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MODELING OF VERTICAL DRAINAGE SYSTEM IN LARGE SCALE GEOTECHNICAL STRUCTURES

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ABSTRACT

This paper presents a homogenized modeling approach for simulating vertical drainage systems in large-scale geotechnical structures. Drainage zones replace individual prefabricated vertical drains (PVDs) with embedded seepage surface elements that simulate volumetric pore pressure dissipation. The method is based on homogenization theory and uses a calibrated drainage parameter to capture the hydraulic effect of dense PVD networks. Implemented in ZSOIL v.2018, the approach allows for efficient large-scale simulations while preserving key consolidation behaviors. Results confirm its effectiveness in replicating detailed models with significantly reduced computational demand.

Keywords: large-scale geotechnical simulation, homogenization, vertical drainage system, numerical modeling.

INTRODUCTION

Large-scale geotechnical structures, such as tailings storage facilities (TSFs) and overburden dumps, pose significant challenges for geotechnical engineers due to their scale and long-term operation. These structures are strategically important components of the mining production chain, enabling uninterrupted disposal of waste materials and supporting ongoing mineral extraction (Łydzba et al., 2024).

Due to their operational nature, such objects are continuously raised over time, often across many years and decades. As a result, progressively deeper subsoil layers become engaged, while the height and weight of the deposited material steadily increase. This is further complicated by the fact that the foundation soils and the waste materials are often low permeable. In such conditions, excess pore water pressures tend to generate not only in the subsoil but also within the deposited layers. A critical factor in maintaining the long-term stability of these systems is the dissipation of excess pore pressures over time. If dissipation is too slow, high pore pressures reduce effective stress and, in turn pose a direct threat to overall stability (Terzaghi et al., 1996).

To manage these risks, the observational method, as outlined in Eurocode 7 (EN 1997-1), is widely employed. It involves continuous field monitoring of displacements, pore pressures and other key

indicators to identify early signs of instability and support operational decision-making (e.g., Bak, 2022). However, observational data alone are insufficient. Numerical modeling is essential to predict future behaviour under varying load conditions, evaluate design scenarios and develop effective management strategies such as additional vertical drainage systems.

Vertical drainage systems, including relief wells and prefabricated vertical drains (PVDs), are widely used to accelerate the dissipation of excess pore water pressure. These two types of drainage elements differ significantly in terms of installation depth, coverage, and modeling approach. Relief wells are typically deep, high-capacity vertical drains installed individually in the subsoil. Due to their limited number and strategic placement, they are often modelled explicitly as single volumetric elements in numerical simulations (Sobótka et al., 2022).

In contrast, PVDs are installed in dense, grid-like mesh throughout the deposited material and near-surface layers. These drains consist of slender, perforated synthetic strips that are usually combined with a well-grained transmission layer to rapidly facilitate the discharge of water flow from PVD. A schematic representation of a typical PVD system is shown in Figure 1. By accelerating pore pressure dissipation, vertical drainage systems increase effective vertical stress, which in turn improves both the strength of the soil and the

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overall stability of the structure (Indraratna et al., 2005).

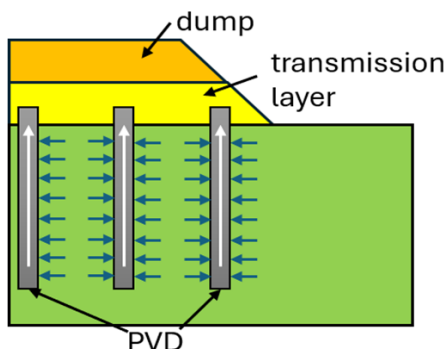


Figure 1 Schematic PVDs system

The numerical modeling of vertical drainage is well-established in the literature, particularly using the finite element method (FEM). For simple cases, a single drain can be modeled within a periodic unit cell to evaluate consolidation behaviour. For smaller or linear structures, 2D plane strain or basic 3D models may be sufficient (Yildiz, 2009). However, for large, spatially complex structures like TSFs and dumps, often containing thousands of drains, such detailed modeling becomes computationally unfeasible.

This paper presents a novel and scalable modeling approach specifically developed for large-scale geotechnical structures with extensive vertical drainage systems. By applying assumptions from homogenization theory, the method allows for the replacement of individual drain modeling with simplified drainage zones embedded within the finite element mesh. These zones represent the collective hydraulic response of densely spaced drains and simulate water outflow using negative sink elements. As a result, the need for highly refined meshes and complex geometries associated with explicit drain representation is eliminated. This significantly reduces the number of elements required, allowing for coarser meshing and improved computational performance in real-case applications. The methodology has been implemented in ZSOIL v.2018 and is suitable for practical engineering design and stability assessments. The following sections present the theoretical background, implementation workflow, modeling results and conclusions.

MATERIALS AND METHODS

To understand the physical basis of the proposed modeling approach, it is first necessary to consider how vertical drainage operates in practice. As illustrated in Figure 1, prefabricated vertical drains (PVDs) are typically installed in a regular grid pattern, with their upper ends connected to a highly permeable drainage layer that enables

rapid water outflow. Water flows into the drains due to excess pore pressures generated in the surrounding soil.

Although water generally moves upward toward the surface, the dominant direction of flow within the soil is lateral, as water flows horizontally toward the PVDs. When the drains are densely spaced, the system behaves volumetrically: the drainage effect is spread across a continuous zone rather than being confined to the vicinity of individual drains. This enables a homogenized modeling approach, where the PVD-soil system is treated as a continuum with an internal source to dissipate pore water.

This volumetric dissipation can be incorporated into the transient flow equation in a porous medium via a sink term:

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

where n is soil porosity, S_r is the degree of saturation, $\mathbf{q}$ is the Darcy velocity vector (a function of pore pressure u) and s is the volumetric sink term representing the effect of drainage. The sink term depends on the pressure difference between the local pore pressure u and a reference pressure u_0 at the drain outlet (typically atmospheric or hydrostatic). The greater the gradient, the more water is removed. This term also implicitly accounts for PVD spacing, soil permeability and drain capacity.

While user-defined codes can implement such formulations directly, commercial FEM software typically requires alternative strategies. This paper demonstrates the application of the proposed approach in ZSOIL v.2018, which, though it does not allow direct modification of equations, provides built-in tools to simulate volumetric drainage.

A key feature is the use of seepage surface elements, which model pressure-driven flow across element boundaries. These surfaces adapt dynamically between pressure and flux conditions, depending on the hydraulic gradient and saturation state. By assigning a reference pressure u_0 and specifying a drainage capacity parameter k_v , it is possible to replicate the effect of PVD-based dissipation. This parameter governs how efficiently excess pore water is removed, reflecting physical characteristics such as drain spacing, soil permeability, and drain material capacity.

Since seepage boundaries are applied across finite element surfaces, the value of k_v is mesh-dependent. Finer meshes require smaller k_v values to achieve the same drainage effect, while coarser meshes demand higher values. This approach allows dense PVD networks to be simulated without explicitly modeling individual drains, significantly reducing model complexity.

A crucial aspect of this method is the calibration of seepage boundary parameters to reflect the true behavior of the PVD-soil system. Rather than matching individual pore pressure readings,

calibration should target global response indicators, especially surface settlement over time, which reflects both consolidation and pressure dissipation in time. This is consistent with homogenization theory, which assumes that microscale effects can be captured through equivalent macroscale responses.

The proposed calibration procedure involves two steps:

1. Reference unit cell model - A small-scale model of a single PVD with surrounding soil is created and subjected to vertical loading. The actual geometry and material properties are included. The resulting time-settlement curve serves as a benchmark for expected consolidation behavior.
2. Homogenized large-scale model - A full-scale model of the real structure is developed with geometry, boundary conditions and loading consistent with project conditions. The PVD network is replaced by seepage boundaries, and the drainage parameter k_v is iteratively adjusted until the settlement response matches that of the unit cell model.

This approach ensures that the simplified model accurately captures both the hydraulic function of the drains and the overall time-dependent consolidation response, key for assessing the stability and deformation of large-scale geotechnical structures. The following section demonstrates the application of this methodology.

RESULTS

The proposed methodology was evaluated through two numerical simulations: a detailed unit cell model representing a single PVD and its surrounding soil and a large-scale homogenized model representing a full PVD network using simplified drainage zones.

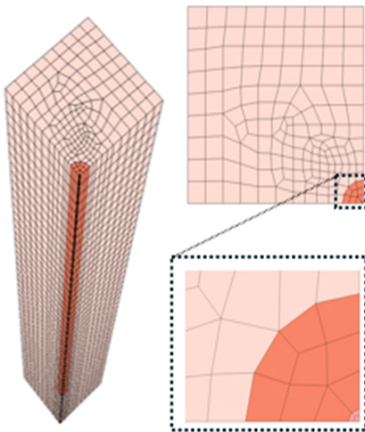


Figure 2 Model of the periodic unit cell with a single PVD and surrounding soil

A reference simulation was performed using a quarter-periodic unit cell (Figure 2), representing one PVD embedded in the soil. The model covered a $2.5 \text{ m} \times 2.5 \text{ m}$ area (corresponding to a full drainage span of 5m), with the soil assigned a hydraulic conductivity of $k_v = 1 \cdot 10^{-8} \text{ m/s}$, Young modulus $E = 40 \text{ MPa}$ and Poisson ratio $\nu = 0.3$.

The PVD, typically rectangular ($0.1 \text{ m} \times 0.02 \text{ m}$), was simplified as an equivalent circular drain of the same cross-sectional area, a common practice in geotechnical modeling for hydraulic equivalence. The drain extended vertically to 20 m. A seepage surface with zero pore pressure ($u=0$) was defined at the top boundary, allowing vertical drainage. A uniform surface load of $\sigma = 200 \text{ kPa}$ was applied to generate excess pore pressure and initiate consolidation. The model consisted of approximately 11,000 finite elements, ensuring sufficient resolution to capture localized flow gradients near the drain. The resulting time-settlement curve was extracted and used as the benchmark for calibrating the large-scale homogenized model (Figure 3).

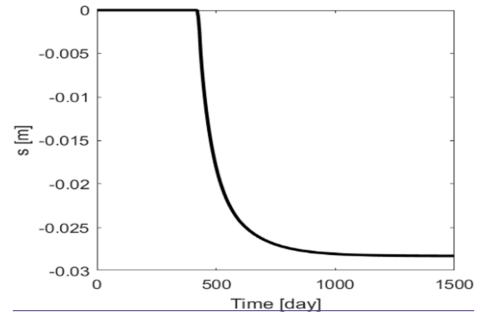


Figure 3 Time-settlement curve from a unit cell model with a single PVD

The second model simulated a large-scale geotechnical domain ($150 \text{ m} \times 150 \text{ m} \times 25 \text{ m}$), containing a dense grid of PVDs spaced every 5 m (Figure 4), amounting to approximately 900 drains. To reduce computational complexity, individual drains were not modeled. Instead, seepage boundary elements were used throughout the zone normally occupied by PVDs and the domain was discretized with coarse finite elements ($25 \text{ m} \times 25 \text{ m} \times 6 \text{ m}$). The total mesh consisted of 108 elements, enabling simulation in under one minute on standard hardware.

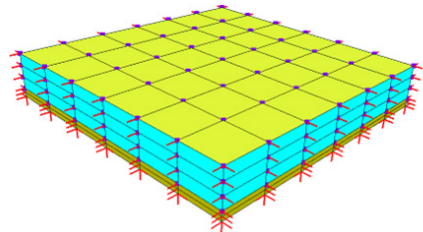


Figure 4 Equivalent large scale model using seepage elements

The same surface loading was applied as in the unit cell. A parametric study was then performed to examine how different values of the drainage parameter k_v affected global settlement. For each trial value of k_v , the resulting settlement was compared to the unit cell result. The fit was quantified using an error function, defined as the mean absolute difference in surface settlement over time between the simplified and detailed models. As shown in Figure 5, the error function displayed a clear minimum, indicating the existence of an optimal k_v value for which the homogenized model accurately reproduces the detailed consolidation response (Figure 6).

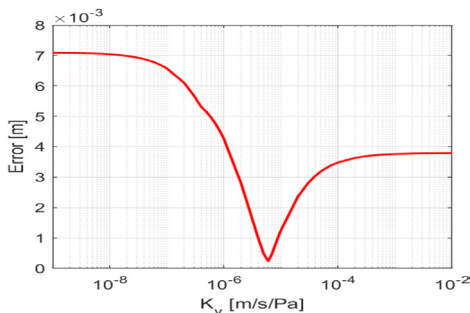


Figure 5 Error function indicating best-fit k_v value

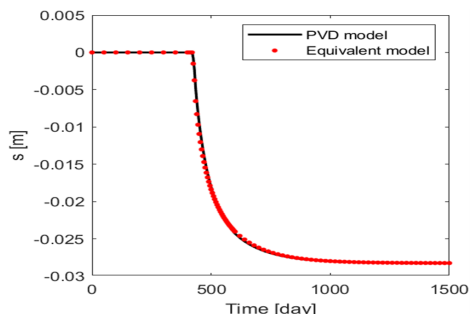


Figure 6 Comparison between unit cell and homogenized model responses

These findings confirm that the proposed method based using seepage surfaces and a calibrated drainage parameter can faithfully replicate the performance of real drainage systems in large-scale FEM models, with dramatically reduced computational effort.

CONCLUSION

Based on the analyses presented in this study, the following conclusions can be drawn:

1. An original modeling approach for simulating PVDs systems in large-scale geotechnical structures has been developed and demonstrated.
2. The proposed methodology enables efficient and practical modeling of dense

PVD networks by replacing individual drain representations with homogenized drainage zones. The procedure follows a two-step workflow: 1. simplified model calibration, followed by 2. implementation in the full-scale model. To ensure consistency, the calibration model must reflect the same mesh density and element size as the target large-scale simulation, making the calibrated parameter k_v directly transferable.

3. If real field data, such as surface settlement measurements, are available, the initial calibration step can be omitted. Instead, the drainage parameter can be adjusted directly based on observed system behavior, further streamlining the modeling process.
4. The presented results should be considered preliminary. The current model assumes a constant k_v , whereas in reality, drainage efficiency may vary over time. Future work will focus on incorporating time-dependent drainage capacity $k_v(t)$ and smear zone effects, which can significantly influence flow behavior around the drains.
5. Application of this methodology to real-world case studies represents the next step in validating and advancing this modeling framework, particularly in assessing how vertical drains influence the overall safety and stability of large-scale geotechnical structures.

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