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Assessment of the impact of vertical drainage system on dump stability

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ABSTRACT: Mine waste dumps are among the largest earth structures, often covering hundreds of hectares and remaining operational for decades. Their staged construction over cohesive, low-permeability soils generates excess pore pressures that strongly influence stability. Prefabricated vertical drains (PVDs) are an effective solution, accelerating pore pressure dissipation by providing thousands of drainage strips. Despite their efficiency in practice, modeling the influence of drains on stability remains challenging. Explicit representation of thousands of drains is computationally infeasible in large-scale simulations. To overcome this, homogenization techniques can be applied, replacing the heterogenous system of drains and soil with an equivalent continuum characterized by calibrated hydraulic properties. This study presents a novel homogenization-based framework for evaluating dump stability with use of real data collected from one lignite mine in Poland. The methodology combines monitoring data, laboratory tests, and advanced 2D/3D numerical modeling. Drains in model were represented by equivalent seepage elements with calibrated drainage capacity, enabling realistic reproduction of pore pressure dissipation without explicit drain modeling. The results show that PVDs significantly improve both global and local stability, with the greatest gains achieved when drains are installed in the foundation level of the dump. The proposed approach provides not only a reliable assessment tool but also a practical design method, allowing optimization of slope geometry and construction schedules while ensuring safe operation. This work demonstrate homogenization-based modeling of vertical drains in anthropogenic dump soils, highlighting its strong potential for large-scale geotechnical applications.

KEYWORDS: dump stability, prefabricated vertical drains, homogenization theory, large-scale geotechnical simulation,

1 INTRODUCTION

Overburden dumps are among the largest human-made earth structures, both in terms of volume and surface area. Classified as large-scale geotechnical systems, they often extend over hundreds of hectares. They are a crucial component of the mineral extraction process, particularly in open-pit mining, where uninterrupted operation requires continuous disposal of vast amounts of overburden. Such structures are long-term in nature, remaining in service for decades to secure stable mining operations. A characteristic example of these facilities are overburden dumps associated with lignite mines, especially common in Central Europe, where extensive coal deposits are exploited. Open-pit extraction necessitates the removal of large soil and rock masses that must subsequently be deposited, forming layered dumps. Typically, the material is placed in successive level: once a level is constructed, it is left to consolidate before the next layer is placed.

As with all large earth structures, the stability of overburden dumps must be assessed. Slope inclinations and overall geometry are designed to maintain required factory of safety (FOS). However, this task is complicated by the specific nature of dump material. Unlike natural soils, anthropogenic dump soils are strongly influenced by excavation, transportation, deposition, and possible mixing with by-products such as power-plant ash. These processes rebuild the natural structure and make mechanical and hydraulic parameters difficult to estimate. The uncertainty in soil behaviour poses a major challenge for stability analysis in such structure (Bagińska et. al, 2020).

When dumps are formed mainly of well-grained soils and groundwater conditions are favourable, consolidation process realize relatively quickly and stability analyses can be simplified. However, in cases involving fine-grained soils and high groundwater levels, the rate of consolidation becomes a key parameter. Excess pore water pressures may remain for long periods, reducing effective stresses and thus threatening overall stability.

To address these risks, well-managed dumps are equipped with dense monitoring networks, including benchmarks for displacement control, piezometers for pore pressure measurement, and observation wells for groundwater monitoring. Such systems enable the application of the observational method recommended by Eurocode 7, ensuring that consolidation progresses at a satisfactory rate (Bąk & Bagińska, 2022). Nonetheless, from both an operational and safety perspective, it is advantageous to accelerate pore pressure dissipation wherever possible.

Nonetheless, even with extensive monitoring, purely observational control is not sufficient. From both an operational and safety perspective, it is advantageous to accelerate the consolidation process and increase the rate of dissipation of excess pore pressures. Technological interventions are thus often employed. Among the most widely used methods are relief wells, which provide localized vertical drainage paths to dissipate pore pressures in specific zones (Sobótka et. al, 2022). Although effective, relief wells are costly and time-consuming to install, which restricts their use to relatively small areas.

As a large-scale alternative, prefabricated vertical drains (PVDs) have gained attention in recent years. A PVD typically consists of a slender synthetic strip, only a few centimetres wide, wrapped in a geotextile filter (Yildiz, 2009). These drains are installed in dense grid patterns, commonly at spacings of 1.0 to 5.0 meters, within low-permeability soils. Their function is to provide short drainage paths for pore water, channelling it into an overlying drainage layer composed of coarse-grained, highly permeable material. As new level of the dump are constructed, pore water pressures generated in the underlying soils are quickly transferred to the PVDs, which then discharge the water into the drainage layer. Provided that the drainage layer has adequate gradients, water is removed efficiently, preventing its accumulation. The overall effect is a significant acceleration of consolidation and a corresponding increase in effective stresses, which in turn improves slope stability. A schematic representation of a PVD system installed in a dump is shown in Figure 1.

The aim of this study is to evaluate the influence of vertical drainage systems on the stability of overburden dumps, with a particular focus on prefabricated vertical drains. The analysis is based on real field measurements from one of the lignite mining dumps in Poland. Numerical modeling was carried out using a homogenization-based approach, as proposed in Rainer et al. (2025, in press). This method enables efficient and computationally feasible simulation of dense drainage networks in large-scale geotechnical structures, while preserving the essential consolidation behaviour.

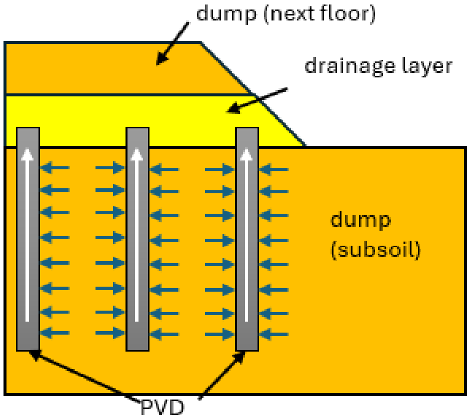

Figure 1. A schematic representation of a PVD system installed in dump

The scope of the paper includes both global and local stability considerations. Two-dimensional analyses were performed to assess the overall stability of the dump, expressed in terms of the global factor of safety. In addition, three-dimensional analyses were conducted to investigate potential local instabilities, such as slope failures within individual sectors of the dump characterized by complex geometry. Subsequent sections present the geotechnical background of anthropogenic soils, details of the numerical model, and the application of the homogenization approach to vertical drainage simulation. The paper concludes with the results of the stability analyses and practical implications for dump management.

2 MATERIAL AND METHODS

To assess the impact of PVDs systems on dump stability, several challenges must be solved to ensure that numerical simulations accurately reflect real conditions. These challenges, which are subsequently discussed in the following subsections, can be summarized as follows:

1) Determination of hydraulic parameters of dump

Reliable characterization of the permeability and consolidation properties of dump soils is essential for reproducing the correct rate of pore pressure dissipation.

2) Dump geometry modelling

In three-dimensional analyses, the geometry of the dump is highly complex due to its staged construction process. The structure grows incrementally in height and area over time, and the modeling framework must capture this temporal evolution

3) Modelling of PVDs system covering large area

PVDs systems installed in dumps often consist of thousands of drains. Representing each individual element explicitly in a finite element model would be computationally infeasible. Therefore, it is necessary to adopt modelling techniques that preserve the hydraulic effect of the drains while maintaining a computationally effective geometry.

2.1 *Determination of hydraulic parameters of dump*

In natural soils, the assessment of hydraulic conductivity is typically realized using standard laboratory test such in oedometer or triaxial apparatus. These well-established methods provide reliable values of permeability and consolidation characteristics under controlled conditions. However, dump soils represent a much more complex material. Their properties are strongly influenced by the processes of excavation, transport and deposition. Even when formed predominantly from fine-grained soils, dump material may exhibit filtration behaviour similar to well-grained soils, particularly in the initial stages of deposition. This phenomena occurs when dump material formed a coarse inclusion or agglomerates, giving an additional paths to water flow.

For this reason, field measurements of pore water pressures provide a more robust basis for parameter estimation (Bąk, 2022). Monitoring data allow direct observation of dissipation trends, making it possible to account for large-scale effects such as heterogeneity, fracture networks, and macro-scale flow paths. By calibrating numerical models against observed pore pressure dissipation, it is possible to more faithfully reproduce the real consolidation process. When the subsoil beneath the dump consists entirely of impermeable or very low-permeability soils, the dissipation of pore pressures can be approximated as a one-dimensional process. In this case, excess pore pressure u is expressed as a function of depth and time, i.e., $u(h,t)$, where h is depth and t is time. Such a process can be modeled using a simple one-dimensional formulation in which all lateral and bottom boundaries are impermeable, while the top boundary is defined as a drainage surface with zero pore pressure ($u = 0$). At this boundary, an additional surface load is applied to simulate the stress from newly deposited material, which in turn generates the initial excess pore pressures within the soil profile. An example view of the model used for calibration is shown in Figure 2.

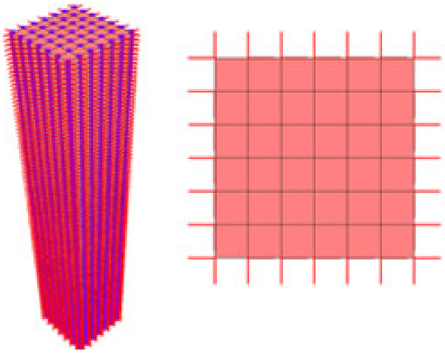

Figure 2. Model for 1D consolidation calibration – 3D and top view

The accuracy of calibration improves significantly when multiple sensors are installed within a single vertical profile. In such cases, model predictions can be simultaneously fitted to several measured values, thereby improving the robustness of the calibrated parameter. Calibration is performed by adjusting the soil permeability coefficient k until the best fit between observed and simulated pore pressures is achieved. For the purpose of calibration, even a simplified numerical model consisting of a single element in plan view (discretized only along the vertical direction) may be sufficient.

Figure 3 shows the error function, expressed as the mean squared error between the numerical and observed values. A distinct minimum is visible, clearly indicating the best-fit value of permeability k.

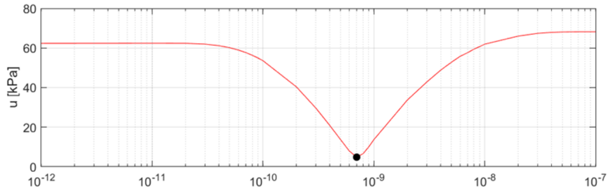

Figure 3. Error function indicating best-fit o k value

Figure 4 presents an example of such calibration results, where the numerical model output (red continuous line) is compared with field measurements (black dots) from two sensors located in one profile at depths of 11 m and 17 m, respectively. The discrepancy between the simulation and monitoring data is small, indicating that the model reproduces the dissipation process with high accuracy.

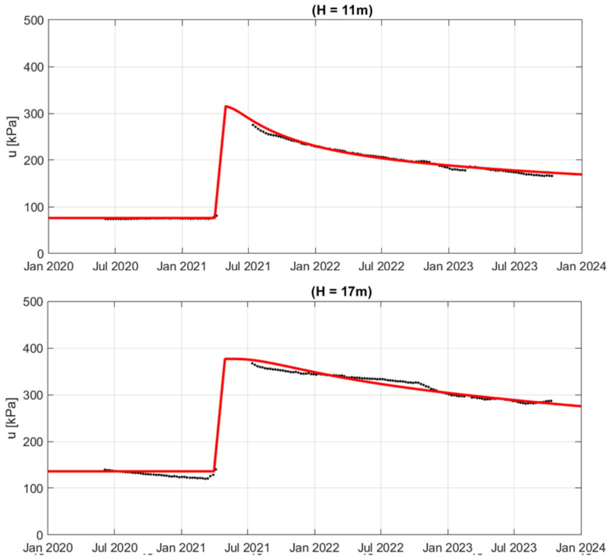

Figure 4. Comparison between numerical calibration results (red line) and field pore pressure measurements (black dots) for sensors installed at depths of 11 m and 17 m in one profile.

The calibration procedure was carried out using data from six pore pressure sensors in total. The resulting range of calibrated hydraulic conductivity values was $k \in \langle 3\times10^{-10}, 1\times10^{-9} \rangle$ m/s. For comparison, laboratory tests performed in oedometers on sixteen soil samples yielded values in the range $k \in \langle 1\times10^{-12}, 3\times10^{-10} \rangle$ m/s. The discrepancy between laboratory and field-derived results highlights the importance of accounting for large-scale effects. Specifically, the presence of macro-cracks and preferential flow paths increases the effective permeability by at least one order of magnitude. This scale effect must be explicitly considered in numerical simulations and stability analyses of dump structures, as it governs the rate of pore pressure dissipation and, consequently, the overall stability of the system.

2.2 *Geometry modeling*

Accurate reproduction of the actual geometry of the dump is essential for reliable stability assessment, as the geometry exhibits considerable variability in multiple dimensions. For global two-dimensional analyses, it is possible to identify representative 2D cross-sections. However, to construct a numerical model that faithfully reflects reality, a use of spatial data sources is required. These include GIS databases, air surveys and geodetic measurements, which can then be imported into the computational environment. All calculations presented in this study were carried out using the ZSOIL software. To achieve an accurate representation, geodetic data were first processed in the CAD environment (Rhino). Within this framework, additional preprocessing was performed with Python scripting, enabling efficient manipulation and refinement of complex geometric data. The resulting geometries were subsequently imported into ZSOIL for numerical analysis. Figure 5 illustrates an example of the final three-dimensional model used for stability assessment. Several time steps are shown, representing the staged construction of the dump and the corresponding evolution of its geometry. Similarly, Figure 6 presents selected stages of development for the two-dimensional model. To reconstruct the stratigraphic configuration of the subsoil, kriging techniques were employed. With the geometric framework thus established, the next step is the modeling of vertical drainage systems within the constructed numerical domains.

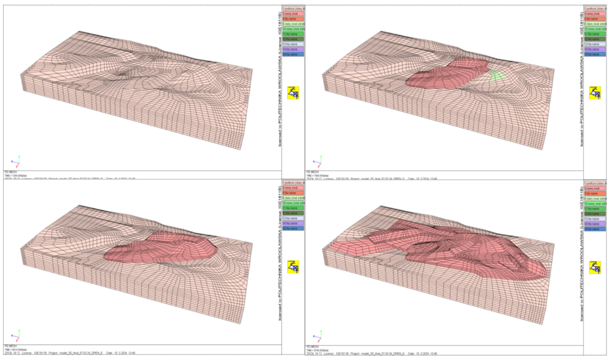

Figure 5. Selected stages of dump development in the three-dimensional model: (1) before dumping; (2) first dump level, (3) second dump level, (4) third dump level.

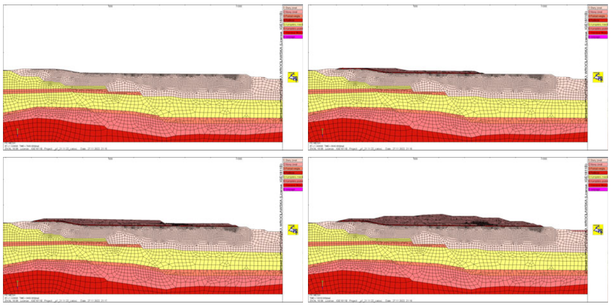

Figure 6. Selected stages of dump development in the two-dimensional mode, corresponding to the stages presented in Figure 5.

2.3 *Modelling of drainage system*

In large-scale numerical analyses, direct modeling of elements with dimensions of only a few centimeters becomes infeasible when the entire problem extends over several hectares. In the case of vertical drainage systems, where hundreds of thousands of drains may be installed in dense grids, explicit meshing of each drain is practically impossible. The number of finite elements required would be computationally prohibitive, making such models unrealistic even with modern hardware. For this reason, simplified modeling strategies are necessary.

One such technique, described in Rainer et al. (2025, in press), is based on homogenization theory. To understand the essence of this approach, it is necessary to first recall the mechanism of pore pressure dissipation in soils with vertical drains. Following the placement of new overburden material, excess pore pressures are generated in the subsoil. Water flow is primarily horizontal toward the drains. Once water enters a drain, it is rapidly discharged vertically upward into the drainage layer. As a result, the drainage system ensures efficient pore pressure dissipation into the overlying permeable layer. Given the dense spacing of drains, the pore pressure dissipation along the vertical direction can be assumed to be relatively uniform, which allows the effect to be conceptualized as a volumetric process.

This volumetric dissipation can be expressed in the transient flow equation for porous media by introducing a volumetric sink term:

$$\frac{\partial(n \cdot S_r)}{\partial t} + \nabla \mathbf{q} = -\mathrm{s} \qquad (1)$$

where n is soil porosity, S_r is the degree of saturation, q is the Darcy velocity vector (a function of pore pressure u), and s is the volumetric sink term representing the drainage effect. The sink depends on the difference between local pore pressure u and a reference pressure u_0 at the drain outlet (typically atmospheric or hydrostatic). A larger gradient results in greater discharge. The value of sink term take into accounts drain spacing, soil permeability and drain capacity.

In commercial software such as ZSOIL, direct modification of governing equations is not possible. However, the effect of volumetric drainage can be introduced using seepage elements. These elements, applied along surfaces (in 3D) or edges (in 2D), allow pressure or flow controlled boundary conditions. In ZSOIL, they dynamically switch between pressure and flux conditions, depending on the hydraulic gradient and degree of saturation. By assigning a reference pressure u_0, the program simulates water inflow when $u < u_0$ and outflow when $u > u_0$. In this way, the hydraulic effect of dense PVD networks can be represented without explicitly modeling each drain. Figure 7 illustrates the equivalent drainage zone concept with seepage elements embedded in the dump material.

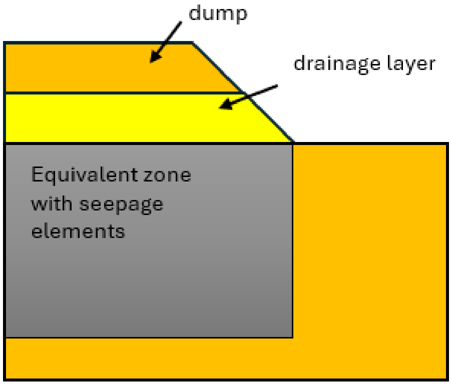

Figure 7. A schematic representation of a PVD system modelled using an equivalent drainage zone with seepage elements

The capacity of these seepage elements is controlled by a parameter k_v, which characterizes the drainage efficiency. This parameter depends on drain spacing, soil permeability, drain capacity and importantly, the finite element mesh size, since seepage elements are assigned along discretized boundaries. The value of k_v must therefore be calibrated and each time matched to specific mesh.

The calibration process follows homogenization principles and uses global response indicators (integral measures), particularly the settlement–time curve, which reflects the combined effect of pore pressure dissipation and consolidation in the whole domain. The procedure consists of two steps:

1) Reference unit cell model.

A small-scale periodic cell with a single drain embedded in the soil is created, as illustrated in Figure 8. Soil parameters are taken from field calibration (Section 2.1), while drain parameters and geometry are provided by manufacturers. A surface load is applied, generating excess pore pressures, and the resulting settlement–time curve is extracted (Figure 9).

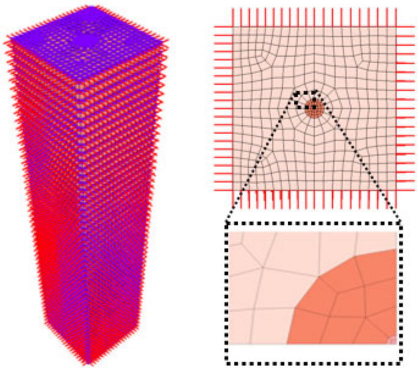

Figure 8. Model of periodic unit cel with single PVD and surrounding soil

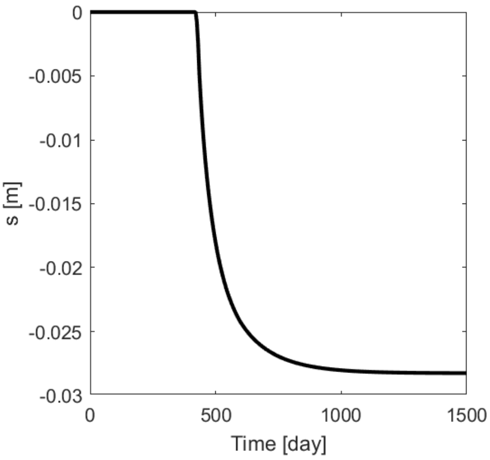

Figure 9. Settlement-time curve from a unit cell model with a single PVD

If available, field settlement data from geodetic benchmarks can be used instead of numerical unit-cell results, providing an even more realistic calibration basis.

2) Homogenized large-scale model

The geometry prepared in Section 2.2 is used, with seepage elements applied in the zones occupied by drains. Since k_v is mesh-dependent, its value must be adjusted to reflect the element size. For example, in the 3D dump model, the average element size was 25 m × 25 m in plan and 6 m in height. An equivalent homogenized model with the same mesh density, but without explicit drains, was created (Figure 10). Parametric analyses were then conducted by varying k_v until the settlement–time curve matched that of the unit-cell model. As a measure of the quality of fit, the error function was defined as the mean absolute value of the difference between the results obtained from the reference unit cell model (Figure 9) and the results obtained from the homogenized large-scale model for a given value of k_v. This definition provides a clear physical interpretation of the error, representing the average discrepancy in vertical displacement between the two models. Consequently, the error is expressed in meters [m], as it directly quantifies differences in displacements.

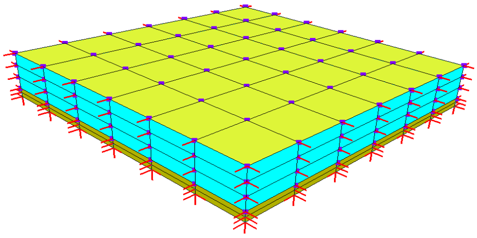

Figure 10. Equivalent model with seepage elements (marked in blue)

Figure 11 and Figure 12 present the comparison between the homogenized model and the reference unit-cell response. The fit is very good, with small discrepancies and a clearly defined error minimum. This confirms that the calibrated parameter k_v successfully reproduces the time-dependent consolidation behaviour, which is directly linked to pore pressure dissipation.

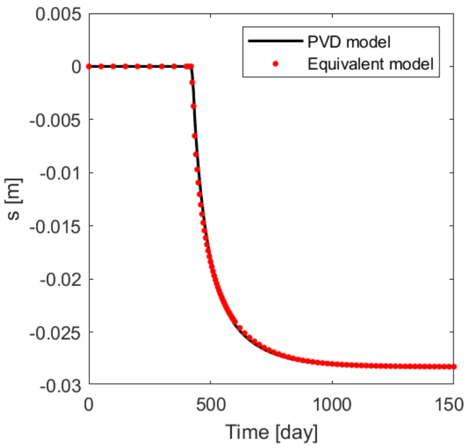

Figure 11. Time- settlement curve from a unit cell model with a single PVD.

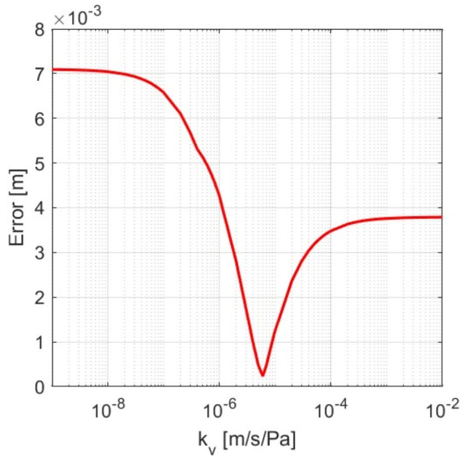

Figure 12. Error function indicating best-fit o k_v value

By incorporating seepage elements into the large-scale 2D and 3D geometries (Figures 5 and 6), this approach makes it possible to account for the influence of vertical drains by reproducing the pore pressure dissipation process. This calibrated representation is then used in the subsequent stability analyses, as presented in the following section.

3 RESULTS

The procedure and modeling workflow described in Section 2 allowed for a detailed assessment of the impact of vertical drains on dump stability. A key advantage of the homogenization-based approach is that it does not significantly increase computational time. Since individual drains do not need to be explicitly meshed, the models remain computationally efficient, which makes the method attractive for practical engineering applications.

The first stage of the analysis focused on global stability. Two-dimensional models were constructed in which the factor of safety (FOS) was calculated using the strength reduction method in ZSOIL. To ensure that results reflected large-scale mechanisms rather than shallow slides, near-surface elements along the outer slopes were locally reinforced. Four scenarios were considered: a reference case without drains (REF), Variant 1 (OLD) with drains placed in the foundation layers of the old dump, Variant 2 (NEW) with drains applied only in the newly constructed level, and Variant 3 (FULL) with drains in both old and new dump material. Since heap construction is a staged process carried out over time, the geometry, loading conditions, and stress state of the system evolve as successive dump levels are deposited. Therefore, the stability of the dump must be evaluated at different stages of construction, which naturally makes the stability analysis a function of time. The time evolution of the relative FOS for these scenarios is presented in Figure 13 and an example of a global failure mechanism for the FULL case at the end of dump construction is shown in Figure 14.

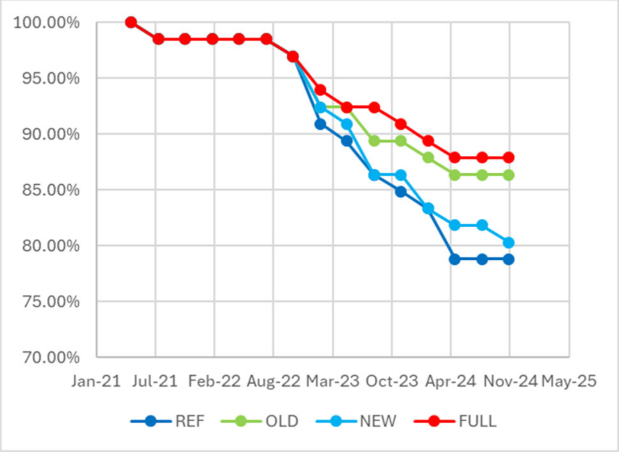

Figure 13. Relative factor of safety over time for REF, Variant 1 (OLD), Variant 2 (NEW), and Variant 3 (FULL)

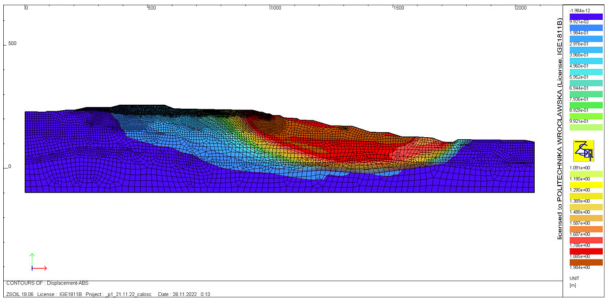

Figure 14. Example of a global failure mechanism at the final stage of dump construction (FULL drainage case)

The reference case without drains provides the lowest stability, as expected, while the FULL scenario achieves the highest FOS throughout the entire construction process. Interestingly, Variant 2 (NEW), where drains are installed only in the upper floor, performs only slightly better than the reference. This indicates that placing drains exclusively in the newly deposited material has a limited influence on overall global stability. In contrast, Variant 1 (OLD), in which drainage is provided in the foundation, produces a marked improvement in stability, almost reaching the values obtained in the FULL case. This finding highlights a critical practical insight: global stability of large-scale dumps is governed primarily by the hydraulic conditions of the foundation zones. Ensuring adequate drainage at the lowest levels of the dump is far more effective than installing drains in the upper levels alone.

The second stage of the study addressed local stability using three-dimensional models, focusing on the behaviour of individual slopes. In this case, only two scenarios were considered: REF (without drains) and FULL (drains in both foundation and new material).

In the REF case, shown in Figure 15, the possible failure mechanism reveals shallow slip surfaces concentrated near the outer slope. These near-surface instabilities, while smaller in scale than global failures, pose a serious risk because they can develop progressively, propagating upslope and undermining operational safety.

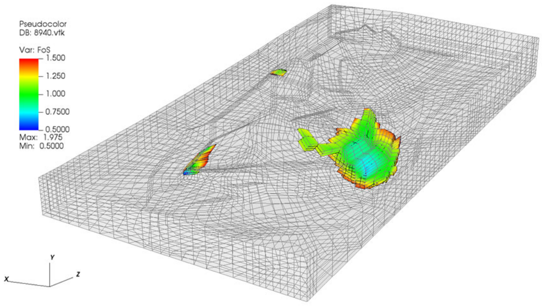

Figure 15. Potential failure mechanism for the REF scenario in selected time

By contrast, the FULL scenario (Figure 16) displays a markedly improved stability profile. The zones of low FOS are considerably reduced in both depth and volume, and many of the unsafe areas observed in the REF case disappear altogether. Slip surfaces become shallower and involve smaller soil masses, which translates into a much lower risk of progressive slope failures.

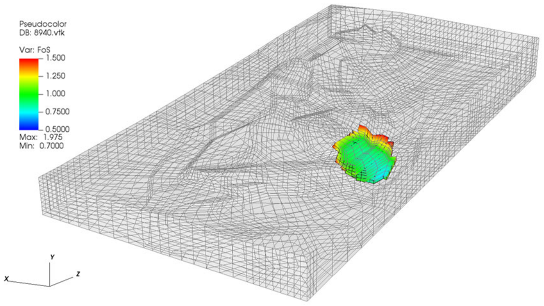

Figure 16. Potential failure mechanism for the FULL scenario in selected time

Taken together, these results provide a consistent picture of the role of vertical drains in improving dump stability. Their installation accelerates the dissipation of excess pore pressures, shortens the consolidation period and increases effective stress levels. This, in turn, leads to higher FOS values and a clear reduction in the probability of both global and local failure mechanisms. The improvement is particularly significant when drains are placed in the foundation layers, confirming that the stability of the entire structure depends largely on the drainage capacity of its lowest zones.

In summary, the analyses demonstrate that vertical drainage systems are highly effective in enhancing stability. Even though the influence of drains in upper lifts is relatively limited in global terms, their cumulative effect, especially when combined with foundation drainage, provides tangible improvements in both global and local safety.

4 CONCLUSIONS

The aim of this study was to evaluate the effectiveness of vertical drain installation on the stability of a large-scale overburden dump. The analysis was based on real data obtained from one of the Polish lignite mines, using actual soil conditions, drainage systems and monitoring results. Both global dump stability and local stability of individual slope were investigated with calculations using fully coupled poromechanical behaviour. The geometry of the dump was reconstructed using geodetic surveys and GIS resources.

Based on the conducted analyses, the following conclusions can be drawn:

1) The assessment of PVDs system in large-scale geotechnical systems, especially in dumps formed from anthropogenic soils, is a challenging task requiring advanced modeling approaches and careful parameter identification.

2) Laboratory tests alone are insufficient for a reliable characterization of dump soils. Incorporating monitoring data, such as pore pressure records, allows for calibration of numerical models, bridging the gap between sample-level and massive-scale parameters.

3) The integration of GIS data provides a robust basis for reconstructing the actual geometry of the dump, which is crucial for realistic stability assessment.

4) Explicit volume-based representation of each drain is impractical in large-scale problems due to computational limitations. Instead, simplified approaches such as homogenization are required. In this work, drains were modeled using seepage elements in ZSOIL, with calibrated drainage capacity parameters (k_v), enabling a computationally efficient and realistic representation of PVD systems.

6) The installation of vertical drains significantly improves dump stability by accelerating consolidation and pore pressure dissipation, which translates into higher factors of safety and safer deposition practices. The proposed approach can also be applied at the design stage, offering opportunities to optimize slope geometry without compromising safety.

7) From the perspective of global stability, drainage of the foundation layers has the most significant impact. Variant analyses demonstrated that installing drains in the old foundation (LOW levels) greatly improves FOS, while drains in the newly placed levels alone provide only marginal benefit. Proper installation and functionality of foundation drainage systems are therefore key to achieving the full effect.

8) To the authors' knowledge, this is the first study that systematically evaluates the impact of vertical drains on the stability of overburden dumps composed of anthropogenic soils, as well as one of the first to demonstrate the applicability of homogenization-based modeling in such large-scale geotechnical problems.

9) The homogenization approach allows easy modification of drain spacing and configuration in numerical models by adjusting a single parameter (k_v). This feature highlights the strong potential of the method for practical use, enabling engineers to rapidly test different design scenarios and integrate monitoring data into stability assessments.

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