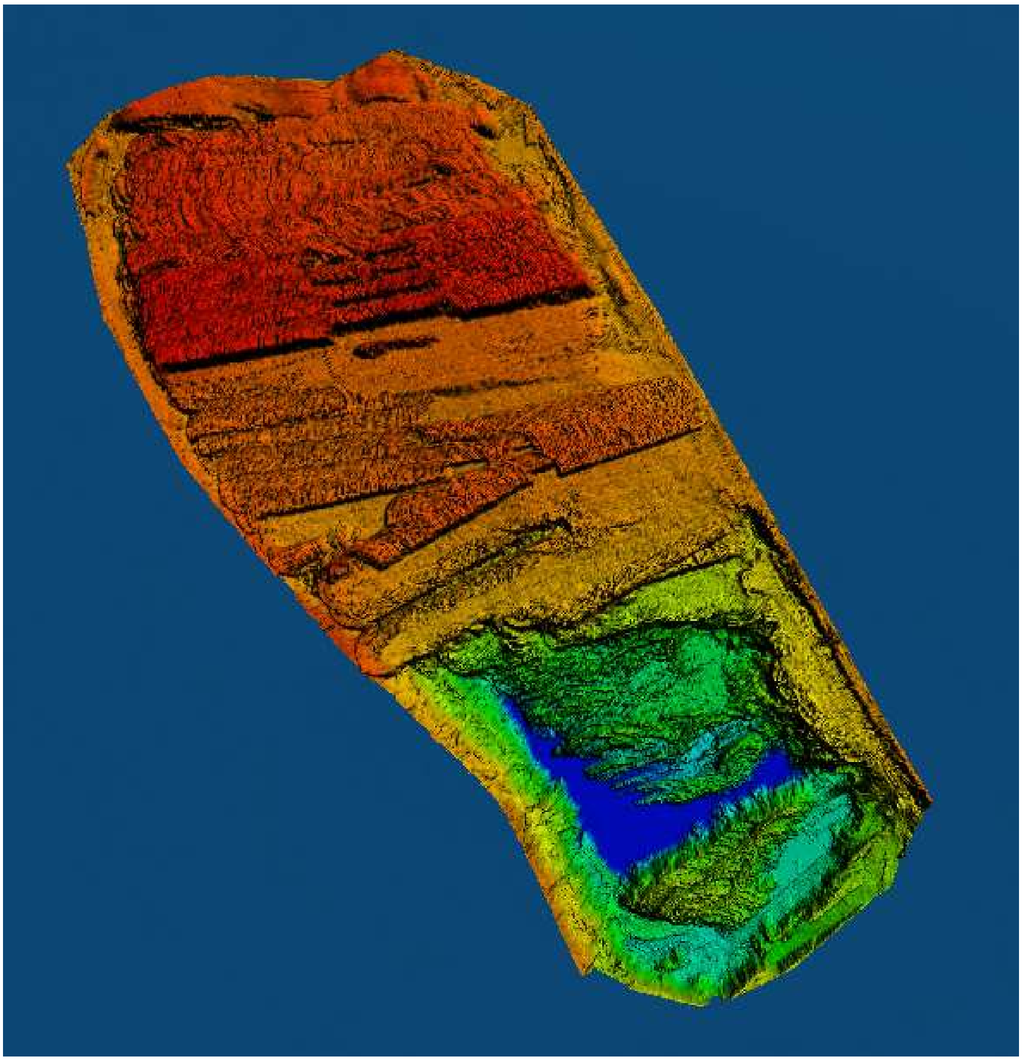


Fig. 28 Pesteana Nord w.d. (view from above) – elevation factor 1/5

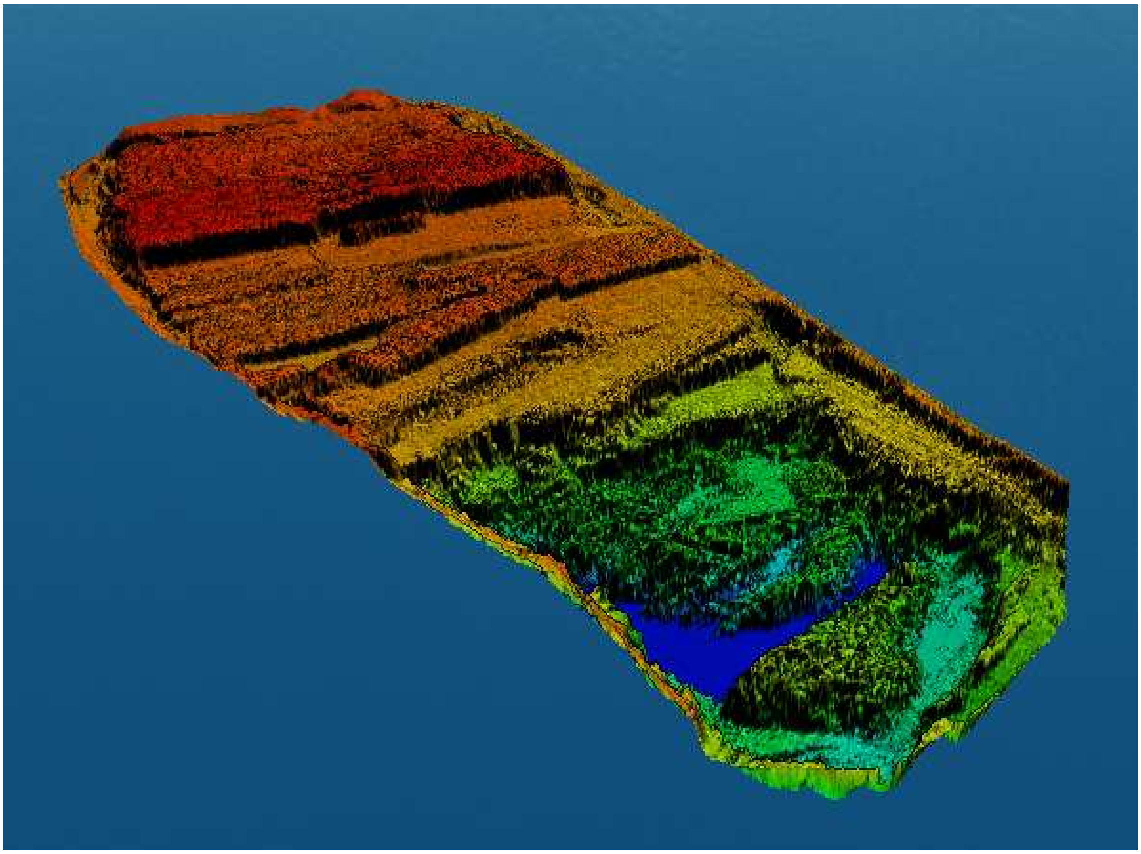


Fig. 29 Pesteana Nord w.d. (S-W view) – elevation factor 1/5

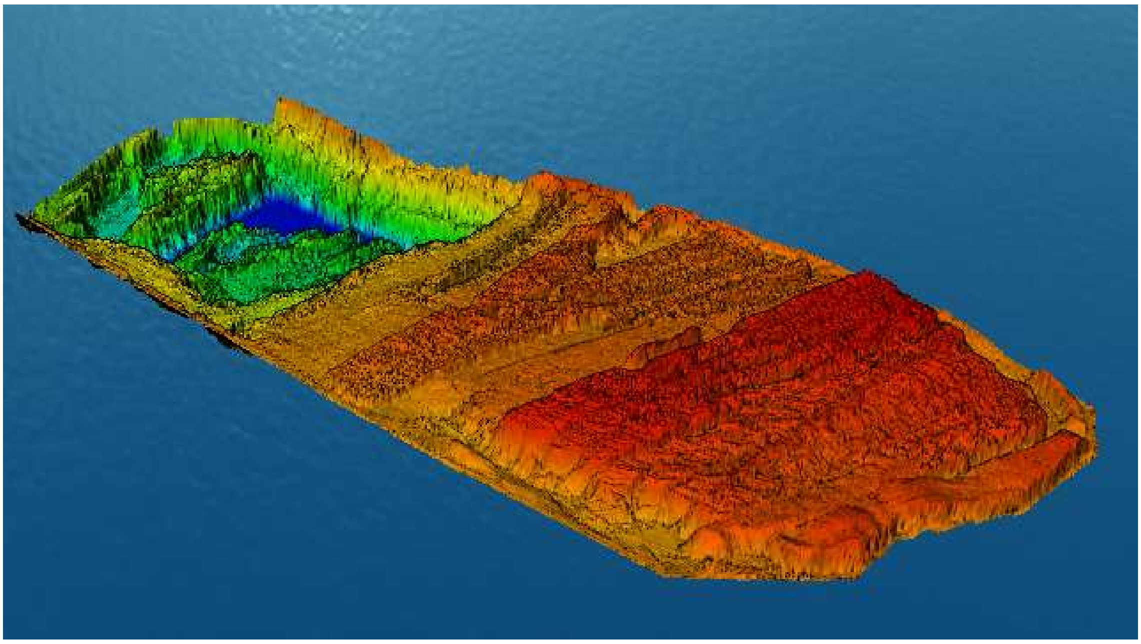


Fig. 30 Pesteana Nord w.d. (N-E view) – elevation factor 1/5

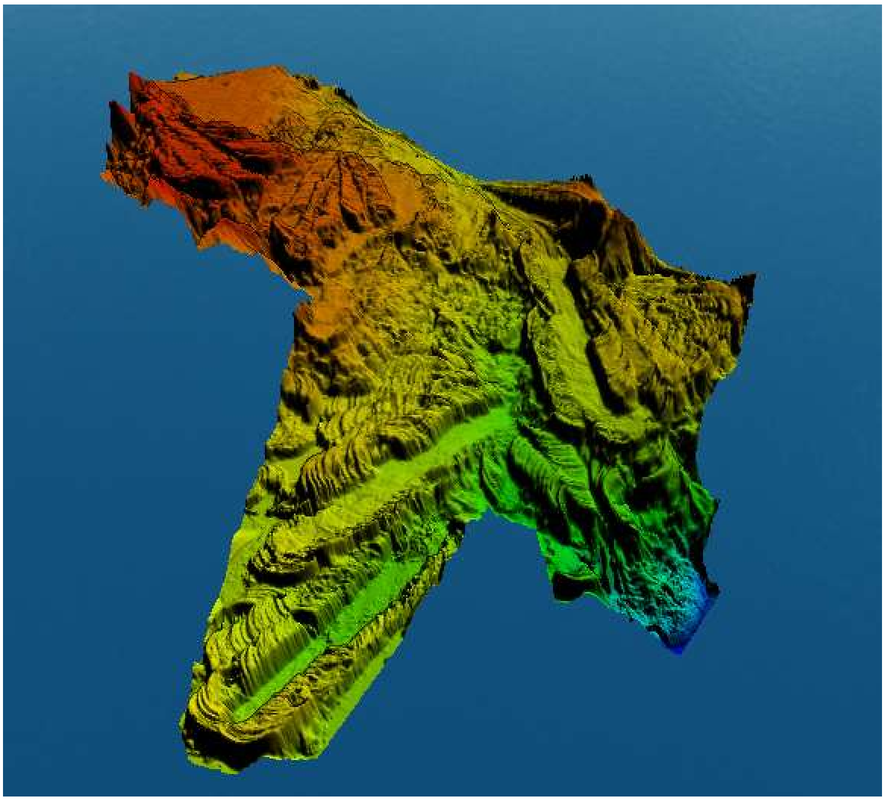


Fig. 31 Valea Negomir w.d. (view from above) – elevation factor 1/5

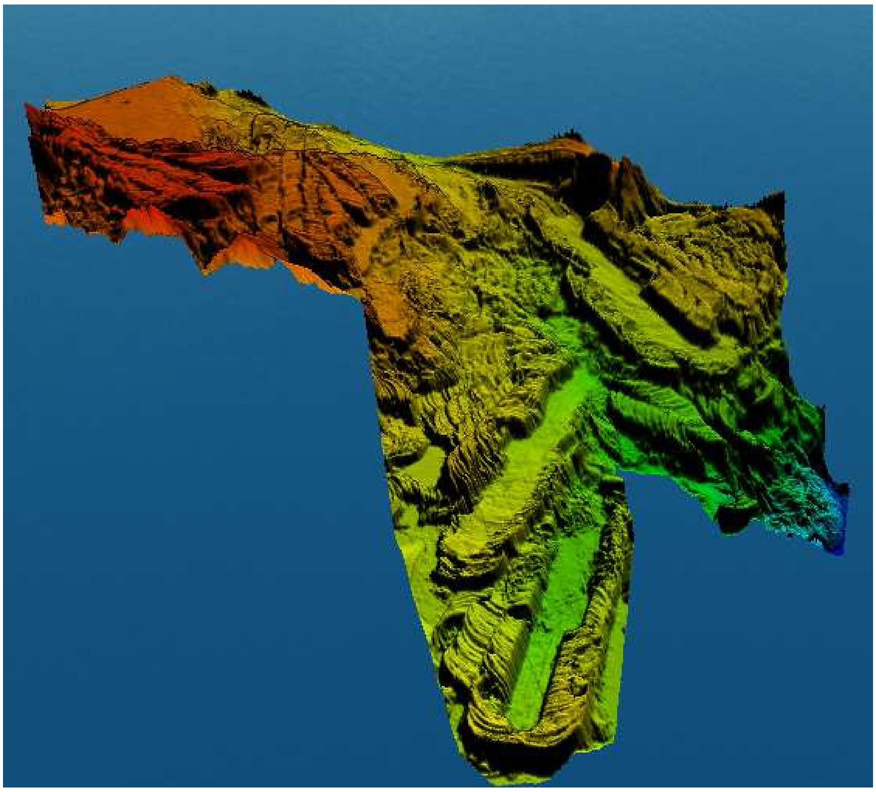


Fig. 32 Valea Negomir w.d. (S-W view) – elevation factor 1/5

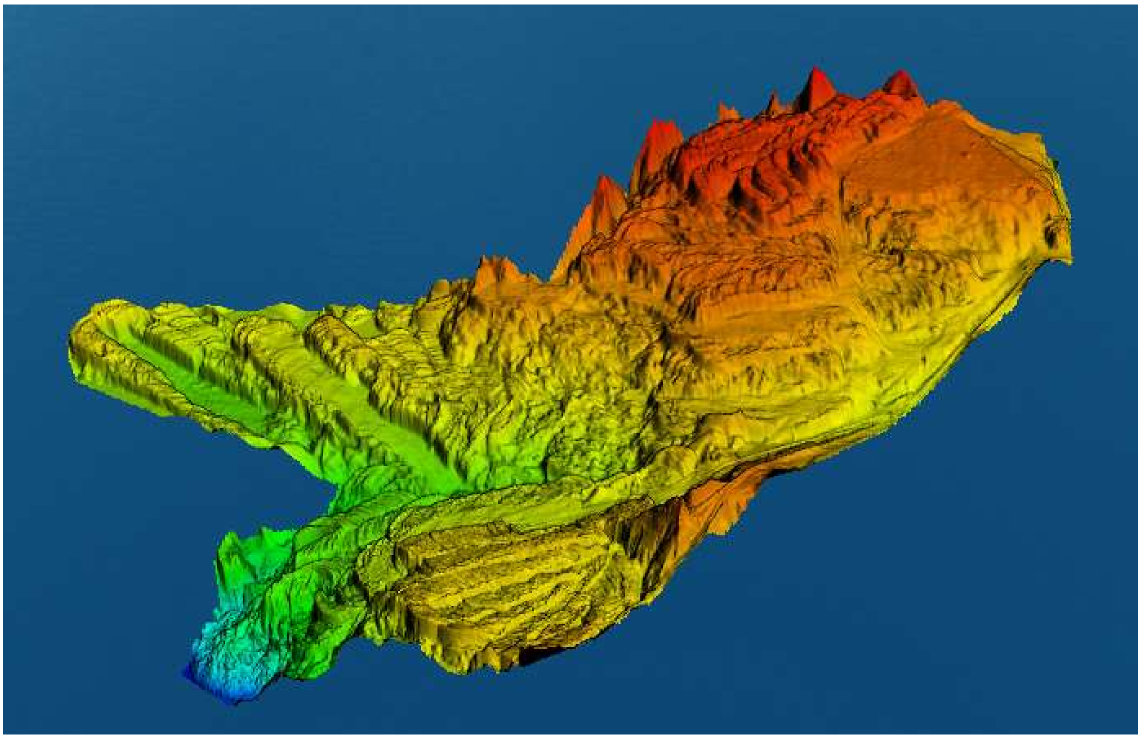


Fig. 33 Valea Negomir (N-E view) – elevation factor 1/5

3 Main characteristics of mine dumps

This chapter presents a comprehensive summary of current research on the geotechnical properties and flow behaviour of coal mine spoil and tailings, underscoring the pronounced heterogeneity of the waste materials and their vulnerability to slope failures. Coal mine waste dumps, often referred to as spoil piles or overburden dumps, are massive accumulations of rock and soil materials generated during coal extraction and processing. These dumps are frequently non-engineered structures, which contributes significantly to their susceptibility to slope failures. Understanding their geotechnical and geometrical properties is crucial for assessing stability, managing environmental impacts, and ensuring the safety of mining operations and surrounding areas.

Recent research initiatives, including the SLOPES (Smarter Lignite Open Pit Engineering Solutions) and RAFF (Risk Assessment of Final pits during Flooding) projects, have focused on improving the understanding and management of stability risks in waste dumps and post-mining environments. These studies reveal extreme variability in both physical properties and stratigraphy, often to an extent that renders deterministic layer-by-layer modelling impractical. Within this context, numerical modelling serves as an indispensable tool, not only to replicate real-world behaviours but also to test the influence of geometric and geological features like slope angles, dump heights, bench configurations, and basal weak zones on stability outcomes. The integration of statistical correlations and variability further refines the reliability of risk assessments by reflecting the negative cross-correlation between shear strength parameters.

Finally, the influence of hydrogeological conditions, especially pore pressure evolution, weak layer triggering, and water filling procedures emerges as a core factor controlling dump behaviour, as demonstrated in the RAFF project’s findings. These experiences collectively confirm the importance of adopting probabilistic frameworks and refined numerical analysis to ensure safe, reliable, and cost-effective inner dump management in complex mining settings. This section sets out the foundational principles, key findings, and practical recommendations that should guide future analyses and numerical modelling of inner dump stability in coal mining environments.

3.1 Geotechnical Characteristics and Landslide Risk

The geotechnical properties of coal mine spoil deposits are highly variable and have a direct impact on the stability of waste dumps (Fityus et al., 2008). Below, the main characteristics of these deposits are presented, along with their influence on stability analysis.

3.1.1 Composition and Rheology

Coal mine spoil consists of a wide variety of rock fragments and soil materials, originating from both disturbed and undisturbed geological layers (Adamczyk, J., 2012). The parent rock types present in spoil deposits include conglomerates, various kinds of sandstones, siltstones, mudstones, shales, claystones, cherts, ironstone, and coal (Kumar et al., 2023). Notably, coal and pyrite concentrations can be considerable, reaching up to 20% and 1%, respectively, in some spoils. Waste deposits are commonly classified into four groups: bituminous shales, shales, bituminous sandstones, and coal (Sánchez et al., 2010).

One of the defining features of coal mine spoil is its significant heterogeneity, with particle sizes spanning from sub-micron scales to fragments exceeding 2 meters (Fityus et al., 2008). This extensive variability in composition and particle size complicates the understanding and precise analysis of spoil behaviour, directly influencing its strength, compressibility, and hydraulic properties (Yu, H., 2015).

The rheological properties are primarily important to investigate when dealing with impounded fine coal refuse or coal slurry. This is because these materials are characterized by high water content and low shear strength, making them highly susceptible to flow failure under both static and dynamic impact loading.

Viscosity is highly dependent on water content; higher initial water content leads to lower viscosity because pore water reduces the particle interactions within the coal refuse. The Bingham Plastic model effectively describes the flow behaviour of impounded fine coal refuse by incorporating plastic viscosity and yield stress. When water content is high, yield stress can become negligible, causing the slurry to behave almost as a Newtonian fluid (Yu, H., 2015).

These rheological characteristics have a direct impact on landslide risk. Lower viscosity, resulting from increased water content, allows for faster and more extensive flow failures, which heightens the risk of property damage, loss of life, and environmental harm. The sensitivity of these spoil materials to water content means that even minor changes can sharply shift them from a stable (non-flowable) to a highly mobile (flowable) state, significantly increasing the potential for hazardous events (Yu, H., 2015).

3.1.2 Granulometry

Spoil materials generated from mining activities exhibit significant heterogeneity in particle size (Fityus et al., 2008). Direct wastes from mining operations can include particles as large as 500 mm, while wastes resulting from coal enrichment processes, such as washery wastes, are typically much finer, ranging from coarse-grained materials (10–250 mm) to fine-grained fractions (0.5–30 mm), and even down to tailings, which are less than 1 mm (Adamczyk, J.,2012).

Freshly extracted waste tends to be dominated by gravel and cobble-sized particles, whereas materials that have been stored for longer periods generally contain a higher proportion of fine grains, largely due to weathering effects (Adamczyk, J.,2012). Analyses of fine coal refuse samples reveal that over 80% of the material can be finer than the No. 200 sieve (0.075 mm), placing it mostly within the silt size category.

The coefficient of uniformity for coal slurry ranges between 11 and 34, suggesting a moderate to narrow distribution of particle sizes (Yu, H., 2015). The prevalence of fine particles is particularly significant for landslide risk, as their presence in saturated conditions can notably alter flow characteristics. Fine-grained, loose materials are more susceptible to liquefaction and flow failures, while cycles of wetting and drying can exacerbate particle degradation, leading to further reductions in both strength and permeability (Yu, H., 2015).

3.1.3 Density and Compaction

The density and compaction characteristics of waste and coal refuse play a crucial role in determining their mechanical behaviour and associated risks (Thiruchittampalam, S. et al., 2024). In Poland, the bulk density of waste typically ranges between 13 and 19 kN/m³, with freshly wrought material exhibiting values from 13 to 16 kN/m³, new heaps ranging from 17 to 18 kN/m³, and old heaps from 15 to 19 kN/m³. The maximum dry density observed is between 14 and 20 kN/m³ (Sánchez et al., 2010).

The specific gravity of coal refuse is highly variable, falling between 1.66 and 2.84. For example, in Poland, the specific gravity ranges between 1.86 and 2.55, in Germany between 1.86 and 2.38, and in the United Kingdom between 1.66 and 2.84; values below 2.2 - 2.3 are indicative of coal, while those around 2.6 - 2.7 are typical of bituminous sandstones and shales. Materials with low specific gravity, particularly those high in coal content (1.25 -1.70), exhibit lower effective stress, resulting in reduced shear strength (Adamczyk, J.,2012).

Freshly deposited materials can have porosities as high as 30%, and density tends to increase over time due to weathering and compaction by environmental factors (Adamczyk, J.,2012). Proper compaction is essential to maximize dry density and achieve optimum moisture content, both of which are influenced by grain size distribution, strength of rock fragments, time of storage and applied compactive effort (Yu, H., 2015).

Regarding landslide risk, low specific gravity creates a loose initial structure even after consolidation, rendering spoil impoundments more vulnerable to dynamic disturbances and flow failures (Kumar et al., 2023). Furthermore, insufficient compaction during placement adds complexity and unpredictability to spoil dump behaviour, increasing the potential for instability.

3.1.4 Water Content and Hydraulic Properties

Water content and hydraulic properties are key factors influencing the stability and behaviour of spoil materials (Fityus et al., 2008). Fresh spoil typically has a moisture content of 4–7%, but this can rise to about 20% in stored material due to the enrichment method and grain size of the waste material (Adamczyk, J.,2012). For effective compaction, the optimal moisture content is approximately 14.9% for silty sandy gravel spoil (Fityus et al., 2008).

The hydraulic properties are notably affected by the presence of coal; while coal is hydrophobic and resists water infiltration, it drains rapidly after saturation. The permeability exhibits considerable variation and generally declines with increased mudrock content. Coarse and typical spoils may show conductivity values greater than 1.3×10^{-4} m³/hr, whereas mudrock-rich average spoil can see a reduction to as low as 1×10^{-5} m³/hr, mainly due to particle disintegration (Fityus et al., 2008). Carbonaceous mudrock (partings) initially resists wetting and drains rapidly, but after thorough wetting, the conductivity drops to 2.5×10^{-5} m³/hr as swelling and disintegration of shales occur. Fine coal refuse is characterized by extremely low hydraulic conductivity, ranging from 10^{-4} to 10^{-9} cm/s, making it nearly impervious to water flow (Yu, H., 2015).

Water content critically governs permeability and flow behaviour (Fityus et al., 2008). Low permeability leads to extended consolidation times and inhibits pore pressure dissipation, resulting in an increased likelihood of liquefaction under static or dynamic loading conditions. The buildup of excess pore pressure reduces shear strength, significantly raising the risk of flow failures (Yu, H., 2015). Rainfall and site hydrology emerge as major factors contributing to instability, highlighting the need for meticulous management of water within spoil dumps to mitigate these hazards (Kumar et al., 2023).

3.1.5 Shear Strength, Cohesion and Friction Angle

Coal waste material typically exhibits moderate to low strength, and it can decrease markedly after inundation or rehandling. For typical spoil, reported peak friction angles are around 33.4°, with residual values close to 32.4°, both accompanied by negligible cohesion. Spoil that has undergone degradation or retesting shows even lower shear resistance, with both peak and residual friction angles dropping to approximately 28° (Fityus et al., 2008).

Under drained conditions, spoil materials generally behave as granular materials, exhibiting effective internal friction angles that can range widely from 22.5° to 50°, paired with very low effective cohesion, ranging from 0 to 26 kPa (Yu, H., 2015).

Weathering processes tend to increase cohesion over time, so older spoil tips may develop higher cohesion values (34–35 kPa) compared to the 5–35 kPa typically found in fresh spoil (Fityus et al., 2008). However, at high water contents, particularly above the liquid limit, shear strength drops sharply, often becoming extremely low (Yu, H., 2015). While consolidation processes impact cohesion more strongly than friction angle, both parameters play critical roles in stability. Inadequate shear strength, whether due to low cohesion, small friction angles, or reductions caused by water saturation, degradation, or liquefaction, is a primary factor leading to slope failure (Adamczyk, J.,2012). Any decrease in shear strength directly elevates the risk of landslides within spoil heaps and impoundments.

3.1.6 Consolidation and Settlement

Consolidation and settlement behaviour of spoil materials are closely linked to their compressibility characteristics (Adamczyk, J.,2012). The compressibility modulus for spoil ranges from 6–8 MPa under low loading conditions (less than 50 kPa) to 17–75 MPa at higher loads (up to 300 kPa). Settlement occurs rapidly at first: approximately 50–70% of the total settlement typically takes place within the first 10 days after loading, while the remaining 30–50% may develop over much longer periods, ranging from 70 to 340 days. Freshly worked spoil generally exhibits higher compressibility modulus compared to weathered materials found in older dumps (Adamczyk, J.,2012).

After sample analysis, their results show that a higher compressibility leads to a lower consolidation and requires greater strain for effective stress to develop within the soil (Yu, H., 2015). This extended consolidation process means that high void ratios and substantial amounts of pore can persist within the spoil mass for many months or even years (Adamczyk, J.,2012). As a result, the rapid accumulation of excess pore pressure in coal waste can further lead to a marked decrease in material strength, significantly heightening the risk of flow failure and landslides (Yu, H., 2015).

3.1.7 Plasticity

Coal refuse typically exhibits liquid limits ranging from 38.1% to 42.5%, plastic limits between 27.8% and 28.3%, and plasticity indices from 9.3% to 14.7% (Yu, H., 2015). The Atterberg limit values categorize coal refuse as a low-plasticity silt, which means the material demonstrates only slight plastic behaviour (Fityus et al., 2008). Low plasticity indicates that the material is not highly sensitive to fluctuations in water content; however, when the water content exceeds the liquid limit, the coal refuse can begin to behave like a fluid. This makes the liquid limit a crucial threshold, as surpassing it can trigger the flow of slurry and significantly increase the potential for flow failures or landslides (Yu, H., 2015).

3.1.8 Swelling and self-ignition

Swelling in spoil materials primarily occurs in components such as clay, marl, mudstone, and shale, and is directly related to their capacity to absorb water. Free swelling tests on waste material have indicated swelling values ranging from 4.7% to 12%, classifying the material as expansive soil. This swelling behaviour is significant from a stability perspective, as it can lead to reductions in shear strength and increase landslide risk (Adamczyk, J.,2012).

Additionally, coal mine spoil is susceptible to spontaneous self-ignition due to the presence of coal (up to 20%) and pyrite (up to 1%). Such reactions can cause internal temperatures to rise as high as 1200°C (Adamczyk, J.,2012). The heat generated during self-ignition can fundamentally alter the mechanical properties of the spoil, potentially leading to material weakening and further compromising slope stability. Both swelling and self-ignition thus represent critical factors that need to be managed to mitigate landslide hazards in spoil dumps.

Table 5 Summary of coal waste dump properties

Country	Material / Context	Unit Weight (kN/m³)	Cohesion (kPa)	Friction Angle (°)	References
Australia	Fine sandstone, mudrocks, ironstone & BMAC* framework spoil categories	18.0 - 20.0 (based on max dry density and BMAC framework)	Negligible (fresh spoil); 0 - 50 (BMAC framework for unsaturated/saturated conditions)	Peak 33.4°, Residual 32.4° (fresh typical spoil); 18 - 35 (BMAC framework for various conditions)	Fityus et al., 2008 / Thiruchittampalam, S. et al., 2024
Spain	Coal mine waste dump material (bituminous shales, shales, bituminous sandstones, coal)	13.0 - 15.0 (in situ density)	0 - 30 (measured/interpreted, including negligible for pure frictional)	33.0 - 40.0 (measured/interpreted for various contexts)	Sánchez et al., 2010
Poland	Coal mining waste	8.0 - 21.0	2 - 80 (general range from various conditions including fresh, old, burned, non-burned)	22.5 - 50.0 (general range from various conditions)	Adamczyk, J.,2012
USA	Fine coal refuse (silt-like powder) from Kentucky & West Virginia	Specific gravity: 2.03 - 2.14 (Liquefied unit weight ~20 kN/m³)	0 - 26 (effective cohesion from consolidated-drained tests)	0 - 30 (effective and undrained friction angles)	Yu, H., 2015
India	Test from samples - Backfilling study	18.65 - 21.65 (from max dry density of 1.901-2.207 Mg/m³)	47.5 - 215	16.0 - 34.0	Agarwal, V. K., 2009

* BHP Mitsubishi Alliance Coal (BMAC)

3.2 Geometrical Characteristics and Landslide Risk

The geometrical configuration of coal mine waste dumps is a critical factor influencing their overall stability, maximize storage capacity, and manage environmental impacts.

3.2.1 Dump Configuration and Design

Waste dumps are constructed as non-engineered structures, with overburden material being randomly deposited (Kumar et al., 2023). To minimize their spatial footprint, it is common practice to extend the dumps vertically, reaching heights of 100–120 meters, and in some cases up to 130 meters. Historical data reveal that older dumps range in height from 55 meters (after 20 years) to 75 meters (after 50 years) (Sánchez et al., 2010). To enhance stability, multiple benches or banks are incorporated into the dump design, not only to retain falling debris and provide access for haul vehicles but also to break the slope into manageable segments. A typical configuration might feature a total height of 130 meters, benches 25 meters wide at various elevations, and an average slope of 3V:1H (Kumar et al., 2023).

Uncontrolled vertical expansion and inadequate bench design in coal mine waste dumps can lead to the formation of critical slip surfaces, significantly increasing the risk of slope failure. This risk is further amplified by the non-engineered nature of these dumps, as well as their excessive heights and steep slopes intended to maximize storage capacity (Kumar et al., 2023). Therefore, proper geometric planning and design are essential to effectively mitigate landslide hazards.

3.2.2 Overall and Individual Slope Angles

The slope angle is a crucial factor in determining the stability of coal mine waste dumps. Generally, flatter slopes provide greater resistance to failure, though excessively flat slopes can be uneconomical due to a reduced storage capacity. Research has explored overall slope angles in the range of 20° to 45°. For example, in Spain, slope inclinations typically range between 35° and 40°, in India, a typical dump was assessed with an overall slope angle of 46°, using individual bench slopes of 3V:1H (approximately 71.5°) (Sánchez et al., 2010). In contrast, an engineered, stability-modified dump demonstrated a safer overall slope angle of 37.5°. Reducing the slope angle has been demonstrated to significantly enhance stability; for example, a configuration with a 0.8V:1H slope achieved a Factor of Safety (FS) of 1.3, indicating much greater resistance to failure (Kumar et al., 2023).

From a landslide risk perspective, steeper slopes generally correspond to lower factors of safety, making them more prone to landslides. While steep configurations are often adopted to maximize storage capacity, this approach comes at the cost of considerably increased instability and heightened vulnerability to slope failure (Kumar et al., 2023).

3.2.3 Bench Design

Benches are incorporated into the design of coal mine waste dumps to improve overall stability. Typical bench might be 25 meters wide, with bench heights varying commonly 50 meters for the initial rise and 25 meters for subsequent rises. In India, a typical bench configuration examines single, double, and triple stage dumping patterns, with benches often 25 meters wide and heights varying from 30 meters generally, up to 90 meters in some cases (Koner, R., 2021).

The inner portion of each bench is designated for arresting falling debris, helping to contain material and prevent uncontrolled movement, while the remaining width provides access routes for haul vehicles (Kumar et al., 2023). However, landslide risk increases when benches are either too narrow or excessively tall; inadequate bench dimensions can undermine stability, and shallow slope failures frequently occur along the faces of benches that are too high (Kumar et al., 2023). Careful consideration of bench width and height is therefore crucial for maintaining slope integrity and reducing the likelihood of slope failure.

3.2.4 Berm width

The width of the berm between stages is critical, not only for ensuring operational access but also for enhancing safety. Berm widths ranging from 12 to 20 meters have been investigated (Koner, R., 2021); the inner section of the bench helps trap falling debris, while the outer section provides a safe route for haul vehicles (Kumar et al., 2023). Common dumping patterns include single-stage, double-stage, and triple-stage configurations (Koner, R., 2021). Among these, double-stage dumping is often found to be the most advantageous, as it can accommodate approximately 1.5 times more waste material than triple-stage dumping for the same base area, while also offering a higher factor of safety (Kumar et al., 2023).

When no benches are used and the dump is constructed as a single, continuous slope, the observed factor of safety is significantly lower; for example, a value of 0.45 compared to 0.71 achieved with benched configurations (Kumar et al., 2023). To enhance stability and comply with safety requirements, an improved dump geometry can be implemented. This typically involves introducing a bench at a designated height, such as 25 meters, and adopting a gentler slope angle, for instance, 2V:1H (Kumar et al., 2023). These modifications help to meet safety guidelines and result in a more stable overall dump structure.

3.2.5 Overall Configuration and Footprint

Optimizing the slope geometry of mine dumps is crucial due to the limited availability of land for safely disposing of overburden geomaterials (Koner, R., 2021). In practice, the early stages of dump development often conform to the irregular forms of the existing topography (Koner, R., 2021). The primary goal in designing these dumps is to achieve the most economical solution by carefully refining the geometry to maximize storage capacity without compromising the safety of the working environment (Kumar et al., 2023). This balance ensures that both land usage and operational safety are effectively managed throughout the life of the mine.

3.2.6 Foundation and underlying material

The stability of a mine waste dump is heavily influenced by the bearing capacity and geological properties of its underlying foundation (Koner, R., 2021). Studies typically consider a multi-layered foundation that reflects the complex lithology found in opencast mining areas, such as sequences of sandstone and coal seams (Kumar et al., 2023).

Dump structures situated on flat and competent soils tend to demonstrate higher stability. However, when the foundation includes thin layers of weak or soft material, or if the ground surface is inclined, there is an increased risk of base failure or block translation (Koner, R., 2021). These risks are further intensified by the presence of high groundwater tables or seismic activity, making the careful assessment of foundation conditions a critical component in dump design and overall safety planning.

Table 6 Summary of main geometric characteristics in coal waste dumps

Slope Angle / Overall Dump Inclination	Total Dump Height	Bench Design				Embankment Construction Methods for Tailings Dams
		Bench Inclination	**Individual Bench / Rise Height**	**Bench Width**	**Number of Benches**	
46° for a typical dump (TD) in Jharkhand, India.	From 100 to 120 m to reduce spatial footprint.	3V:1H (~18.4°) in a typical dump (TD).	H1 = 50 m; H2 = H3 = H4 = 25 m (TD, Jharkhand, India).	25 m each (TD and ED, Jharkhand, India).	Multiple benches (TD); a total of five benches (ED).	Three main methods: downstream (more stable, requires more material), upstream (simpler, economical, less stable), and centerline (compromise).
37.5° for an engineered dump (ED) in Jharkhand, India; complies with DGMS 2017 guidelines stating the angle should not exceed 37.5°.	125 m (Jharkhand, India), or 130 m (TD, Jharkhand, India).	2V:1H in an engineered dump (ED).	Addition of a bench at H = 25 m (ED, Jharkhand, India).	Bench widths greater than 25 m resulted in a constant factor of safety (FoS) of 0.70. The inner part of the bench width is used to arrest falling debris, while the remaining area serves for material conveyance.		
Mainly between 35° and 45° for dumps in Spain (zones with inclination less than 35°, greater than 40°, or between 35° and 40°).			Each bench rise should not exceed 30 m (DGMS 2017 guidelines).			
A minimum slope angle of 0.8V:1H (38.66°) yielded stability (FS=1.3).						
A slope angle of 3.75V:1H (75.07°) reduced the FoS to 0.65.						

61/67

3.3 Previous experiences and lessons learned

Here, is detailed a comprehensive analysis of the geometrical and geotechnical properties of inner dumps and their critical role in terms of numerical stability modelling. The documented experiences provide foundational principles necessary for conducting further inner dump stability analysis. Two Research Fund for Coal and Steel - RFCS projects, SLOPES and RAFF, were taken as case studies to obtain practical insights for the MidSafe project. Their primary focus areas and key objectives are presented below:

The SLOPES (Smarter Lignite Open Pit Engineering Solutions) project is focused on documenting detailed datasets concerning the physical and mechanical characteristics of spoil materials in European open-pit lignite mines. The core objective was to characterize this extreme variability through statistical frameworks and provide reliable parameters for numerical simulations.

The RAFF project focused on intensive risk analysis and mitigation strategies specifically for reservoir slopes in post-mining environments. Numerical simulations were performed emphasizing the destabilizing effects of weak contact layers and the critical influence of pore pressure evolution and water level fluctuations during pit flooding. Key results emphasise the definition of corrective and protective measures, such as confirming that rapid water filling can guarantee stability, and establishing a methodology for developing a threshold-based warning system to monitor slopes during excavation and closure activities.

In previous studies have been documented modelling experience in stability waste dump analysis. Here is a summary about the main studied spoils:

- **Vršany Mine, Czech Republic**: Core samples shows that the spoils are made by a large content of fines, with clay content ranging from 40 to 60 weight percent (wt.%). Atterberg limits classified these materials as representing low and high plasticity clay.
- **Bełchatów Mine, Poland**: Superficial samples from this mine were found to be mainly sands with only occasional low clay contents. These materials were typically identified as loam and clay loam.
- **Soulou Spoil Heap, Greece**: This enormous waste embankment, approximately 5 km long, 1 km wide, and up to 150 m high, presented material classification ranging from low and high plasticity clay to occasional argillaceous sand, silt, and organic clay.

The central challenge identified in these major projects is that the stratigraphy of spoil heaps is greatly variable (or even nearly chaotic), making an explicit distinction among different stratigraphic layers practically impossible.

Given the chaotic nature of the spoil materials, deterministic modelling based on average properties is inadequate. Experience dictates that numerical calculations must integrate probabilistic principles and analysis methods to accurately incorporate geotechnical uncertainty.

3.3.1 The Uniform Spoil Scenario

To manage this uncertainty, one effective approach, demonstrated using data from the Soulou Spoil Heap, is to treat the spoil as a uniform material. This approach yields statistical insights critical for back analysis:

Geotechnical Property	Mean	COV (Coefficient of Variation)
Effective Cohesion (KPa)	21.9	1.01
Effective Friction Angle (°)	22.2	0.27
Permeability (m/s)	3.24E-09	0.98

The COV for effective cohesion at 1.01 is notably high, exceeding the typical literature range of 0.1–0.6, highlighting the extreme variability of cohesion in this material.

A crucial experience derived from the statistical process on the uniform spoil material (Soulou) is the existence of a high negative cross-correlation between the effective shear strength components (effective cohesion and effective friction angle). The linear correlation coefficient was found to be -0.8. This high negative correlation must be utilized in reliability calculations. Neglecting it may lead to unrealistic and conservative estimations of geotechnical safety risk.

3.3.2 Geometrical and Stratigraphic Factors in Stability Assessment

Numerical models show that stability is highly sensitive to slope geometry and the presence of localized weak zones. The geometry of the inner dump slope directly affects the Safety Factor (SF). Here, some results obtained from modelling scenarios:

- Slope Angle: An increase of just 2° in the slope's inclination can decrease the SF by 8% to 14%.
- Slope Height: Decreasing the overall slope height from 200m to 100m was shown to increase the SF by 12% to 20% in numerical models.
- Bench Configuration: The effect of benches on overall stability is often marginal; ignoring benches in simulations results in a marginally lower SF, providing conservative results (the difference in SF does not exceed 11% in analysed configurations).

3.3.3 The Risk of the Weak Zone Hypothesis

The presence of weaker layers in the analysed complex is a critical geotechnical risk. A common instability hypothesis involves a very weak contact layer at the bottom of the dump bodies.

The numerical models validated this risk in the RAFF project considering the clay-type weak contact: Initially the SF without a contact layer modelled was 2.2. Then, SF dropped to 1.4 when the contact layer was modelled.

For numerical back analysis of potential failure surfaces, the most critical parameters regarding stability reduction were found to be the inclination of the weak zone and the friction angle, causing SF differences of 39% and 50%, respectively, while the thickness of the weaker layer was determined to be insignificant.

The overall stability of the inner dump, unlike natural pit walls, is generally not significantly affected by the different configurations of the angle of the bedding planes of the rock mass surrounding the dump. Stability is primarily conditioned by failure events specific to the spoil material itself or its basal contact.

3.3.4 Hydrodynamic Influence and Kinetic Behaviour

Hydrogeological conditions and pore pressure variations play a key role, especially during post-mining processes.

Pore Pressure and Weak Layer Interaction

The high-water pore pressure in a clay-type weak contact layer (as in the RAFF project) can significantly worsen the stability of the dump slopes, making them liable to failures due to the low shear strength of that basal layer. The analysis revealed that the most critical surface approximated a composite slide passing through the contact layer at the base of the deposit. Increases in pore pressure generally led to a reduction in the SF.

Management of Water Filling Speed

The process of filling the pit with water has a positive impact on the stability factor of the inner dump, as the water pressure acts on the slope surface as a supporting force. However, the speed of water filling is critical. Numerical results show that rapid filling can guarantee stability, while a slower process can lead to failure incidents.

Furthermore, numerical simulations confirmed that the repetition of water level fluctuations facilitates the consolidation process in the spoil mass, leading to a higher stability factor over time.

3.4 Conclusions

- Probabilistic Approach: Adopting probabilistic concepts is essential to incorporate and express the large geotechnical uncertainty inherent in highly variable materials such as waste dump material. Utilize the statistical framework (mean, standard deviation, COV) developed for spoil materials, acknowledging that the COV for effective cohesion can be exceptionally high (e.g., 1.01).

- Correlated Shear Strength: Utilize the high negative correlation (ρ=-0.8) between effective cohesion and effective friction angle into geotechnical reliability calculations to ensure accurate risk estimation. Neglecting this relationship may lead to unrealistic and conservative estimations of geotechnical safety risk.
- Weak Zone Simulation: The presence of a weak basal contact layer is a critical factor leading to potential major instabilities. The inclination and friction angle of this weak zone are the most influential parameters. It's recommended to model the potential for a basal weak layer, recognizing its profound impact on SF reducing it from 2.2 to 1.4, as seen in the RAFF project. Focus the calibration on the inclination and friction angle of this layer.
- Hydrodynamic Simulation: Monitoring and controlling the evolution of the pore pressure parameter during excavation or dumping activities is fundamental for establishing control and warning thresholds. Employ coupled flow-deformation analyses to evaluate the effects of rapid water level fluctuations, drawdown, and filling rates, ensuring the pore pressure response within the heterogeneous spoil material is accurately captured.
- Coal mine spoils present considerable geotechnical and landslide risks due to their pronounced heterogeneity, variability in composition and particle size, and often non-engineered, steep geometries. Key geotechnical properties, such as low and variable shear strength, high water content, reduced permeability, and unpredictable rheological behaviour, contribute to instability and the potential for flow failures or liquefaction, especially under dynamic loading or poor drainage conditions.

4 References

- Adamczyk, J. (2012). Basic geotechnical properties of mining and processing waste a state-of-the-art analysis. AGH Journal of Mining and Geoengineering, 36(2), 31-42.
- Agarwal, V. K. (2009). Geotechnical investigation of coal mine refuse for backfilling in mines. National Institute of Technology Rourkela.
- Apostu, I.M. (2019) Research on geotechnical risks in conditions of flooding of remaining voids of lignite open pits (in Romanian), Doctoral Thesis, University of Petrosani.
- Apostu I.M, Lazăr M., Faur F. (2020) Analysis of liquefaction risk of sterile material in the inner dump of North Pesteana quarry in the conditions of flooding of the remaining gap, 9th Edition of the International Symposium on Occupational Health and Safety – SESAM 2019, MATEC Web of Conferences, Vol. 305, no. 00005. https://www.matec-conferences.org/articles/matecconf/abs/2020/01/matecconf_sesam20_00005/matecconf_sesam20_00005.html
- Apostu I.M, Lazăr M., Faur F. (2021) Assessing the suffosion risk for the final in-situ slopes of the North Pesteana open-pit, Mining Revue, Vol. 27, Issue 1, pp. 24-33, ISSN-L 1220-2053/ISSN 2247-8590, Sciendo. DOI: 10.2478/minrv-2021-0003. https://issuu.com/revmin/docs/nr1ro2021, https://www.sciendo.com/issue/MINRV/27/1
- Apostu I.M, Lazăr M., Faur F., Traistă E. (2024) An overview of sustainable mining practices for ecological rehabilitation of degraded lands in the Rovinari Mining Basin. Case study: North Peșteana interior dump, Inżynieria Mineralna (Mineral Engineering) - Journal of the Polish Mineral Engineering Society, ISSN: 1640-4920, Vol. 2, No 1/2024, pp. 235–245, https://doi.org/10.29227/IM-2024-01-114, Krakow, Poland, WOS:001318657100028, IDS Number: G7V0V, https://inzynieriamineralna.com.pl/index.php/testowe/article/view/608
- Apostu I.M, Lazăr M., Faur F. (2025) Restoring soil fertility on degraded mining lands. A case study from Romania, Lambert Academic Publisher, ISBN 978-620-9-20643-6, 120 pag.
- Bajcar, A. (2021). WPŁYW WYBRANYCH WARUNKÓW ATMOSFERYCZNYCH NA STATECZNOŚĆ ZBOCZY WYROBISK POEKSPLOATACYJNYCH KOPALŃ WĘGLA BRUNATNEGO WYPEŁNIANYCH WODĄ. Górnictwo Odkrywkowe. https://www.igo.wroc.pl/wp-content/uploads/2021/12/GO_02_2021_3_12_14.pdf
- Bajcar, A. (2022). THE INFLUENCE OF SELECTED WEATHER CONDITIONS ON THE SAFETY OF SLOPES OF POST EXPLOITATION LIGNITE PITS FILLING WITH WATER. Górnictwo Odkrywkowe. https://www.igo.wroc.pl/wp-content/uploads/2023/01/GO_04_2022_5_30_32.pdf
- Bajcar, A., Szczepiński, J., & Rogosz, B. (2022). Bathymetry Surveys of Post-Mining Pit Lakes Formed after Exploitation of Lignite. Materials Proceedings, 5(1), 117. https://doi.org/10.3390/materproc2021005117
- Bajcar, A., Szczepiński, J., Rogosz, B., Resak, M., & Piróg, K. (2020). Lubstów Open-Pit. In Post Exploitation Lakes. Risk Assessment of Final Pits During Flooding (RAFF). Zpravodaj hnědé uhlí.
- Documentation CEO, 2022 – 2025.
- Faur F., Lazăr M., Apostu I.M., Brujan (Predoiu) M. (2023) Verifying the Stability of the Working Fronts of Lignite Open Pits Developed in Hilly Areas — A Case Study of Jilț North Open Pit (Romania), Applied Sciences 2023, Vol. 13 (20), Art. No. 11480, 23 p. WOS:001099657800001, IDS Number: X6PV3 https://www.mdpi.com/2076-3417/13/20/11480, https://doi.org/10.3390/app132011480
- Fityus, S., Hancock, G., & Wells, T. (2008). Geotechnical characteristics of coal mine spoil. Australian Geomechanics Journal, 43(3), 13-22.
- Koner, R. (2021). Estimation of the optimum geometric configuration of mine dumps in Wardha valley coalfields: a case study. Journal of Mining and Environment (JME), 12(4), 907–927.

- Kumar, A., Das, S. K., Nainegali, L., Raviteja, K. V. N. S., & Reddy, K. R. (2023). Probabilistic Slope Stability Analysis of Coal Mine Waste Rock Dump. Geotechnical and Geological Engineering, 41(7), 2969-2986.
- Sánchez et al. (2010). Geotechnical characterization and stability study of coal mine dumps. Paper presented at the 6th International Congress on Environmental Geotechnics, New Delhi, India (pp. 445-450).
- Thiruchittampalam, S., Banerjee, B. P., Glenn, N. F., & Raval, S. (2024). Geotechnical characterisation of coal spoil piles using high-resolution optical and multispectral data: A machine learning approach. Engineering Geology, 329, 107406.
- Yu, H. (2015). Geotechnical properties and flow behaviour of coal refuse under static and impact loading (Doctoral dissertation, Case Western Reserve University).