Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-1861

Improving Undrained Analysis: Overcoming oscillating pore pressures

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ABSTRACT: This paper examines and compares various strategies used in the development of Oasys Gofer to overcome the common problem of oscillating pore pressures in geotechnical finite element analysis during undrained effective stress analysis. The common practice is to compute pore pressures at the integration points, by including the stiffness of water in the global stiffness matrix, then multiplying the very small computed volumetric strains by the very large bulk stiffness of water. This approach can lead to oscillating pore pressures for second order element types, and a number of smoothing or stabilization methods are described in the literature. Our investigations with Oasys Gofer explored an alternative method which uses a consolidation solution with a very short time step and relatively low soil permeability. This method incorporates a fully implicit nonlinear solver which computes excess pore pressures at the nodes iteratively to reduce the volumetric strain to near zero, thus producing a smooth and very stable pore pressure field across the mesh. Sensitivity analyses tested the range construction of valid permeabilities, different element formulations (changing the pore pressure degrees of freedom), as well as implementation and tuning of adaptive error control and acceleration methods to aid convergence. The results show the influence of correct selection of element type and the importance of an accurate initial state for subsequent longer term consolidation analysis. The proposed method thus avoids the need for additional smoothing or stabilisation techniques, and produces a stable pore pressure and displacement field for subsequent analyses.

KEYWORDS: Pore pressure oscillations, undrained effective stress method, finite element modelling.

1 INTRODUCTION

In traditional geotechnical finite element (FE) modelling, short-term construction stages under fully saturated conditions are typically analysed using either drained or undrained assumptions. These approaches do not consider the time-dependent changes in pore pressure and effective stresses, and thus avoid the longer computing times associated with fully coupled consolidation analysis.

The undrained condition is commonly assumed for clayey soils with low permeability or in scenarios involving rapid loading, where excess pore pressures do not have sufficient time to dissipate. A typical FE model involving clay soils may therefore consist of a sequence of undrained construction stages, followed by a fully coupled consolidation phase in which excess pore pressures are allowed to dissipate and the soil undergoes time-dependent deformation.

During the undrained stages, the undrained effective stress approach is often used to simulate the generation of excess pore pressures in low-permeability soils. In many commercial FE software, this is implemented by computing pore pressures at integration points. This is done by multiplying the very small volumetric strains by the very large bulk modulus of water, while simultaneously incorporating undrained stiffness parameters into the global stiffness matrix. Although this classical approach is widely adopted, it can lead to a discontinuous distribution of pore pressures across the mesh. These discontinuities are often smoothed for presentation, but they reflect a deeper numerical issue: pore pressure oscillations, which are a well-documented artifact in undrained FE analysis of saturated soils. These oscillations remain pronounced when using second-order displacement elements with fully implicit solvers and can result in mesh-dependent displacement behaviour.

In the context of Gofer, this classical formulation has been observed to produce unstable excess pore pressures and inconsistent deformation patterns in certain edge cases. To address this issue, a new stable undrained method has been introduced in Gofer. This method approximates the undrained response by solving a consolidation problem over a very short time step, using a relatively low permeability. This approach eliminates the need for additional stabilisation methods or smoothing techniques. It also enables Gofer to use the same consolidation solver throughout all construction stages, making it a more efficient finite element package.

This paper presents the development and implementation of this improved undrained method in Gofer. It outlines the theoretical basis of the approach, compares its performance against the classical formulation through benchmark simulations, and demonstrates its effectiveness in producing stable, mesh-independent results. The findings highlight the method's potential to improve the reliability of undrained effective stress analysis, particularly in scenarios where traditional formulations are prone to numerical artefacts.

2 BACKGROUND AND PROBLEM STATEMENT

Various types of pore pressure oscillations have been widely documented in undrained analyses, arising from different assumptions in geotechnical modelling approaches—such as element interpolation order, the choice between explicit and implicit solvers, and the location of the pore pressure solution (i.e., whether computed at integration points or element nodes).

Most pore pressure oscillations stem from the incompatibility between the interpolation of displacement and pore pressure fields, particularly when the inf-sup (Ladyzhenskaya–Babuška–Brezzi) condition is not satisfied. A number of smoothing and stabilisation methods have been proposed in the literature to address this issue (Zienkiewicz et al. 1990; Sheng et al. 2005; Sanavia et al. 2006; de Souza Neto et al. 2008).

2.1 *Classical undrained calculation approach*

This paper focuses on oscillations that occur when using second-order displacement elements in combination with a fully implicit nonlinear solver. In most commercial FE software, the undrained effective stress approach computes excess pore pressures at integration points by multiplying small volumetric strains by the large bulk modulus of water (i.e. $\Delta p_e = (K_w/n)\Delta\varepsilon_v$ where Δp_e is the excess pore pressure increment, K_w is the bulk modulus of water, n is the porosity, and $\Delta\varepsilon_v$ is the volumetric strain increment). This approach contains a simplified algorithm where only the static equilibrium of a continuum media is solved as:

$$\nabla \cdot \boldsymbol{\sigma} + \rho \boldsymbol{b} = 0 \tag{1}$$

where $\boldsymbol{\sigma}$ is stress vector, $\boldsymbol{b}$ is the body forces, and ρ is bulk density. The resulting finite element governing equation solves only for the incremental displacement field (i.e. displacement degrees of freedom):

$$\mathbf{K_u}\Delta\boldsymbol{u} = \boldsymbol{f}_{\text{ext}} - \boldsymbol{f}_{int} = \Delta F \tag{2}$$

where $\mathbf{K_u}$ is the global stiffness matrix which is assembled by considering the combined effect of a solid skeleton and pore water. $\Delta\boldsymbol{u}$ is the incremental displacement, $\boldsymbol{f}_{\text{ext}}$ is the external force vector, $\boldsymbol{f}_{int}$ is the internal force vector, ΔF is the unbalance force vector. Computed $\Delta\boldsymbol{u}$ is used to compute stresses and pore pressure increments at integration points.

When second-order elements are used, the strain field may contain high-frequency numerical noise, which is amplified by the water stiffness, resulting in non-physical pressure spikes.

To mitigate these effects, commercial software and academic literature have introduced various stabilisation techniques, including the Enhanced Assumed Strain (EAS) method (MIDAS Information Technology Co., Ltd 2025), quartic or higher-order elements (PLAXIS 2025), and reduced integration methods. For details of the implementation of these techniques in each product the reader is referred to the technical product manuals. Despite these efforts, the classical technique of computing pore pressures at integration points can still lead to oscillations and mesh-dependent displacement behaviour in certain cases.

2.2 *Observed behaviour for classical approach*

In many instances, the displacement solution remains acceptable despite the presence of pore pressure oscillations. However, mesh-dependent displacement behavior has been observed under specific conditions—such as when the factor of safety is close to 1, the model contains geometric singularities, or the mesh is finer or irregular, as shown in Figure 1 (i.e., pressure oscillations originate at corners of elements). This example uses the Mohr-Coulomb model with effective stiffness and undrained strength parameters. The factor of safety is approximately 1.3, and mesh-dependent displacement behavior has been observed. A coarser mesh produces accurate displacement fields, although pore pressure oscillations are present. However, the displacement field becomes inaccurate when the mesh is finer and contains mixed element types.

Furthermore, when oscillatory pore pressure fields are present during undrained stages, the final consolidation stage often experiences convergence difficulties. This behaviour was observed in Gofer when using second order elements with lower order integrations (i.e. QUAD8 elements with 4 integration points and TRI6 with 3 integration points).

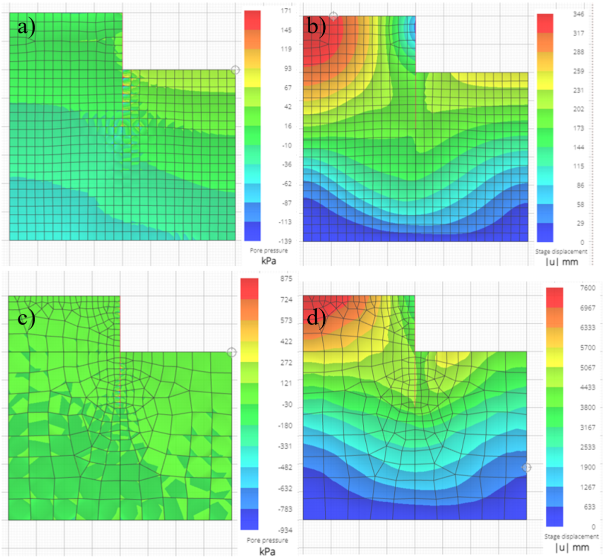

Figure 1. Mesh dependent excess pore pressure and displacement behaviour with classical undrained calculation method. (a) shows excess pore pressure oscillations with associated displacements in (b). For the same model geometry and parameters but a finer mesh, larger excess pore pressure oscillations are seen in (c), with associated larger deflections in (d).

3 OVERVIEW OF THE PROPOSED APPROACH

The proposed approach involves using the consolidation solution over a very short time period with relatively low permeability, allowing the capture of undrained behavior. This method was explored in Gofer due to its existing robust, fully coupled, fully implicit nonlinear iterative solver for consolidation analysis. Reusing the same solver for short-term construction stages was considered beneficial in terms of both numerical stability and computational efficiency.

Figure 2 presents a comparison between the proposed approach and the classical undrained effective stress formulation. Unlike the classical method, which computes pore pressures at integration points, the consolidation solution directly solves for both incremental displacements and incremental excess pore pressures at the element nodes (i.e., displacement and excess pore pressure degrees of freedom). This is because the consolidation solution incorporates three governing equations: static equilibrium of a continuum medium, Darcy's law, and the continuity equation for water flow. As shown in Figure 2, the consolidation solution solves two systems of equations within the nonlinear iteration loop.

Numerical stability is further improved by assigning the excess pore pressure degrees of freedom one order lower than those of the displacement field (i.e., only the element corner nodes are used for pore pressure calculations, whereas both mid-side and corner nodes are used for displacement calculations).

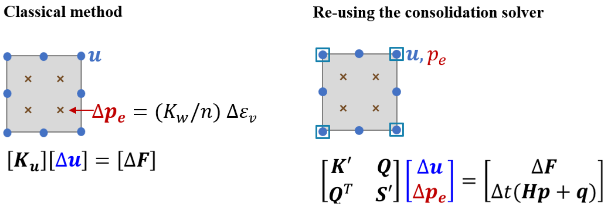

Figure 2. Difference between the classical approach (left) and the proposed approach (right).

Gofer computes excess pore pressures at the nodes iteratively to reduce volumetric strain to near zero. These computed pore pressures are then interpolated to the integration points to calculate total stresses and assemble the force vectors. This approach results in a smooth distribution of excess pore pressures and a stable pore pressure field.

The algorithm for undrained materials with excess pore pressure generation is shown in Figure 3. The full derivation and the definitions for this algorithm can be accessed through Gofer theory manual (Oasys Gofer 2025).

For undrained materials, a default permeability value of 1×10^{-12} m/s is used when computing the $\mathbf{H}$ matrix. The solution is run for a short time step and it is computed using the minimum time step criterion: $l^2/6c_v$, where l is the maximum element length and $c_v = (1-\nu)E/(\rho_w g(1+\nu)(1-2\nu))$. If the model has drained material layers, the associated nodes are not considered into excess pore pressure degrees of freedom. This is because the drained material layers do not generate excess pore water pressures. More details can be found in the Gofer theory manual.

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Form components for K assembly (i.e. $\mathbf{K}_\mathrm{e} = \int \mathbf{B}^T\mathbf{D}_\mathrm{e}\mathbf{B}\,dV$; $\mathbf{Q} = \int \mathbf{B}^T\boldsymbol{m}\mathbf{N}_\mathbf{p}\,dV$;
    $\mathbf{S} = \int \boldsymbol{N}_\mathrm{p}^T \frac{n}{K_w}\mathbf{N}_\mathbf{p} dV$; $\mathbf{H} = \int (\nabla\mathbf{N}_\mathbf{p})^T \frac{\mathbf{k}_\mathbf{sat}}{\rho_w g}(\nabla\mathbf{N}_\mathbf{p})\,dV$)
Form $\mathbf{K} = \begin{bmatrix} \mathbf{K}_\mathrm{e} & \mathbf{Q} \\ \mathbf{Q}^\mathrm{T} & -(\mathbf{S}+\Delta t\mathbf{H}) \end{bmatrix}$ and obtain $\mathbf{K}^{-1}$
New step $i \to i+1$ (load incrementation)
    Calculate unbalance load vector $\Delta\boldsymbol{F}^{i+1} = \begin{bmatrix} \boldsymbol{f}_\mathrm{ext} - \boldsymbol{f}_\mathrm{int}^i \\ \Delta t\boldsymbol{q}_\mathrm{b}^{i+1} + \Delta t\mathbf{H}\boldsymbol{p}_\mathrm{e}^i \end{bmatrix}$
    Reset displacement & excess pore pressure increments $\Delta\boldsymbol{u} = \Delta\boldsymbol{p}_\mathrm{e} = 0$
    New iteration $j \to j+1$ (predict incremental $\delta\boldsymbol{u}$ & $\delta\boldsymbol{p}_\mathrm{e}$)
        Solve nodal $\delta\boldsymbol{u}$ & $\delta\boldsymbol{p}_\mathrm{e}$: $\begin{bmatrix} \delta\boldsymbol{u} \\ \delta\boldsymbol{p}_\mathrm{e} \end{bmatrix}^{j+1} = \mathbf{K}^{-1}\,\Delta\boldsymbol{F}^{i+1,j}$
        Update nodal $\Delta\boldsymbol{p}_\mathrm{e}$ & $\Delta\boldsymbol{u}$: $\Delta\boldsymbol{u}^{j+1} = \Delta\boldsymbol{u}^j + \delta\boldsymbol{u}^{j+1}, \Delta\boldsymbol{p}_\mathrm{e}^{j+1} = \Delta\boldsymbol{p}_\mathrm{e}^j + \delta\boldsymbol{p}_\mathrm{e}^{j+1}$
        Calculate element effective stresses based on constitutive model:
            $\boldsymbol{\sigma}'^{i,j+1} = \boldsymbol{\sigma}'^{i} + \Delta\boldsymbol{\sigma}'^{j+1}; \Delta\boldsymbol{\sigma}'^{j+1} = D_\mathrm{ep}\delta\boldsymbol{\epsilon}^{j+1}; \delta\boldsymbol{\epsilon}^{j+1} = \mathbf{B}\delta\boldsymbol{u}^{j+1}$
        Calculate element total pore pressure: $\boldsymbol{p}_\mathrm{ele}^{i,j+1} = \boldsymbol{p}_\mathrm{steady,ele} + \boldsymbol{p}_\mathrm{e,ele}^i + \Delta\boldsymbol{p}_\mathrm{e,ele}^{j+1}$
        Calculate internal force vector ($\boldsymbol{f}_\mathrm{int}^{i,j+1} = \sum\int \mathbf{B}^T\boldsymbol{\sigma}^{i,j+1}\,dV$; where $\boldsymbol{\sigma}^{i,j+1} = \boldsymbol{\sigma}'^{i,j+1} + \mathbf{m}\boldsymbol{p}_\mathrm{ele}^{i,j+1}$)
        Calculate unbalance load vector $\Delta\boldsymbol{F}^{i+1,j+1} = \begin{bmatrix} \boldsymbol{f}_\mathrm{ext} - \boldsymbol{f}_\mathrm{int}^{i,j+1} \\ \Delta t\boldsymbol{q}_\mathrm{b}^{i+1} + \Delta t\mathbf{H}\boldsymbol{p}_\mathrm{e}^{i,j+1} - \boldsymbol{Q}^T\Delta\boldsymbol{u}^{j+1} + \boldsymbol{S}\Delta\boldsymbol{p}_\mathrm{e}^{j+1} \end{bmatrix}$
    Accuracy check for nonlinear iteration: $e^\mathrm{nl} > e_\mathrm{tolerated}^\mathrm{nl} \to$ new iteration
    Update nodal $\boldsymbol{u}^{i+1} = \boldsymbol{u}^i + \Delta\boldsymbol{u}^{j+1}$ and $\boldsymbol{p}_\mathrm{e}^{i+1} = \boldsymbol{p}_\mathrm{e}^i + \Delta\boldsymbol{p}_\mathrm{e}^{j+1}$;
    Update element $\boldsymbol{\sigma}'^{i+1} = \boldsymbol{\sigma}'^{i} + \Delta\boldsymbol{\sigma}'^{j+1}, \boldsymbol{\epsilon}^{i+1} = \boldsymbol{\epsilon}^i + \Delta\boldsymbol{\epsilon}^{j+1}, \boldsymbol{p}_\mathrm{e,ele}^{i+1} = \boldsymbol{p}_\mathrm{e,ele}^i + \Delta\boldsymbol{p}_\mathrm{e,ele}^{j+1}$
Check for termination criterion $\to$ next load step $\Delta t$
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Figure 3. Numerical algorithm.

4 SENSITIVITY ANALYSIS

4.1 *Effect of standard elements*

The pore pressure oscillations and mesh-dependent displacement values observed in the classical approach can be eliminated by switching to the proposed consolidation algorithm. As part of a sensitivity study, standard elements were initially used in the solver. Standard elements are defined as those which use the same order of expansion for displacement and excess pore pressure. Later in this paper, the impact of using composite elements is also discussed. In this context, we use the term "composite elements" to refer to the reduced-order pore pressure field. Figure 4 illustrates the differences between standard and composite elements for a QUAD8 element. Composite elements use a lower order of expansion for excess pore pressure than standard elements.

The same excavation model shown in Figure 1 was run using the alternative consolidation algorithm approach using standard elements, and the results are presented in Figure 5. Issues with the classical method were initially resolved by using the consolidation solution.

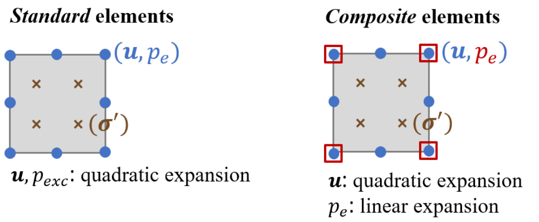

Figure 4. Definition of standard elements (left) and composite elements (right) for QUAD8.

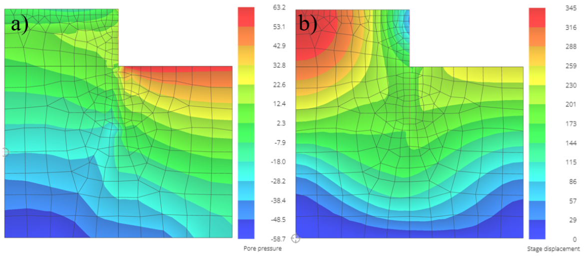

Figure 5. Impact of using the consolidation solution with standard elements. (a) shows excess pore water pressure and (b) shows stage displacement.

4.2 *Effect of permeability value on standard elements*

Further investigation into stability was carried out to assess the impact of permeability values on the results using standard elements. A different model was selected that shows a significant impact due to the permeability values. Figure 6 and Figure 7 show the effect of permeability on excess pore pressures. There was no impact on the displacement profile.

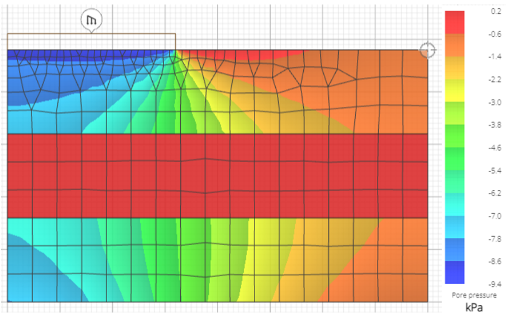

Figure 6. Excess pore pressure variation on standard elements with 1×10^{-6} m/s permeability.

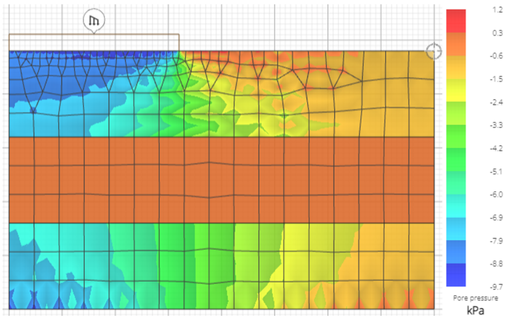

Figure 7. Excess pore pressure variation on standard elements with 1×10^{-12} m/s permeability.

This model consists of layered MC soil, where the top and bottom layers are solved using undrained effective stress parameters, and the middle layer is solved using drained parameters. A uniformly distributed load of 10 kPa is applied vertically downward, and the stability of the results was investigated.

It was observed that pressure oscillations still occur when the permeability is very low. Although higher permeability values produce a smoother excess pore pressure profile, they slightly underpredict the maximum excess pore pressure, although the displacement values predicted from various permeabilities are similar. Predicting the correct range of excess pore pressure and achieving a smoother field is especially important for convergence and accuracy in the subsequent consolidation analysis. Through various sensitivity studies (i.e. tested permeability values in the range of $1\times10^{-3} - 1\times10^{-15}$ m/s m/s), it was found that standard elements sometimes exhibit pressure oscillations even within the applicable permeability range, indicating that further improvements are needed. The main assumption in undrained modelling is that it should represent fully incompressible behaviour, meaning no pore pressure dissipation occurs. To achieve this, the permeability value must lie within the incompressible or very low permeability range typical of standard soils.

4.3 *Effect of composite elements*

The impact of permeability was further investigated using composite elements (i.e. Figure 4). When excess pore pressure degrees of freedoms were only considered at corner nodes, the oscillatory pore pressure field was completely eliminated. The results are shown in Figure 8 for 1×10^{-12} m/s permeability.

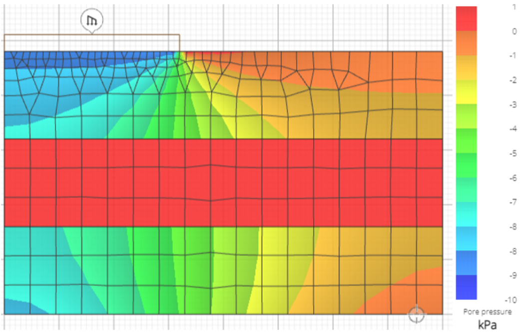

Figure 8. Excess pore pressure variation on composite elements with 1×10^{-12} m/s permeability.

Use of the consolidation algorithm to model undrained effective stress soil with composite elements, using a default permeability value of 1×10^{-12} m/s, has shown very stable results. This method reduces the need to use other types of stabilization methods or smoothing of results. It also provides a way to obtain very stable and accurate predictions in the preceding consolidation stage.

4.4 *Boundary conditions*

All models have been analysed with consistent boundary conditions. Horizontal displacements were constrained to zero along the left and right hand model boundaries while vertical displacements remained free. The bottom boundary was fully fixed. Closed consolidation boundaries were modelled along the left, right, and base of the model

5 FURTHER IMPROVEMENTS

In Gofer, the nonlinear implicit iterative algorithm for the consolidation problem is derived using the initial stiffness method for linear elastic and Mohr-Coulomb soil models. In this approach, the linear elastic stiffness matrix is used to compute the initial global stiffness matrix, rather than employing the more complex tangential stiffness matrix that requires updating at each iteration. This method has proven to be both robust and accurate, as the material stiffness values remain constant throughout the iterations.

Gofer employs a strict default force convergence tolerance, which is evaluated against the out-of-balance force vector—defined as the difference between the internal and external force vectors—ensuring accurate results. Two approaches were investigated to reduce computational time during nonlinear iterations. The speed of the iterative procedure was significantly improved through the use of an acceleration scheme and an adaptive error control method. The modified Thomas scheme, as formulated by Sloan et al. (2002), is implemented in Gofer and has reduced iteration time by approximately 80–90%.

Further reduction in iteration time was achieved through a newly implemented method called “adaptive error control,” which monitors the rate of displacement change over a specified number of iterations. The process is terminated once displacement changes stabilize within a predefined accuracy threshold, resulting in an additional 5–8% reduction in iteration time.

6 CONCLUSIONS

This paper has presented a stable and efficient alternative to the classical undrained effective stress formulation in geotechnical finite element analysis. By approximating the undrained response through a short-term consolidation solution with low permeability, and assigning excess pore pressure degrees of freedom only at corner nodes via composite elements, the proposed method eliminates the need for additional smoothing or stabilisation techniques. Sensitivity analyses confirmed that this approach significantly improves numerical stability, removes oscillatory behaviour, and yields smooth, mesh-independent pore pressure distributions.

The use of a unified consolidation solver throughout all construction stages enhances both numerical stability and computational efficiency. The proposed method improves the reliability of undrained effective stress analysis and offers a practical solution to overcome pressure oscillations in saturated soil modelling during short-term construction stages, supporting more stable and accurate geotechnical design outcomes.

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