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Serviceability Assessment of a Mining Waste Dump for Photovoltaic Power Plant Installation

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Abstract

This study evaluates the suitability of an open-pit mining waste dump for the installation of a photovoltaic (PV) power plant, with emphasis on the serviceability limit state (SLS). A comprehensive geotechnical investigation, including field testing, laboratory analysis, and numerical modelling, was conducted to assess deformation behaviour and material properties under PV loading conditions and leaching effects.

The results indicate that global stability is generally satisfactory under static conditions but becomes critical under seismic loading. Finite element modelling shows that the ground is prone to non-uniform (differential) settlements. Ongoing chemical and physical degradation in the near-surface zone, driven by leaching and environmental exposure, continuously alters the granulometric composition and reduces strength and deformability. These processes are expected to persist even after cessation of active leaching. Differential settlements cannot be precisely localized; however, geodetic monitoring and numerical results indicate that the highest values are expected along the margins of the dump benches.

Design recommendations include slope reduction, full surface reclamation, and measures to prevent further oxidation and infiltration processes. Proper design of surface and leachate drainage systems is also essential. The study demonstrates that, with appropriate geotechnical assessment and mitigation measures, mine waste dumps can be successfully repurposed for photovoltaic energy production.

Keywords

Differential Settlements, Mining Waste Dump, PV power plant, Slope Stability.

1 Introduction

The aim of this paper is to examine and present a potential repurposing of a mine waste dump, covering an area of approximately 40 hectares, for the installation of a photovoltaic power plant instead of conventional site reclamation.

The construction of the waste dump began in 1979. Over an extended period, blasted waste rock of varying lithological composition and deposition intensity was placed, resulting in an embankment structure composed of coarse rockfill material. The dump currently reaches heights exceeding 120 m in some areas, with slope angles ranging between 33° and 36°. These characteristics require a rigorous geotechnical approach for any further assessment related to the construction of engineering structures on the site. This is also the first case in North Macedonia where detailed geotechnical analyses have been carried out for the potential reuse of a waste rock dump for alternative purposes.

In addition to the classical factors considered in design, interpretation of results, and operational assessment, an additional critical factor in this case is the induced leaching process, which was active from 2013 until the end of 2022. This process is expected to remain partially active over a longer period and may affect bearing capacity and potentially induce future settlements. An illustration of the expected internal condition of the dump is shown in Figure 1.

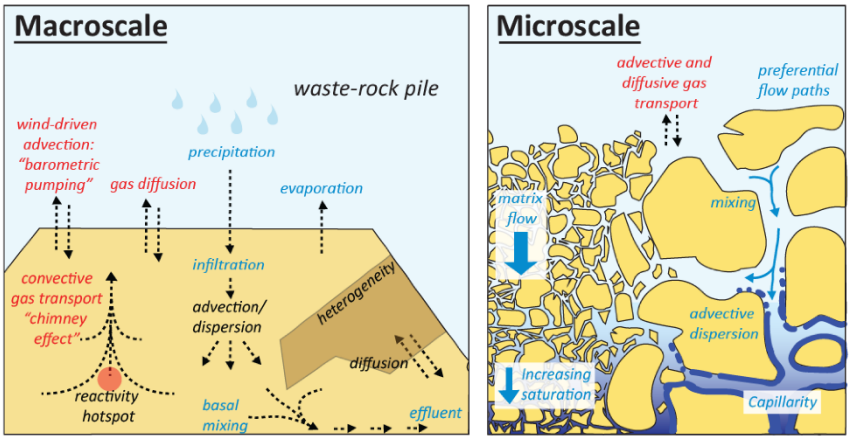


Fig. 1 Schematic illustration of relevant aqueous (blue) and gaseous (red) mass transport processes in waste-rock piles, distinguishing between macroscale (a) and porescale or microscale (b) processes. (Vriens et al. 2020).

Valenzuela et al. (2008) reported that the mechanical and hydraulic properties of waste rock dumps evolve over time as a result of particle crushing, increasing lithostatic stresses, and weathering processes associated with leaching. These mechanisms may lead to a reduction in shear strength, changes in permeability and porosity, and an increase in the proportion of fine particles. Consequently, drainage obstruction, elevated saturation levels, and, under unfavourable conditions, static liquefaction may occur. The authors emphasize the importance of long-term monitoring of groundwater conditions and effective surface water management to ensure the stability and environmental safety of waste rock facilities.

Zavodni et al. (1984) highlighted that significant long-term settlements can develop in high waste rock dumps due to self-weight consolidation and particle rearrangement. Settlements were observed to be non-uniform, typically concentrated in specific zones, particularly near the outer slopes, and may continue for several years after dump construction.

Tincopa et al. (2015) emphasized the importance of coupled hydro-mechanical-chemical processes in heap leach facilities, where geochemical reactions may alter porosity and permeability, thereby influencing both hydraulic and geotechnical behaviour. Their numerical simulations indicated that leaching can increase porosity by approximately 4% in a 50 m high heap; however, this effect may be partially offset by mechanical compaction and particle rearrangement.

An IGF case study from Kimberley, British Columbia, Canada, demonstrates the potential for repurposing reclaimed mine waste facilities for renewable energy production. Following reclamation activities carried out between 2003 and 2010, feasibility studies conducted from 2011 to 2014 supported the development of a 1.05 MW photovoltaic plant, which was subsequently commissioned in 2015. The project highlighted challenges related to heterogeneous dump composition and complex

surface topography, emphasizing the need for site-specific geotechnical investigations when implementing photovoltaic systems on reclaimed mine lands.

Sowers et al. (1965) proposed a method for predicting long-term settlement in rockfill deposits. In the analysed case, a 3.1 m thick reclamation layer was considered on the surface of a 90 m high waste dump. Post-closure settlements were divided into creep-induced deformations and settlements due to collapse upon saturation; the latter was not expected for the Bucim mine dump. Creep settlements were estimated to account for only 1.4% of the total deformation. The study suggests that appropriate modelling of the final embankment geometry represents the most cost-effective approach to reducing long-term settlements. The total predicted settlement was 6.5 m, expected to occur within the first 10 years after closure, with the largest deformations concentrated in the central part of the dump, which differs from observations reported in other studies.

The Best Available Techniques (BAT) Reference Document for the Management of Waste from Extractive Industries (EU JRC, 2018) emphasizes that monitoring of settlement and stability is a fundamental component of both operational and post-closure management of waste facilities. It further notes that most sites considered for renewable energy redevelopment (e.g., photovoltaic installations) have undergone appropriate reclamation to reduce environmental risks and mitigate differential settlements. Monitoring is typically conducted on a monthly or quarterly basis and includes instruments such as inclinometers, settlement plates, vibrating-wire piezometers, geodetic benchmarks, and accelerometers. Geotechnical characterization is carried out through regular inspections and testing annually during operation and every two years after closure, while external audits are commonly performed every ten years. In cases where differential settlements are expected, the use of geosynthetic clay liners (GCL) is recommended for reclamation. The document also outlines additional requirements aligned with European regulatory frameworks and best engineering practices.

2 Site Characteristics

For the purpose of accurate design and proper characterization of the site materials, extensive geotechnical investigations were carried out in order to define the geomorphological, engineering-geological, hydrogeological, seismotectonic, and geotechnical conditions of the area. These investigations included both field and laboratory testing aimed at determining:

- the compressibility of the near-surface material, which has been (or was) most intensively affected by the leaching process. The compressibility modulus was determined using a light drop-weight tester for dynamic plate load testing, in accordance with standard MKTS 1012:2015;

- the bulk density of the fine fraction using the standard sand-cone method (MKS 1004:2013). This test was performed in order to assess the effects of leaching on the waste rock dump and the variability in fine particle content within the deposited rock mass. Specifically, the rock mass (dumped blocks of gneiss and andesite) is subjected to chemical and physical degradation during the leaching process, resulting in the formation of finer material, ranging from sand-sized particles to silt and dust. This material is present in varying quantities throughout the investigated depth in the excavations and was also identified during geological exploratory drilling;

- the lithological and geotechnical properties of the subsurface materials, based on 12 trial pits excavated to a depth of 3.0 m;

- the physical-mechanical and strength properties of the materials, obtained through laboratory testing of a representative number of intact rock samples.

The foundation of the waste dump consists of fine-grained biotite gneiss (Gmb), commonly hydrothermally altered and locally fractured at the surface, with variable strength characteristics. In certain areas, andesites (α) are also present, occurring in complex structural relationships with the gneissic formations.

The dump is composed of anthropogenic fill materials (N) representing mine waste, consisting of blasted blocks and fragments of gneiss and andesite. These rock fragments are relatively homogeneous in terms of lithological classification; however, they exhibit significant variability in alteration

processes, with silicification, feldspathization, and kaolinization being the most dominant. Over time, the dump has been subjected to natural consolidation processes, further enhanced by continuous dumping operations. The movement of heavy mining equipment (up to 170 t) has contributed to additional compaction and mechanical fragmentation of the material.



Fig. 2 Investigation points and field tests.

As a result, coarse-grained fractions dominate, with block sizes exceeding 1.0 m in diameter, while finer fractions ranging from 10 to 15 cm are more common in the internal parts of the dump. This indicates a highly heterogeneous grain size distribution. The heterogeneity is further increased due to uncontrolled dumping in different zones.

A major factor contributing to the increasing heterogeneity, not only in the central part but also along the slopes, is the leaching process using dilute sulfuric acid, applied for the recovery of additional copper from the dumped material. This process leads to chemical and physical degradation of the near-surface zone of the dump, with effects observed down to the maximum investigated depth in this study (locally exceeding 3.0 m). It is expected that these processes extend to significantly greater depths depending on local porosity and permeability conditions within the dump body. Geological boreholes have indicated that the zone of degradation locally extends up to 8.0 m, while isolated degraded zones have also been identified at greater depths.

During degradation, the extent of chemical and associated physical breakdown varies depending on the local mineralogical composition of the material. In some areas, complete degradation to sand- and silt-sized particles is observed, while in others the alteration is minimal or negligible. All of the above observations indicate that the waste dump is characterized by highly variable physical-mechanical and stress–strain properties across different spatial and depth intervals within the investigated area.

In terms of hydrogeological conditions, the majority of the waste dump is considered to function as a highly permeable collector, acting as a conduit for infiltration water (both atmospheric precipitation and leaching solutions) toward the lower horizons within the dump body. Based on the loosening coefficient, mapping of test pits in the near-surface zone, and mapping of final slopes, the porosity of the dump material is assessed as highly variable both spatially and temporally (primarily due to leaching effects), ranging from a few percent up to approximately 30% in certain zones. This variability is expected for such materials, despite previous compaction and reworking during dumping operations.

Surface precipitation is rapidly drained and transmitted through the dump mass, a behaviour that also applies to the leaching solution used in previous operational periods.

From a material classification perspective, according to the Unified Soil Classification System (USCS), the dumped material is classified as GP–GM. Based on the grain size distribution, the material consists of approximately 50–60% coarse fractions (blasted and dumped blocks of andesite and gneiss with diameters exceeding 50 cm), 40–50% intermediate fragments with sizes of 10–20 cm, and 5–10% sand and silt fractions, particularly in the near-surface zone. These proportions vary significantly across the site; locally, the 10–20 cm fraction may dominate, with coarser material

prevailing near the dumping front, while finer sand- and silt-sized particles are more prevalent in the central parts of the dump.

The experimentally determined material properties from both laboratory and field investigations are presented in the following table.

Table 1. Basic Physical and Mechanical Parameters of Intact Rock Samples.

Material	**Density γ [kN/m^3]**	**Point Load Strength Index Js(50) [MPa]**	**UCS σp=22*Js(50) [MPa]**	**Tensile Strength σz=1.5*Js(50) [MPa]**
Gneiss(Gmb)	24.17-25.7	1.96-6.18	43.03-98.76	2.93-9.27

Table 2. Results of field investigations of the embankment.

Material	**Density γ [kN/m^3]**	**Ev$_d$ [MN/m^2]**
Embankment N	4.09-78.95	15.26-24.93

The results indicate a material with variable compressibility characteristics and spatially varying bulk density across different zones of the site, clearly reflecting the heterogeneity of numerous geotechnical parameters. This heterogeneity ultimately leads to significant variations in compressibility and deformability.

Overall, the presented findings highlight the complex internal structure of the waste dump from lithological, engineering-geological, geochemical, and hydrogeological perspectives. This complexity is directly reflected in the geotechnical behaviour of the site in both the medium and long term.

3 Measurements and Monitoring

As part of the continuous monitoring program, geodetic measurements of vertical displacements (settlements) of the waste dump have been conducted. The following figure presents the vertical displacements [cm] recorded over the period 2013–2022.

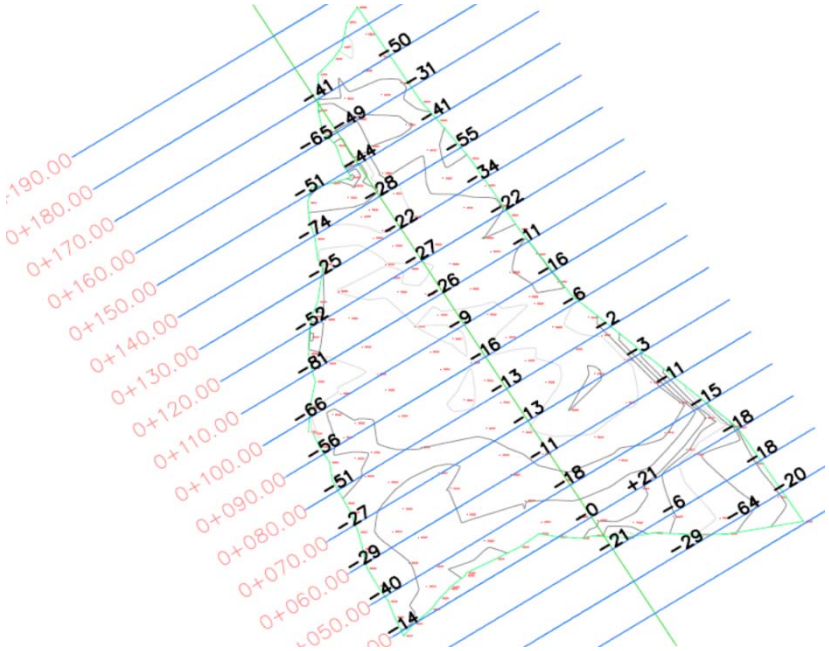


Fig. 3Vertical Displacements (cm) of a Section of the Waste Dump during the Monitoring Period 2013–2022.

In the dumping front zone, a process of natural settlement and material stabilization is observed. These settlements reach values of up to 80 cm, and in some areas are likely even higher. Variable settlement magnitudes are also recorded in the central part of the analyzed bench, again exhibiting a non-uniform pattern of natural deformation.

4 Stress–Strain Analysis

Considering all previously presented findings, as well as the limitations in the availability of monitoring data (geodetic, hydrogeological, and geotechnical), and the current use of the waste dump for leaching operations, together with the planned installation of a photovoltaic power plant, it became necessary to perform stress–strain (stress–deformation) analyses. For this purpose, an assessment of the relevant parameters required for numerical modelling was carried out.

For the shear strength of the embankment material, the empirical Barton–Kjaernsli (1981) criterion was also applied, which is a widely accepted approach for estimating the shear strength of rockfill materials. According to this method, shear strength is primarily governed by the granulometric composition of the dump material, the uniaxial compressive strength of intact rock, the void ratio (porosity) of the rockfill, the roughness of the rock blocks, and the basic friction angle. This approach provides a practical framework for evaluating the mechanical behaviour of coarse granular and blasted rock materials used in waste dumps and embankments. Table 2 presents the adopted parameters used in the analysis.

Table 3. Results of field investigations of the embankment.

Parameter	**Model Colour**	**Density γ [kN/m^3]**	**e_0 [/]**	**φ [°]**	**c [kPa]**	**E [MPa]**	**ν [/]**
Embankment N		20	0.33	37	0	20-40	0.28
Degraded N		20	0.33	32	0	10	0.30
Bedrock		23	/	/	/	30000	0.23

The stability condition of the waste dump was modelled using the finite element software package PLAXIS. A two-dimensional plane strain analysis was performed, in which the embankment body was simulated using the Mohr–Coulomb failure criterion, while the underlying bedrock was represented by a linear elastic model.

The analysis of the representative dump profile was carried out in stages reflecting both the in-situ conditions and the anticipated material degradation due to the leaching process:

Phase 1: Initial stress and deformation state;

Phase 2: Consolidation analysis of stresses and deformations over a period of 365 days;

Phase 3: Consolidation analysis over 365 days, incorporating simulated degraded layers resulting from the leaching process;

Phase 4: Pseudo-static analysis

The geometry of the numerical model is shown in Figure 11. According to recent geological drilling activities carried out at the waste dump during the preparation of this analysis, it was observed that the near-surface layer of the dump, in certain zones (with thicknesses up to 8.0 m), exhibits a significant degree of degradation of the dumped rock material. Specifically, under the influence of the leaching process, chemical and physical degradation of the rock blocks occurs. Depending on their mineralogical composition, these blocks progressively break down into smaller fragments and ultimately into sand- and dust-sized particles.

In some boreholes and test pits, the proportion of this fine fraction reaches 20–30%, causing the material to locally behave more like a soil-like medium than a rockfill. This degradation phenomenon of the dump is expected and results in a time-dependent reduction of the strength and deformability parameters of the material, with effects that are anticipated to continue long after the cessation of the leaching process.

For this reason, a near-surface layer with a thickness of 8.0 m was explicitly defined in the model and assigned reduced geotechnical properties based on available data and relevant literature. Such weakened zones are present both laterally and vertically, depending on the intensity of chemical weathering, oxidation processes, and the formation of preferential groundwater flow paths carrying infiltrated water and solution.

Therefore, a separate analysis (Stage 3) was performed in which these time-dependent degradation processes were simulated. The objective was to assess whether the embankment would undergo uniform consolidation; otherwise, differential settlements could develop, potentially affecting future surface structures.

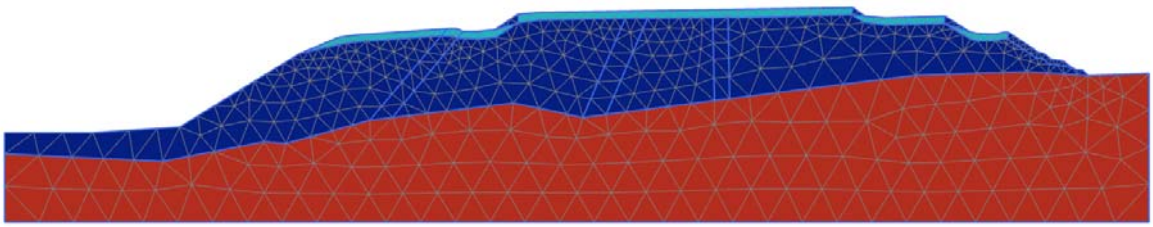


Fig. 4 Numerical Model of the Waste Dump (Current State) and Finite Element Mesh.

In the following section, the results of the analysis of the representative waste dump profile are presented. The results primarily refer to the total and vertical deformations (settlements) as well as the stress distribution across the different calculation stages..

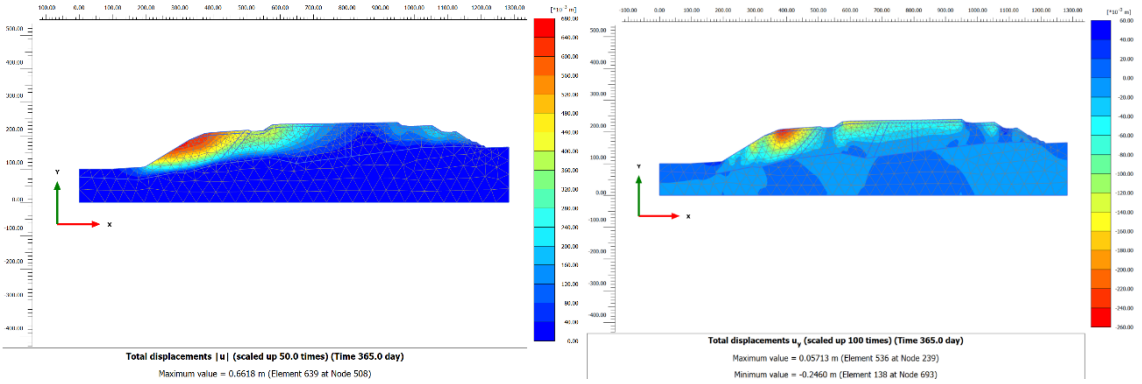


Fig. 5 Total and Vertical Deformations for Stage 2.

The maximum total deformations of the embankment amount to 66.18 cm and occur along the naturally formed dumping slope. The maximum vertical deformations reach 24.6 cm and are observed at the crest of the naturally formed slope; however, these deformations are not uniformly distributed.

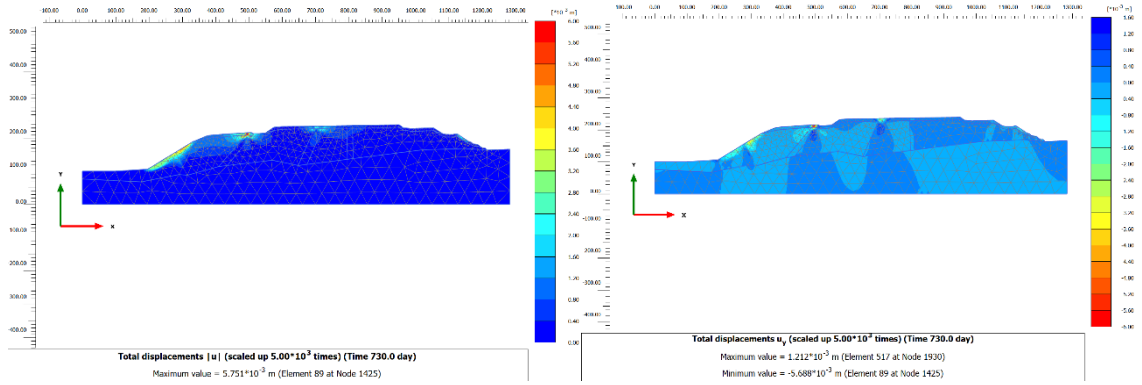


Fig. 6 Total and Vertical Deformations for Stage 3.

The maximum total deformations in the degraded zones of the embankment amount to 5.7 mm and are predominantly vertical in nature. When considering representative horizontal sections along the surface, it can be observed that differential settlements are likely to occur at the ground surface.Figure 7 presents the deformations that may occur under seismic loading conditions.From the conducted seismic analysis, it can be concluded that the maximum deformations occur along the slope, which may indicate potential instability under seismic loading conditions. In the horizontal part of the embankment, differential settlements are observed, with a maximum value of 4.59 cm.

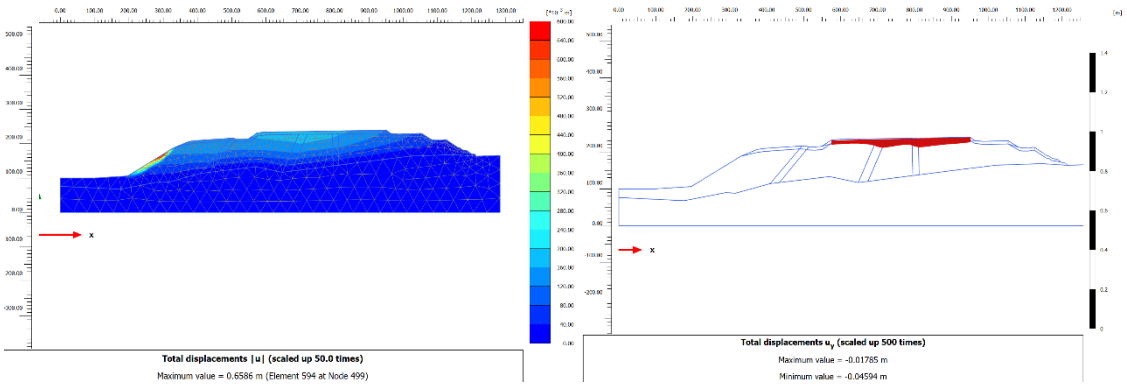


Fig. 7 Horizontal Profile of Differential Settlements for Stage 4.

In the second analysis, a reduced-scale model was developed to assess settlements within a single photovoltaic segment. A vertical weakened zone of assumed width and depth extending to the bedrock was considered. Although such a continuous zone may be unlikely under real conditions, it is introduced as a conservative assumption. This weakened zone may develop as a result of leaching processes, future water infiltration, and continued material degradation over time. The considered condition represents a worst-case scenario. The final foundation (column) of the segment is placed above this zone, while the remaining foundations are positioned at appropriate spacing according to the geometry and loading conditions imposed by the photovoltaic panels.

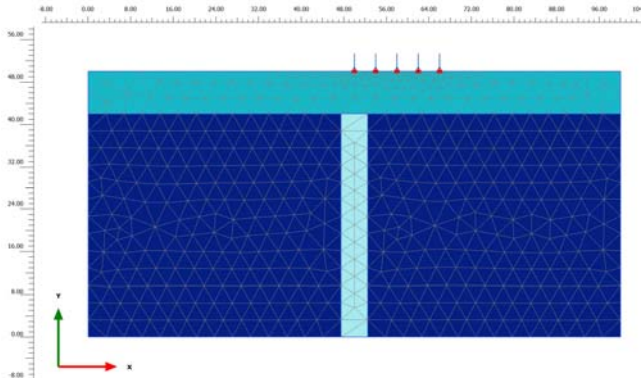


Fig. 8 Horizontal Profile of Differential Settlements for Stage 4.

The analysis was carried out in stages according to the loading conditions:

- Stage 1: Initial stress and deformation state;

- Stage 2: Consolidation analysis of stresses and deformations over a period of 365 days, including simulation of loading from photovoltaic segments and the presence of a degraded layer;

- Stage 3: Pseudo-static analysis (ax=0.2g и ay=0.1g).

The objective was to assess the potential occurrence of differential settlements between individual foundations within a single segment or between adjacent segments. In the following section, the results of the analysis for this profile are presented, focusing primarily on the vertical deformations (settlements) of the foundations.

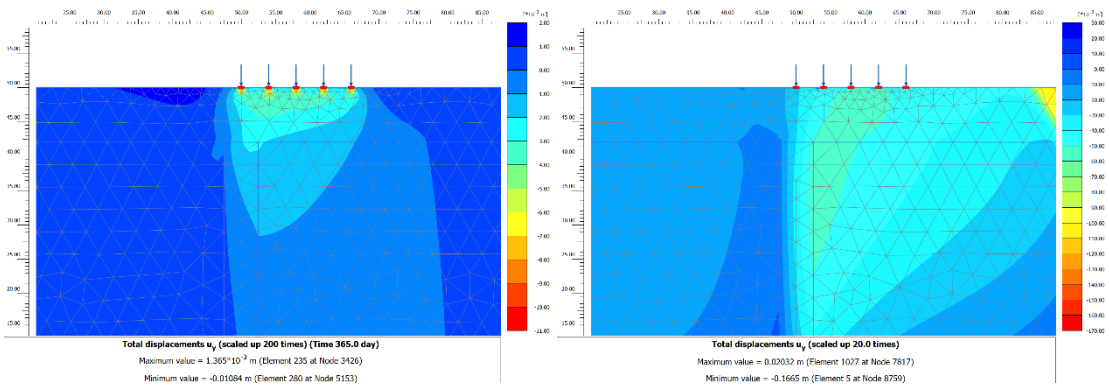


Fig. 9 Vertical Deformations for Stages 2 and 3.

The maximum settlements under static conditions amount to 1.08 cm and occur beneath the supports, while under seismic conditions they reach up to 9.0 cm. These settlements are differential when a representative horizontal section beneath the foundations is considered, as shown in the following figures, particularly under seismic loading conditions.

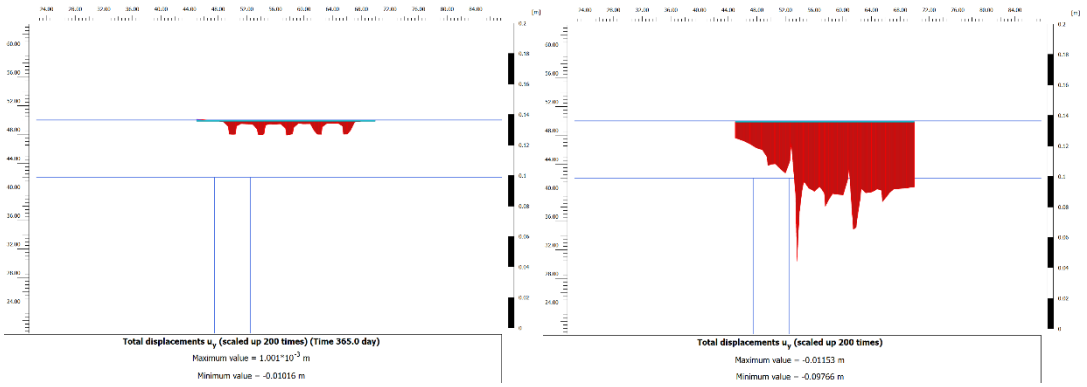


Fig. 10 Horizontal Profile of Differential Settlements for Stages 2 and 3.

5 Conclusions

The conducted study demonstrates that the investigated waste rock dump, with an area of approximately 40 hectares and heights exceeding 120 m, represents a highly heterogeneous anthropogenic geotechnical system characterized by complex mechanical, hydrogeological, and geochemical behaviour. The long-term deposition history, combined with continuous mechanical compaction and ongoing leaching processes, has resulted in significant spatial variability in material properties.

Geotechnical investigations confirmed that the dump material exhibits strongly variable compressibility, bulk density, and grain size distribution. The presence of coarse rock blocks mixed with progressively generated fine fractions due to chemical and physical degradation leads locally to soil-like behaviour, particularly in near-surface zones. The leaching process significantly contributes to this degradation, with observed effects extending to depths exceeding 8 m in certain areas.

The leaching process, in combination with atmospheric precipitation, also promotes the development of locally concentrated and spatially irregular drainage pathways within the dump body. This results in a highly non-uniform internal hydraulic regime. Consequently, porosity locally reaches values of up to 30%, creating zones of highly permeable material that are particularly susceptible to differential settlements. Conversely, in areas where leaching intensity was lower or reactions with the rock mass were less pronounced—especially along former haul roads and inter-bench ramps—the material is significantly more compacted due to repeated mechanical loading, fragmentation, and long-term trafficking of heavy mining equipment.

It is further emphasized that leaching processes have fundamentally altered the physical and mechanical properties of the waste rock dump, and these processes are expected to continue in the future, regardless of whether they occur naturally or are induced. Therefore, the near-surface zone of the dump should be treated in a manner that mitigates further degradation processes and contributes to homogenization of its deformation characteristics to the extent possible.

Hydrogeologically, the waste dump behaves as a highly permeable medium acting as a drainage body for both precipitation and leaching fluids. High spatial variability in porosity and permeability indicates non-uniform internal hydraulic conditions, which may influence long-term stability and settlement development.

Numerical modelling using the finite element method (PLAXIS) indicates that the waste dump is prone to significant deformations, with total settlements reaching up to 66 cm under static conditions and increasing further under seismic loading. The results also show pronounced differential settlements, particularly in zones affected by material degradation and along the naturally formed slopes.

The introduction of photovoltaic infrastructure further highlights the importance of assessing serviceability limit state (SLS) criteria. The analysis of a reduced-scale model with degraded zones demonstrates that differential settlements may occur at foundation level, reaching values of up to 9 cm under seismic conditions, which may be critical for structural performance depending on tolerance limits of the supporting system.

Overall, the results indicate that the stability and deformation behaviour of the waste dump is strongly time-dependent, hydraulically non-uniform, and spatially heterogeneous. Consequently, any future use of the site particularly for structural applications such as photovoltaic installations requires detailed geotechnical assessment, conservative design assumptions, surface treatment measures, and continuous monitoring to ensure long-term performance and safety..

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