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Numerical Modelling of Secant Caisson Shoring in High-Stress Shallow Bedrock

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Abstract

Large circular shafts excavated into shallow bedrock under high and anisotropic in-situ stress conditions present design challenges that are not adequately captured by conventional earth-pressure-based approaches. In such environments, excavation response is governed by rock mass stress redistribution, stress-path dependence, deformation compatibility, and construction sequencing rather than gravity-driven loading alone.

In the stress regime considered herein, the in-situ stress state within bedrock is dominated by three principal components. The vertical stress component (σ_3) represents pre-existing tectonic and geological loading within the rock mass and is substantially greater than the stress arising from self-weight alone. The horizontal principal stresses (σ_1 and σ_2), oriented along orthogonal horizontal directions, are similarly elevated and anisotropic, resulting in a strongly stress-controlled excavation environment. This stress configuration leads to non-uniform load transfer and directional stress concentration around the shaft perimeter during excavation.

This paper presents a generalized and transferable workflow for the design of secant caisson shoring systems embedded in high-stress shallow bedrock. The methodology integrates staged three-dimensional finite-element ground–structure interaction modelling with sensitivity analysis and complementary rock stability screening. The numerical framework explicitly captures anisotropic in-situ stress conditions, staged soil and rock excavation, partial caisson penetration into bedrock, internal ring activation, and progressive engagement of shotcrete and passive rock anchors in the rock-socketed portion of the excavation.

Results demonstrate that interface stresses and rock mass response are highly non-uniform and directionally controlled by the in-situ stress field and excavation sequence, rather than by classical earth-pressure assumptions. Observed stress redistribution and stress-history effects highlight the importance of deformation-permissive support concepts that allow controlled stress release. Sensitivity analyses are used to bound uncertainty in rock mass properties and stress conditions, supporting a risk-informed, observational design approach applicable to other high-stress shallow bedrock shaft excavations.

Keywords

Numerical modeling, High-anisotropic in-situ stress, Secant caisson wall, Deformation-permissive support, Risk management, Observational approach.

1 Introduction

Large-diameter shafts excavated through overburden soils and into shallow bedrock are increasingly required for underground infrastructure. When excavation extends into bedrock under elevated, anisotropic horizontal in-situ stress, governing mechanisms differ fundamentally from those assumed in conventional earth-pressure-based shoring design. Excavation response becomes controlled by rock mass stress redistribution, deformation compatibility, and construction sequencing rather than by gravitational loading alone.

2 Ground conditions and design constraints

The workflow addresses shafts excavated through overburden soils into competent sedimentary bedrock where horizontal in-situ stresses are high relative to vertical stress. The soil–rock transition is critical because stiffness contrast and stress transfer mechanisms change rapidly with depth, and groundwater may be present in both soil and rock.

For the representative application informing this paper, the excavation comprises a large circular shaft supported by a continuous secant caisson wall socketed into shallow bedrock. Key geometric and construction features include: (i) staged excavation with activation of internal rings, (ii) excavation diameter reduction below the soil–rock interface to provide a rock ledge and shotcrete support, (iii) passive rock anchors below the caisson toe to manage stress release, and (iv) temporary surcharges and construction tolerances considered in design.

The authors were not involved in the original geotechnical exploration program or rock mass characterization; modelling inputs are based on interpreted parameters provided in project geotechnical documentation and are treated with explicit uncertainty through sensitivity analyses.

3 Shoring concept and rock mass design philosophy

The temporary support system consists of a circular secant caisson wall in soil with partial penetration into bedrock, supplemented by internal structural rings to control ovalization and mobilize hoop compression. Below the soil–rock interface, rock excavation is supported by shotcrete and passive anchors.The overall configuration and interaction between the wall, internal rings, and rock support elements are illustrated conceptually in Fig. 1.

A deformation-permissive concept is adopted in the rock portion: shotcrete provides the initial surface stabilization and limits rapid stress release, while passive anchors provide redundancy that engages progressively with increasing deformation. This approach aims to manage stress redistribution in high-stress rock while maintaining stability and limiting long-term load transfer to permanent works.

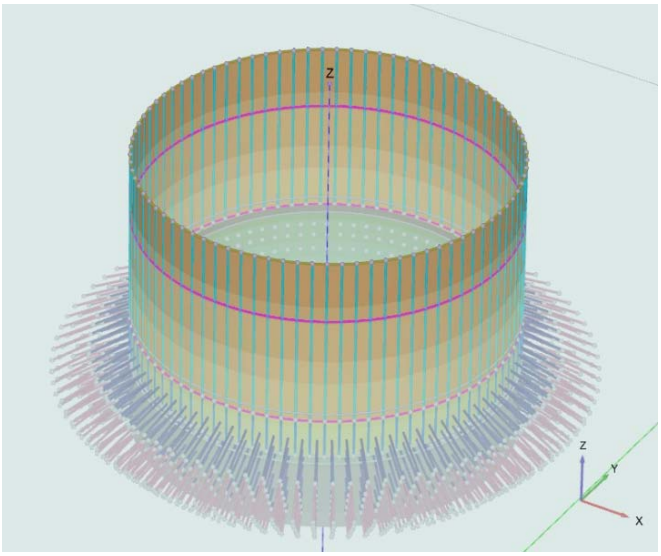


Fig. 1 Conceptual arrangement of the secant caisson wall system with internal rings and rock support elements.

4 Numerical modelling methodology

A three-dimensional finite-element ground–structure interaction model is implemented in PLAXIS 3D to capture stress-path dependence, anisotropic in-situ stress conditions, and the staged excavation and the support installation sequence. The numerical model explicitly represents the soil–rock stratigraphy, secant caisson wall, and supporting elements in three dimensions. Model extents are selected to minimize boundary effects, with local refinement applied in the vicinity of the shaft and the soil–rock transition. The overall model geometry and representative domain extents adopted for the analyses are shown in Fig. 2.

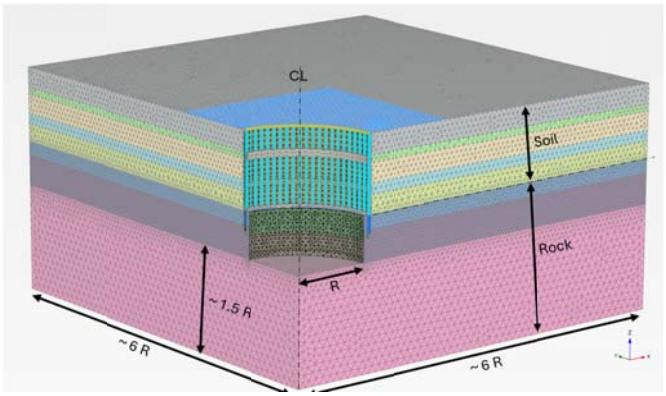


Fig. 2Numerical model geometry and domain extents used in the three-dimensional finite-element analysis.

4.1 Staging and structural representation

Construction is simulated through phases including stress initialization, caisson installation, staged excavation with ring activation, and rock excavation with activation of shotcrete and passive anchors. Structural components are represented using linear-elastic elements to extract deformations and internal forces for subsequent structural checks.

4.2 Constitutive models and parameterization

Soils are represented using a hardening soil model with small-strain stiffness to capture stiffness decay with strain and unloading/reloading response typical of excavation.

Bedrock behaviour is represented using the non-linear Hoek–Brown rock mass failure criterion to capture stress-dependent strength and deformation under elevated horizontal in-situ stress. For large-diameter shafts excavated into shallow bedrock, excavation response is governed primarily by stress redistribution and deformation compatibility rather than by discrete block detachment alone; a continuum representation is therefore appropriate for the numerical modelling scale adopted.

Rock mass parameters are derived from intact properties and GSI-based characterization reported by others and applied using standard Hoek–Brown relationships. Uncertainty associated with these inputs is addressed through sensitivity analysis. The Hoek–Brown continuum model is used to evaluate stress redistribution and deformation demand, while potential discontinuity-controlled mechanisms are addressed separately through complementary stability screening methods.

4.3 In-situ stress field, groundwater, and interfaces

High horizontal stress conditions are initialized as anisotropic principal stresses aligned with the dominant horizontal stress direction. Groundwater is represented using hydrostatic heads consistent with measured/anticipated groundwater levels in soil and bedrock. Concrete–ground interaction is represented using reduced-strength interface elements with gap-closure to avoid non-physical tensile separation.

4.4 Verification and numerical quality checks

Numerical verification checks were performed for both soil and rock components to ensure that predicted responses are governed by material behaviour and excavation sequencing rather than numerical artefacts. For soil, small-strain stiffness implementation was verified through appropriate unloading–reloading response and modulus-reduction behaviour consistent with laboratory observations.

For the rock mass, verification focused on numerical stability and realism of stress redistribution under high horizontal in-situ stress. Mesh density and element formulation near the shaft were assessed to confirm that tangential stress concentrations were not unduly influenced by discretization, and sensitivity checks showed that further mesh refinement did not materially alter stress distribution patterns around the excavation.

Rock deformation response was reviewed to ensure consistency with expected continuum behaviour under the Hoek–Brown representation, avoiding unrealistically brittle failure or excessive localization. Stress paths during staged excavation were examined to confirm that changes in confinement and tangential stress were driven by excavation sequencing and support activation rather than boundary effects or numerical imbalance. Stable equilibrium and convergence were achieved at all stages under anisotropic stress initialization.

These checks provide confidence that the model captures the dominant stress-controlled rock mass response relevant to excavation support behaviour, while recognizing that discontinuity-controlled mechanisms are addressed separately through stability screening.

5 Key modelling outputs and Sensitivity analysis

Sensitivity analyses are performed to bound uncertainty in rock mass stiffness/strength and in-situ stress magnitude and orientation. The analyses assume time-independent rock mass behaviour; time-dependent mechanisms such as creep or swelling are not explicitly modelled over the construction timeframe. However, based on available geotechnical data, creep and/or swelling are not expected to be significant and are unlikely to affect temporary shoring stability.

Key outputs used for design and risk management include: (i) lateral pressure distributions around the shaft, (ii) wall deformations and ovalization response with ring activation, and (iii) tangential stress distributions in bedrock for screening of stress-induced damage potential. These outputs are used to calibrate simplified structural models where required and to define monitoring targets for an observational approach.

Fig. 3 presents the distribution of interface normal stress plotted as a function of circumferential angle relative to the major principal in-situ stress direction. The pronounced directional variation reflects stress-path dependence and redistribution associated with staged excavation under anisotropic in-situ stress conditions, rather than uniform earth-pressure behaviour. The scatter in values at a given circumferential orientation reflects depth-dependent variations in normal stress along the rock–secant wall interface, with different symbols representing stresses extracted at different elevations; the resulting spread illustrates the stress history developed during staged excavation.

Radial deformation of the secant caisson wall extracted from the three-dimensional numerical model is used to support cross-checking of wall response against simplified structural modelling. Fig. 4 illustrates the circumferential distribution of radial deformation at the base of the secant caisson wall, demonstrating directionally dependent deformation consistent with the anisotropic in-situ stress field.

Tangential stress concentrations around the excavation, used for screening of stress-induced damage potential in shallow bedrock, are also shown separately in Fig. 5and are discussed in Section 6 (Stability Screening and Risk Controls).

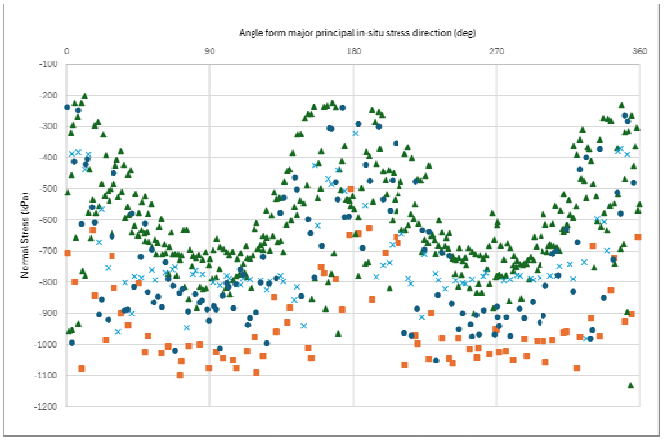


Fig. 3 Normal stress at the rock–secant wall interface plotted versus circumferential angle relative to the major principal in-situ stress direction; different symbols represent stresses extracted at different bedrock elevations. Negative values indicate compressive rock–wall interaction.

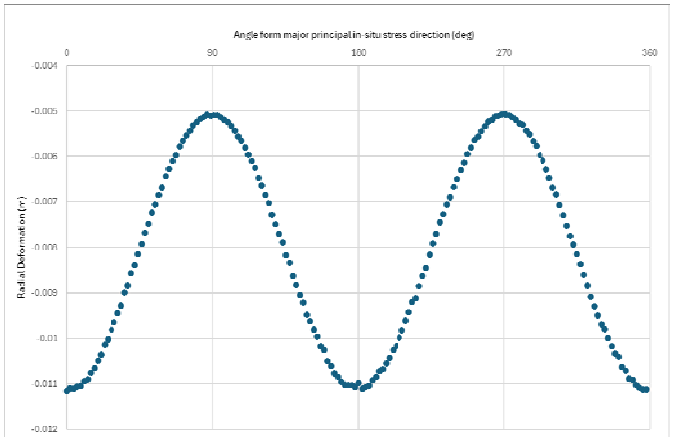


Fig. 4 Radial deformation of the lower portion of the secant caisson wall versus circumferential angle relative to the major principal in-situ stress direction; negative values indicate convergent deformation toward the shaft center.

6 Stability screening and risk controls

Rock stability is evaluated through complementary screening mechanisms addressing both stress-controlled and discontinuity-controlled responses. Stress-induced damage potential is assessed by comparing tangential stresses around the excavation to representative crack-initiation or spalling thresholds expressed as a fraction of intact strength. Discontinuity-controlled instability is screened using representative wedge/block concepts based on bedding-parallel and inferred sub-vertical joint sets.

Global stability is evaluated using a conservative numerical screening approach compatible with the Hoek–Brown rock mass model. As conventional C-φ strength-reduction methods are not directly applicable, adverse conditions are explored by increasing the rock mass disturbance factor to induce instability. Following introduction of shotcrete and passive anchors, the supported excavation exhibits stable deformation without numerical failure, indicating adequate stability under conservative assumptions. The screening results inform risk controls such as groundwater management, staged support timing, exclusion-zone load management, and predefined contingency measures consistent with an observational construction approach.

Tangential stress concentration is evaluated using the σ_{xx} stress component as a representative indicator at locations where the excavation boundary is aligned with the global coordinate system, with zones of elevated stress highlighted in red used to identify potential areas of maximum tangential stress concentration for screening purposes.

Stress-based screening relies on tangential stress indicators such as those shown in Fig. 5, while interface stress redistribution trends inform the risk-control framework as demonstrated in Fig. 3.

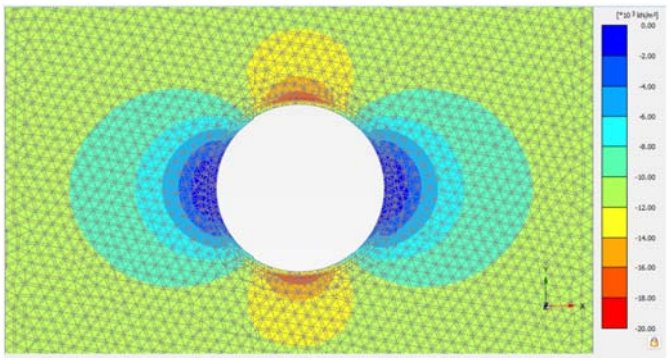


Fig. 5 Contours of σ_{xx} stress component around the excavation at the lower portion of the secant wall, used as a representative indicator of tangential stress concentration for stress-induced damage screening. Red zones indicate locations of elevated tangential stress under anisotropic in-situ stress conditions.

7 Risk management and observational approach

The workflow is intended as a decision-support tool rather than a single deterministic predictor. Risk management is achieved by: (i) identifying governing construction stages; (ii) bounding response with conservative parameter sets; (iii) designing passive, redundant support that engages progressively; and (iv) implementing an observational approach in which field monitoring targets are linked to trigger levels and predefined mitigation actions. This reduces reliance on a single model realization and supports defensible construction decision-making in high-stress rock.

Normalized stress and deformation metrics derived from the numerical analyses provide a practical basis for defining monitoring trigger levels and pre-defined mitigation actions consistent with an observational construction approach.

8 Conclusions

The design of secant caisson shoring embedded in high-stress shallow bedrock is governed primarily by rock mass stress redistribution and deformation compatibility rather than by conventional soil earth-pressure mechanisms. A deformation-permissive support concept using shotcrete and passive anchors below the caisson toe can manage stress release and reduce long-term load transfer to permanent works while maintaining excavation stability.

Three-dimensional staged modelling, combined with sensitivity analysis and stability screening, provides a robust basis for support optimization and risk management.

Interface stress redistribution trends (Fig. 5) reinforce that bedrock response is governed by anisotropic stress history and deformation compatibility rather than uniform pressure assumptions.

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