Malaysian Journal Of Civil Engineering

Full Paper

INFLUENCE OF INTERFACE REDUCTION FACTOR ON SOIL-NAIL INTERACTION IN FINITE ELEMENT MODELLING USING PLATE ELEMENTS

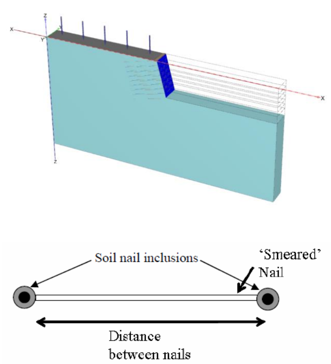
Khoo Chee Min[a,b]*

[a]Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak, Malaysia
[b]CMKS Consultancy Sdn Bhd, 40460 Shah Alam, Selangor, Malaysia

Article history
Received
26 March 2026
Received in revised form
29 Junel 2026
Accepted
01 July 2026
Published online
30 July 2026

*Corresponding author
cmkhoo@cmksgroup.com

Graphical abstract



Abstract

Finite element modelling of soil-nailed systems requires appropriate representation of soil-nail interaction to ensure reliable assessment of stability and deformation behavior. In simplified modelling approaches, soil nails are commonly represented using plate elements with interface elements governed by the interface reduction factor (R_{inter}). However, the selection of R_{inter} remains largely empirical and may significantly influence analysis results. This study investigates the influence of R_{inter} using three-dimensional finite element modelling through a parametric study. System performance is evaluated in terms of axial load development, global stability, and horizontal deflection, with comparisons made against embedded beam modelling as benchmarks. The results indicate that R_{inter} has a significant effect on system behavior. Lower values result in insufficient axial load mobilization and conservative predictions, while higher values may lead to overestimation of interface bonding and system stiffness. Although plate-based modelling can reasonably reproduce global behavior, discrepancies remain in axial load prediction. Overall, $R_{inter} \approx 0.3$ provides the most balanced representation. The study highlights the need for careful calibration of interface parameters and consideration of modelling assumptions, including nail spacing and stress-dependent interaction behavior, to ensure reliable numerical predictions.

Keywords: Soil nailing, PLAXIS, R_{inter}, interface reduction factor, finite element analysis

1.0 INTRODUCTION

1.1 Principles of Soil Nailing

Soil nailing is widely recognized as an efficient and economical technique for stabilizing slopes and excavations. The in-situ reinforcement method involves the installation of closely spaced steel bars or tendons into the ground, which are subsequently grouted to provide corrosion protection and enhance load transfer between the soil and the reinforcement. The nails are typically installed in a horizontal or slightly inclined orientation to intercept potential failure surfaces.

The primary function of soil nails is to improve the stability of the ground by mobilizing tensile resistance and increasing the normal stress along potential slip surfaces, thereby enhancing the overall shear strength of the soil mass. Through this mechanism, the reinforced soil behaves as a composite system, where the interaction between soil and nails enables the formation of a stable and coherent mass. This reinforced zone effectively acts as a gravity-like structure, providing support to the retained soil behind it.

A facing system is usually incorporated at the exposed surface to maintain stability during construction and in the long term, which may be designed as either a flexible system (e.g. shotcrete) or a rigid structural facing, depending on project requirements.

Soil nailing is widely applied for both temporary and permanent stabilization works. It is commonly used in the stabilization of natural and man-made slopes, as well as for providing support to vertical or near-vertical excavations in infrastructure projects such as roads, railways, and tunnel portals (Lee et al., 2011). In urban environments, it is also extensively adopted for deep basement excavations (Liew & Khoo, 2006; Tan & Chow, 2011), particularly where ground conditions are favorable for staged construction and the installation of passive reinforcement systems.

1.2 Numerical Simulation of Soil-Nail Interaction

Finite element modelling of soil-nailed system represents a complex soil-structure interaction problem, which is inherently three-dimensional in nature. The behavior of such systems is governed by the interaction between the soil mass, the reinforcement elements (soil nails), and the facing system. Key factors influencing performance include soil constitutive behavior, nail stiffness, construction sequence, installation effects, and the interaction mechanisms at the soil-nail and nail-facing interfaces (Babu & Singh, 2007).

Accurate simulation therefore requires careful selection of constitutive models, structural elements, and interface formulations. Previous studies have demonstrated that advanced constitutive soil models and interface elements are essential to realistically capture stress-strain behavior and load transfer mechanisms in soil-nailed systems (Tan et al., 2004; Farias et al., 2005; Singh & Babu, 2010). Recent numerical studies have continued to expand the application of finite element modelling in soil nailing analysis under various loading and construction conditions, including staged excavation and dynamic effects (Mohamed et al., 2023; Maleki et al., 2025). Consequently, the reliability of finite element analysis depends not only on the computational tools employed, but also on the user's understanding of the underlying geotechnical behavior and the appropriate selection of modelling parameters.

A critical aspect in the modelling of soil-nailed systems is the representation of soil-nail interaction, particularly the mobilization of shear resistance along the soil-nail interface. This interaction governs both global stability and deformation behavior. In PLAXIS analyses, different modelling approaches are available to simulate soil nails. Embedded beam elements represent soil-nail interaction through pre-defined bond-slip relationships, whereas geogrid and plate elements rely on interface elements characterized by the interface reduction factor (R_{inter}), which defines the ratio of interface strength relative to that of the surrounding soil.

Geogrid elements are axial members capable of resisting tensile forces only, while plate elements, typically formulated based on Mindlin's plate theory (Bathe, 1982), possess both axial and bending stiffness, allowing for a more versatile representation of structural behavior. In both approaches, soil nails are commonly represented using simplified or "smeared" techniques, whereby discrete reinforcement elements are idealized as continuous structural components within the soil mass, as illustrated in Figure 1.

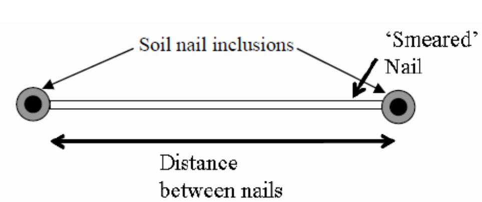


Figure 1"Smeared" technique for equivalent soil nail parameters (Tan et al., 2004)

In a recent study by Khoo et al. (2025), various modelling approaches - including geogrid, plate and embedded beam elements - were evaluated. The study demonstrated that while smeared techniques provide a practical and computationally efficient approach for finite element analysis, they require careful calibration to realistically represent soil-nail interaction. In particular, the selection of interface parameters was identified as a key source of variability in the predicted behavior.

Despite its importance, the selection of R_{inter} remains largely empirical and varies significantly in practice. Inappropriate assumptions may lead to inaccurate assessment of global stability and deformation, potentially resulting in unsafe or overly conservative designs. Although discrepancies between different modelling approaches have been highlighted in previous studies (Khoo et al., 2025), limited attention has been given to systematically evaluating the influence of R_{inter} in plate-based soil nailing modelling.

Therefore, this study aims to investigate the influence of the interface reduction factor (R_{inter}) on the behavior of soil-nailed systems using finite element analysis. A parametric study is conducted to quantify its impact on axial load development, global stability, and deformation, with comparisons made against embedded beam modelling to establish a rational basis for the selection of appropriate R_{inter} values.

1.3 Objective of the Study

The primary objective of this study is to investigate the influence of the interface reduction factor (R_{inter}) on the behavior of soil-nailed systems modelled using plate elements in finite element analysis. Particular emphasis is placed on understanding how R_{inter} affects global stability, deformation response, and axial load development within the soil nails.

In addition, the study evaluates the suitability of plate-based modelling approaches by comparing the results with those obtained from embedded beam modelling, which provides a more rigorous representation of soil-nail interaction (Khoo et al., 2025). Through this comparison, a rational basis for the selection of appropriate R_{inter} values is established.

Ultimately, the findings aim to improve the reliability of simplified finite element modelling techniques for soil nailing and to provide practical guidance for engineering analysis and design.

2.0 METHODOLOGY

The analyses in this study were carried out using both finite element and limit equilibrium approaches. Three-dimensional finite element modelling was performed using PLAXIS 3D to evaluate the global stability, deformation behavior and internal force development of the soil-nailed system. This software enables the simulation of soil nailing in a manner the closely replicates the staged construction process encountered during actual excavation. In addition, conventional limit equilibrium analysis was conducted using SLOPE/W to provide a benchmark comparison in terms of global stability.

The modelling framework, including geometry, material properties, and analysis procedures, is described in the following sections.

2.1 Numerical Model Configuration

The numerical model was developed to represent a typical soil-nailed slope configuration commonly encountered in practice. The model consists of a 12 m high slope with an inclination of 4V:1H, representing a relatively steep reinforced cut.

The slope is stabilized using a system of uniformly distributed soil nails installed along the exposed face. Each soil nail has a length of 12 m, approximately equal to the slope height, ensuring adequate anchorage beyond the potential failure surface. The nails are installed at an inclination of 15° below the horizontal, which is consistent with common design practice to enhance pull-out resistance and facilitate effective grouting. In this study, a constant vertical spacing of 1.5 m and a horizontal spacing of 1.2 m are adopted.

The soil nails comprise a grouted system with a nominal diameter of 125 mm, incorporating a steel reinforcement bar of 32 mm diameter. The material properties of the reinforcement and grout are defined by a yield strength of 460 N/mm^2 and a compressive strength of 30 N/mm^2, respectively. A structural facing system consisting of 125 mm thick shotcrete is included to represent the surface support. Overall, these parameters are representative of typical soil nailing practice and provide a consistent basis for evaluating the influence of interface behavior in the subsequent analysis.

To minimize boundary effects in three-dimensional analysis, the numerical domain was extended beyond the region of interest. The model dimensions were defined as 40 m in height, 80 m in length, and 6 m in width, which are considered sufficient to avoid boundary influence on the results. Appropriate boundary conditions were applied, whereby lateral fixities were assigned perpendicular to the vertical boundaries, while both vertical and horizontal displacements were restrained at the base of the model. Consequently, movements normal to the vertical boundaries and in all directions at the base were restrained. Figure 2 illustrates the perspective view of the developed three-dimensional numerical model.

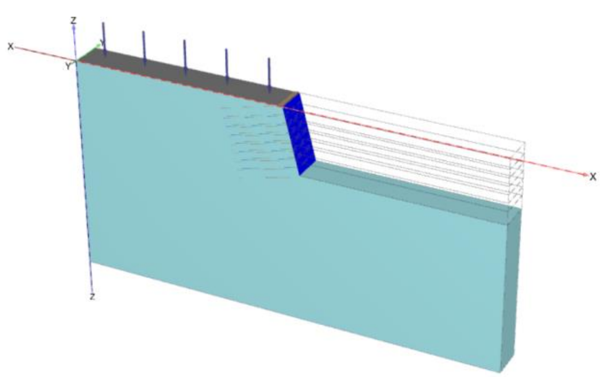


Figure 2 Perspective view of the developed 3D numerical model

The finite element discretization was carried out using 10-node tetrahedral elements to represent both the soil and structural components. A "medium" density was initially adopted, and its adequacy was subsequently verified through mesh sensitivity analysis. This involved iterative refinements of the mesh until the changes in computed displacements became negligible (Maleki & Hosseini, 2022). The results confirmed that the selected mesh density is sufficient to achieve the desired level of accuracy.

2.2 Soil Constitutive Model and Material Properties

The soil behavior was simulated using the Hardening Soil (HS) model, an advanced elasto-plastic constitutive model that accounts for stress-dependent stiffness and distinct stiffness moduli for primary loading, unloading/reloading, and oedometer loading conditions. The HS model is derived from the hyperbolic model originally proposed by Duncan & Chang (1970), with further enhancements described by Schanz et al. (1999). Compared to the conventional Mohr-Coulomb model, the HS model provides a more realistic representation of soil behavior, particularly for problems involving stress path dependency and deformation analysis. As highlighted by Singh & Babu (2010), the use of advanced soil constitutive model is essential for accurately capturing the relatively small lateral displacements associated with soil-nailed systems.

The HS model is defined by three primary stiffness parameters: the secant stiffness in standard drained triaxial loading (E_{50}^{ref}), the tangent stiffness for primary oedometer loading (E_{oed}^{ref}), and the unloading/reloading stiffness (E_{ur}^{ref}). In addition, the model incorporates strength parameters, namely effective cohesion (c'), and friction angle (ϕ'), together with the dilatancy angle (φ) and a stress dependency exponent (m), which governs the variation of stiffness with confining pressure. This formulation enables a more accurate simulation of both non-linear soil response and stiffness degradation under loading. The adopted soil parameters for the analysis are summarized in Table 1.

Table 1 Soil parameters

Parameter (unit)	Notation	Value
Soil model	-	HS
Drainage type	Model	Drained
Unsaturated unit weight (kN/m^3)	γ_{unsat}	18.0
Saturated unit weight (kN/m^3)	γ_{sat}	18.0
Secant stiffness (kN/m^2)	E_{50}^{ref}	5.0 x 10^4
Tangent stiffness (kN/m^2)	E_{oed}^{ref}	5.0 x 10^4
Unloading/reloading stiffness (kN/m^2)	E_{ur}^{ref}	1.5 x 10^5
Poisson's ratio	ν	0.2
Power for stress-level dependency of stiffness	m	0.5
Cohesion (kN/m^2)	c'^{ref}	5
Friction angle (°)	ϕ'	30
Dilatancy angle (°)	φ	0

For the grouted nails, the equivalent modulus of elasticity (E_{eq}) was determined based on the combined stiffness contribution of the grout and the steel reinforcement, in accordance with the principles of mechanics of materials, as expressed in Eq. (1).

$$E_{eq} = E_g \left(\frac{A_g}{A}\right) + E_b \left(\frac{A_b}{A}\right) \tag{1}$$

where

E_g = modulus of elasticity of grout material
E_b = modulus of elasticity of reinforcement bar
A_g = cross-sectional area of grout cover
A_b = cross-sectional area of reinforcement bar
A = total cross-sectional area of grouted soil nail

For plate-based elements, the 'smeared' technique was adopted to transform the discrete circular soil nails into equivalent continuous plate elements. The equivalent axial stiffness ($E_{eq}A_n$) and bending stiffness ($E_{eq}I_n$) were derived based on the nail geometry and spacing. I_n and E_n are the moment of inertia and cross-sectional area based on the soil nail (drilled hole) diameter. The equivalent plate thickness (d_{eq}) was subsequently determined using Eq. (2), ensuring that the structural behavior of the nails is appropriately represented within the two-dimensional framework.

$$d_{eq} = \sqrt{12(\frac{E_{eq}I_{eq}}{E_{eq}A_{eq}})} \quad (2)$$

The interaction between the soil and the plate elements were modelled using interface elements, with their strength governed by the interface reduction factor, R_{inter}. The interface shear strength was defined as a reduced value of the surrounding soil strength, expressed as:

$$c_{interface} = R_{inter} \cdot c_{soil} \quad (3)$$

$$\tan\phi_{interface} = R_{inter} \cdot \tan\phi_{soil} \quad (4)$$

This formulation allows for the simulation of varying degrees of bonding and slip between the soil and reinforcement. The selection of R_{inter} therefore plays a critical role in controlling the mobilization of axial forces within the soil nails and, consequently, the overall system response.

2.3 Construction Sequence and Analysis Procedure

The analysis was conducted using a staged construction procedure to simulate the progressive excavation and installation of soil nails. The excavation process was modelled in a series of stages (E1 to E7), as illustrated in Figure 3. In each stage, the corresponding soil cluster representing the excavation lift was deactivated, followed by the activation of the soil nails and the facing system.

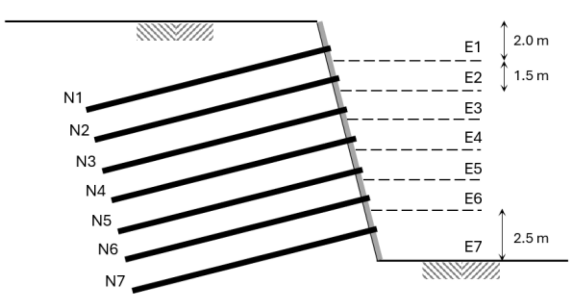


Figure 3 Staged construction sequence simulated in finite element analysis

This analysis was performed using a "plastic" calculation type, allowing the model to reach equilibrium at each stage before proceeding to the next. Upon completion of the construction sequence, displacement results were extracted to assess the deformation behavior of the system. In addition, the global factor of safety was evaluated using the strength reduction method (phi-c reduction) with the "safety" calculation option.

2.4 Parametric Study

A systematic parametric study was carried out to evaluate the influence of the interface reduction factor (R_{inter}) on the behavior of soil-nailed systems. In this study, R_{inter} was varied over a range from 0.1 to 1.0, representing conditions from very weak interface interaction (approaching fully slip) to fully bonded behavior. This range encompasses typical values adopted in practice while allowing assessment of extreme cases to better understand the sensitivity of system response.

For each value of R_{inter}, the numerical model was analyzed under identical geometry, soil properties, boundary conditions, and loading scenarios, such that any variation in results can be attributed solely to the changes in interface behavior.

The system response was evaluated based on three key parameters:

(i) Axial load development in soil nails
The axial force distribution along the soil nails were examined to provide insight into the load transfer mechanism. Axial load development reflects the degree of mobilization of soil-nail interaction and is directly influenced by the interface behavior governed by R_{inter}. For each analysis case, axial force profiles were extracted at the end of each excavation stage. Particular attention was given to the magnitude and evolution of peak axial loads to assess the mobilization of resistance within the reinforced zone.

(ii) Global stability (Factor of Safety, FOS)
The global stability of the soil-nailed system was evaluated using the strength reduction method implemented in PLAXIS. The shear strength parameters of the soil, namely cohesion (c') and friction angle (ϕ'), were progressively reduced until failure occurred, and the corresponding reduction factor at failure was taken as the factor of safety (FOS). This parameter was used to quantify the influence of R_{inter} on overall system stability.

(iii) Maximum horizontal deflection
The serviceability performance of the system was evaluated based on the maximum horizontal deflection at the slope face. This parameter is of practical importance, as excessive deformation may lead to structural damage or serviceability issues even when overall stability is deemed acceptable. The maximum horizontal deflection was extracted from the computed displacement profiles for each R_{inter} value, providing an indication of deformation control under different interface conditions.

Overall, the combined evaluation of axial load development, global stability (factor of safety), and deformation enables a comprehensive assessment of internal load transfer mechanisms, ultimate limit state (ULS) behavior, and serviceability limit state (SLS) performance. This integrated approach provides a more holistic understanding of the influence of interface behavior on soil-nailed systems.

2.5 Benchmark Comparison

To establish a reference for evaluating the results obtained from the plate-based modelling approach, additional analyses were conducted using alternative methods commonly adopted in engineering practice. These include the embedded beam elements within PLAXIS and the conventional limit equilibrium method (LEM).

(i) Embedded Beam Element Modelling

The embedded beam element modelling approach adopted in this study is based on the methodology established in Khoo et al. (2025), where soil nails were simulated as structural elements characterized by predefined axial stiffness and bond strength parameters. In this formulation, soil-nail interaction is internally modelled through interface springs that simulate the mobilization of skin friction along the nail length.

Unlike plate-based modelling, which requires explicit definition of interface properties through the interface reduction factor (R_{inter}), the embedded beam formulation incorporates bond behavior directly through input parameters. As demonstrated by Khoo et al. (2025), this method provides a more rigorous representation of soil-nail interaction, particularly in capturing axial load mobilization and load transfer mechanisms.

Accordingly, the embedded beam model is adopted as a benchmark reference in this study to assess the validity and performance of the plate-based modelling approach under varying interface conditions.

(ii) Limit Equilibrium Method (LEM)

In addition to finite element analysis, the global stability of the soil-nailed system was evaluated using a conventional limit equilibrium method. The analysis was carried out using established procedures, whereby the factor of safety is determined by satisfying force and moment equilibrium along a potential failure surface.

The LEM approach provides a widely accepted reference for slope stability assessment in engineering practice. However, it does not explicitly account for deformation or stress-strain behavior, and soil-nail interaction is typically represented using simplified assumptions. Despite these limitations, LEM results remain valuable for benchmarking purposes, particularly for comparison of global stability.

The results obtained from the parametric study with varying R_{inter} were compared against those derived from embedded beam modelling and LEM analysis. The comparison focuses on:

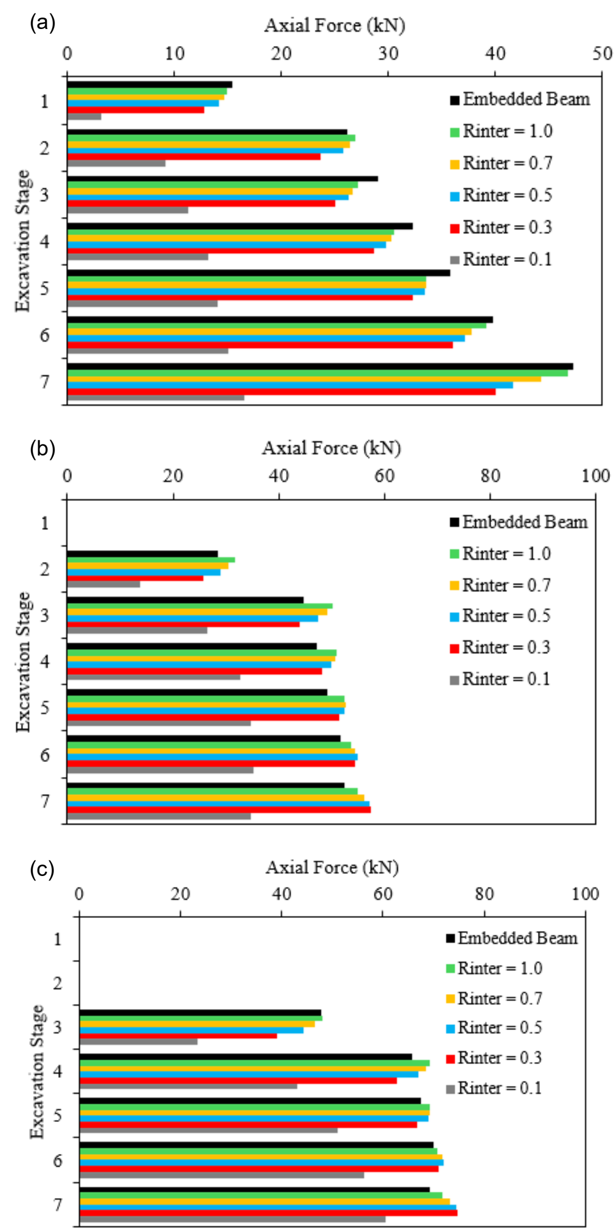
(i) Axial load development in soil nails (for finite element approach)
(ii) Global stability (Factor of safety, FOS) (for both finite element and limit equilibrium approaches)
(iii) Maximum horizontal deflection (for finite element approach)

This comparative assessment enables evaluation of the extent to which different values of R_{inter} can reproduce the behavior predicted by the embedded beam approach established in Khoo et al. (2025), as well as conventional LEM results. Furthermore, it provides a rational basis for identifying an appropriate range of R_{inter} that yields consistent and reliable predictions for practical engineering applications.

3.0 RESULTS AND DISCUSSION

3.1 Influence of R_{inter} on Axial Load Development

The influence of the interface reduction factor (R_{inter}) on axial load development in soil nails is illustrated in Figure 4, which presents the variation of maximum axial forces mobilized at different excavation stages (E1 to E7) for both plate-based modelling and embedded beam elements.



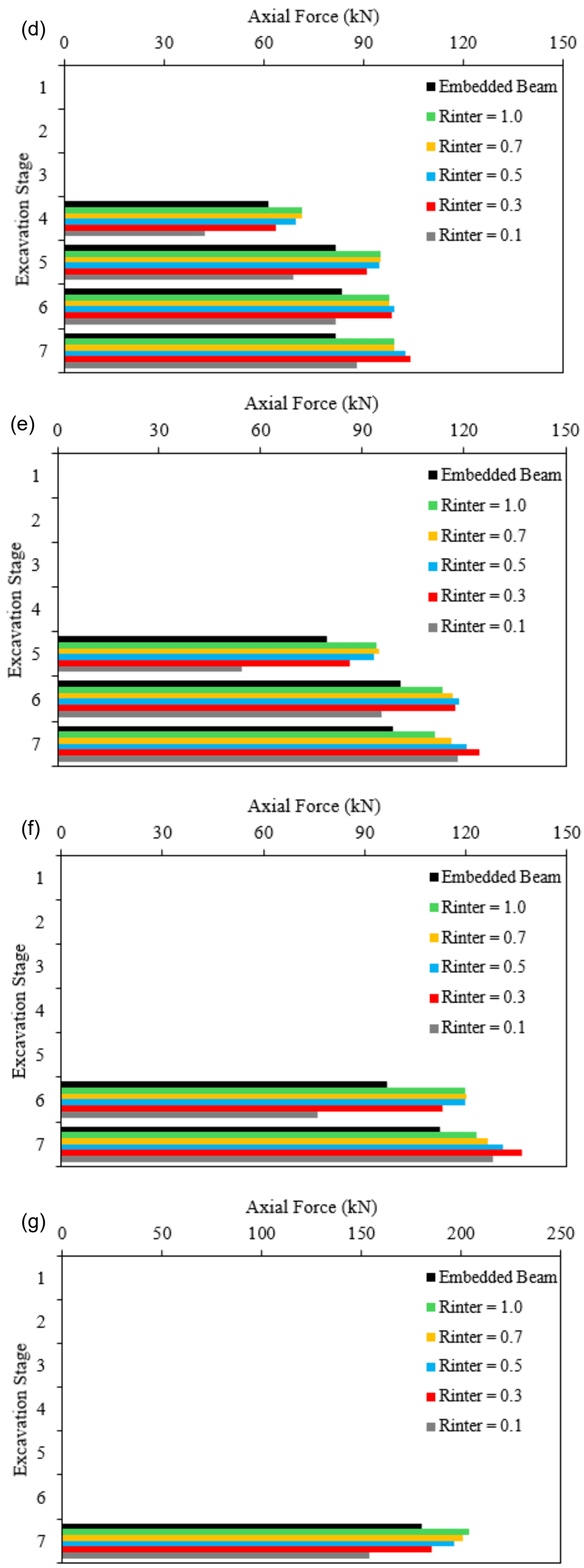


Figure 4 Comparison of maximum axial load developed during each excavation stage between the embedded beam elements and varying R_{inter} values in plate-based modelling: (a) soil nail N1, (b) soil nail N2, (c) soil nail N3, (d) soil nail N4, (e) soil nail N5, (f) soil nail N6, and (g) soil nail N7

Overall, the axial load response provides fundamental insight into the load transfer mechanism between the soil and the nail. The development and distribution of axial forces along the soil nails reflect the degree of mobilization of interface shear resistance, which governs the effectiveness of the reinforcement system. As such, understanding the influence of R_{inter} on axial load development is essential, as it directly underpins the global stability and deformation behavior discussed in the subsequent sections.

At low R_{inter} values (e.g. 0.1), the axial loads developed in the plate-based modelling are almost consistently lower than those predicted by the embedded beam model across all excavation stages. This behavior reflects weak interface bonding, where significant slips occur between the soil and the nail, resulting in inefficient load transfer and limited mobilization of tensile forces.

As R_{inter} increases to 0.3, a noticeable increase in axial load mobilization is observed. In general, this value provides the closest overall agreement with the embedded beam results in terms of the order of magnitude of axial loads. Nevertheless, discrepancies remain evident, particularly in the distribution and peak locations of axial loads along different excavation stages.

At higher R_{inter} values (≥ 0.5), the axial loads predicted by the plate-based model tend to exceed those of the embedded beam model, although the degree of overestimation varies between stages. This suggests that the assumption of stronger interface bonding leads to more efficient load transfer, but may also result in unrealistic mobilization of tensile forces under certain conditions.

It is also observed that axial load response varies significantly with excavation stages. While deeper nails (e.g. N4 to N7) generally experience higher axial forces due to increased overburden and mobilization of earth pressures, the degree of agreement between modelling approaches is not consistent across all stages. In some cases, the plate-based model underestimates axial loads at shallow levels while overestimating them at deeper levels, indicating differences in load transfer mechanisms between the two modelling approaches.

The observed variability can be attributed to fundamental differences in how soil-nail interaction is represented. In plate-based modelling, load transfer is governed by interface elements defined through R_{inter}, which provides a simplified representation of bond behavior. In contrast, the embedded beam formulation simulates soil-nail interaction through distributed bond-slip relationships, allowing for a more realistic representation of load mobilization along the nail length.

Overall, the results suggest that while $R_{inter} \approx 0.3$ provides a reasonable approximation in terms of axial force magnitude, the plate-based modelling approach is less capable of consistently capturing the detailed axial load distribution compared to the embedded beam model. This highlights the limitation of simplified interface-based approaches and underscores the need for careful calibration when using plate elements to simulate soil nails in finite element analysis.

3.2 Influence of R_{inter} on Global Stability (Factor of Safety)

The variation of factor of safety (FOS) with the interface reduction factor (R_{inter}) is presented in Figure 5. The results indicate a pronounced non-linear relationship, highlighting the critical role of interface behavior in governing global stability.

At low values of R_{inter} (e.g. 0.1), the computed FOS is approximately 1.52, reflecting relatively low stability due to insufficient mobilization of shear resistance along the soil-nail interface. As R_{inter} increases, the FOS rises significantly, reaching approximately 2.11 at R_{inter} = 1.0. This demonstrates the strong sensitivity of stability predictions to interface strength assumption.

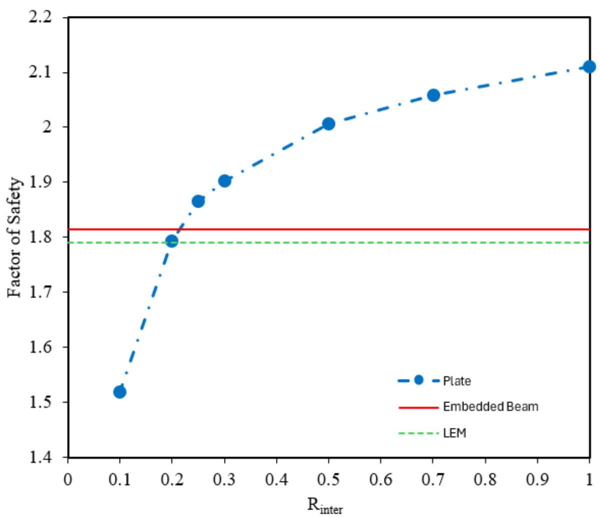


Figure 5 Relationship between factor of safety and interface reduction factor (R_{inter}) for plate-based modelling, compared with embedded beam and LEM approaches

A closer examination of the trend reveals two distinct behavioral regimes:

(i) Low R_{inter} regime (0.1 – 0.3)
A steep increase in FOS is observed, indicating that the system is highly sensitive to small changes in interface strength within this range. The relatively weak interface limits the transfer of shear stresses, resulting in only partial mobilization of soil nail capacity and reduced contribution to overall stability.

(ii) Transitional to high R_{inter} regime (≥ 0.3)
As R_{inter} increases beyond 0.3, the rate of increase in FOS gradually diminishes and the curve begins to plateau. This behavior suggests that the interface approaches a sufficiently bonded condition, where further increases in R_{inter} provide limited additional improvement in load transfer efficiency.

To evaluate the reliability of the plate-based modelling approach, the computed FOS values were compared with benchmark results obtained from embedded beam modelling and limit equilibrium analysis. The embedded beam model yields a FOS of approximately 1.81, while the limit equilibrium method produces a FOS of about 1.79, indicating close agreement between the two approaches.

Comparison with the parametric results shows that the FOS predicted using plate elements approaches the benchmark values at R_{inter} = 0.2. At lower R_{inter} values (< 0.2), the model tends to underestimate stability due to insufficient interface shear mobilization. Conversely, at higher R_{inter} values (> 0.3), the model may overestimate stability, reflecting an overly strong interface assumption.

Overall, the results demonstrate that the selection of R_{inter} has a significant influence on stability assessment. In particular, a value of R_{inter} around 0.2-0.3 provides a reasonable approximation of the global stability predicted by more established modelling approaches.

3.3 Influence of R_{inter} on Horizontal Deflection

The relationship between maximum horizontal deflection and the interface reduction factor (R_{inter}) is presented in Figure 6. In contrast to the factor of safety, the deformation response exhibits an even higher sensitivity to interface behaviour, particularly at low R_{inter} values.

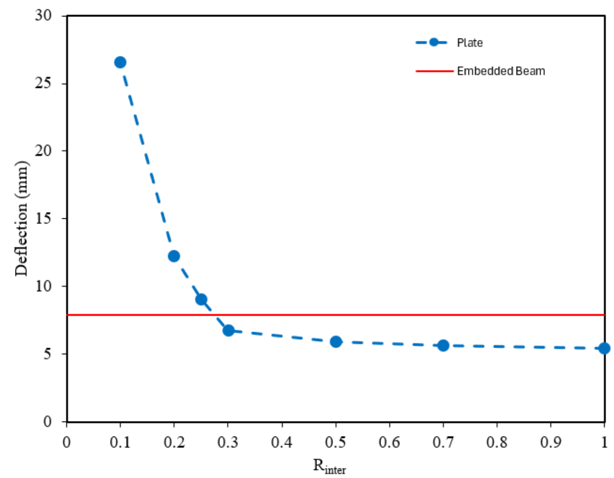


Figure 6 Relationship between horizontal deflection and interface reduction factor (R_{inter}) for plate-based modelling, compared with embedded beam approach

At R_{inter} = 0.1, the maximum horizontal deflection is approximately 27 mm, indicating substantial deformation due to poor interaction between the soil and the nail. As R_{inter} increases to 0.3, the deflection reduces sharply to about 6 mm, representing a reduction of nearly 75%. This pronounced decrease highlights the critical role of interface shear transfer in governing system stiffness.

Beyond R_{inter} = 0.3, the rate of reduction in deflection becomes marginal, with values stabilizing at approximately 5 mm. This indicates that once sufficient bonding is achieved, the system response is no longer governed by interface slip but instead controlled primarily by the stiffness of the soil mass and reinforcement.

The observed behavior can be explained by the load transfer mechanism of load transfer along the soil-nail interface. At low R_{inter} values, significant relative displacement occurs between the soil and the nail, leading to inefficient mobilization of tensile forces within the reinforcement. As R_{inter} increases, improved bonding enhances axial force mobilization, resulting in increased system stiffness and reduced deformation. This behavior is consistent with the axial load development discussed in Section 3.1.

A comparison with the embedded beam model shows that the predicted maximum horizontal deflection is approximately 8 mm. The plate-based modelling results indicate that comparable deflection values are obtained at R_{inter} ≈ 0.3. At lower R_{inter} values (« 0.3), the model significantly overestimates deformation, while at higher R_{inter} values (> 0.3), it tends to underestimate deflection, suggesting a potentially unconservative prediction in terms of serviceability performance.

These observations highlight the importance of calibrating R_{inter} to achieve realistic deformation predictions. In particular, R_{inter} ≈ 0.3 provides the most consistent agreement with benchmark behavior for the conditions considered.

3.4 Discussion of Results

Overall, the results consistently demonstrate that the interface reduction factor (R_{inter}) plays a governing role in controlling the behavior of soil-nailed systems in finite element modelling. The influence of R_{inter} is most evident in the mobilization of axial forces, which directly governs both global stability and deformation response.

While higher R_{inter} values trend to enhance stability and reduce deformation, they may also lead to overestimation of interface bonding and unrealistic load transfer behavior. Conversely, low R_{inter} values result in under-mobilization of axial forces, leading to conservative predictions of stability and excessive deformation.

It is also observed that although plate-based modelling is capable of reproducing global behavior with appropriate calibration, discrepancies remain in the prediction of axial load distribution when compared with embedded beam modelling. This highlights the inherent limitation of simplified interface-based approaches in capturing the complex and progressive soil-nail interaction mechanisms, including load transfer and bond mobilization, as observed in real-world applications. Similar observations have been reported by Lanzieri and Avesani Neto (2025), where a three-dimensional finite element model with explicit soil-nail interface representation was calibrated against field monitoring data, demonstrating the importance of realistic interface modelling for reliable prediction of deformation and nail force mobilization.

Based on the combined assessment of axial load development, global stability, and horizontal deflection, a value of R_{inter} around 0.3 is found to provide the most balanced and consistent representation of soil-nail interaction for the conditions analyzed. This emphasizes the importance of careful calibration of interface parameters when adopting plate-based modelling approaches in practical engineering analysis.

It should be noted that the present study adopts a constant horizontal spacing of 1.2 m in the smeared modelling approach. In this formulation, the equivalent plate width is directly related to the nail spacing, which in turn governs the interface area available for load transfer between the soil and reinforcement. An increase in spacing would result in a larger equivalent interface area, which may enhance the overall shear transfer capacity and influence the mobilization of axial forces along the soil nails.

In addition to geometric considerations, the results presented in Section 3.1 indicate that overburden pressure also plays a significant role in governing axial load distribution, particularly in plate-based modelling. It was observed that deeper nails tend to attract higher axial loads due to the increased confining pressure and enhanced interface shear mobilization at greater depths. This depth-dependent behaviour reflects the combined influence of stress level and interface properties, which is inherently coupled in the smeared modelling approach. Consequently, the calibrated value of R_{inter} identified in this study may be influenced not only by the assumed nail spacing but also by the stress-dependent load transfer mechanisms associated with overburden pressure. Variations in spacing may alter the effective interaction area, while changes in stress conditions along the nail length may further affect the distribution and magnitude of axial forces, leading to different optimal R_{inter} values.

These observations highlight the need for careful consideration of both geometric assumptions and stress conditions when applying the smeared plate modelling approach, and suggests that further parametric studies on nail spacing and depth-dependent behaviour would be beneficial. In addition, geometric parameters such as nail inclination may also significantly influence system stability and load transfer behaviour, as demonstrated by Iftikhar and Artati (2024).

4.0 CONCLUSIONS AND RECOMMENDATIONS

This study investigated the influence of the interface reduction factor (R_{inter}) on the behavior of soil-nailed systems modelled using plate elements in three-dimensional finite element analysis, with particular focus on axial load development, global stability, and horizontal deformation.

The results demonstrate that R_{inter} has a significant influence on the soil-nail interaction and overall system response. Lower R_{inter} values result in insufficient axial load mobilization, lower factors of safety, and larger horizontal deflections due to weak interface bonding. Conversely, higher R_{inter} values improve stability and reduce deformation, but may overestimate interface bonding and axial load transfer.

Comparison with embedded beam modelling and limit equilibrium analysis indicates that a R_{inter} value in the range of 0.2 to 0.3 provides the most reasonable overall agreement, with R_{inter} ≈ 0.3 giving the most balanced representation of axial load mobilization and deformation behaviour of the conditions analyzed.

Overall, the study confirms that while plate-based modelling can reasonably reproduce the global behaviour of soil-nailed systems, discrepancies remain in axial load prediction and careful calibration of R_{inter} is essential to achieve reliable predictions. Future studies are recommended to investigate the influence of nail spacing and stress-dependent interface behaviour to establish more generalized guidance for practical applications.

Acknowledgement

The author would like to acknowledge the valuable assistance of Mr. Nicholas Ooi Zhong Kai in conducting the analyses for this study and express appreciation for his dedicated effort and significant contributions.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

References

[1] Babu, G.L.S., and Singh, V.P. 2007. Plaxis Practice – Stabilization of Vertical Cut Using Soil Nailing. *Plaxis Bulletin*, 22: 6–9.

[2] Bathe, K.J. 1982. Finite Element Analysis in Engineering Analysis. New Jersey: Prentice-Hall.

[3] Duncan, J.M., and Chang, C.Y. 1970. Nonlinear Analysis of Stress and Strain in Soil. *Journal of Soil Mechanics and Foundations*, 96: 1629–1693.

[4] Farias, M.M., Durand, R.D., and Nakai, T. 2005. Analysis of An Excavation with Soil Nailing Using Embedded Finite Elements and Advanced Constitutive Models. In *Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering, Osaka, Japan*, 897–901.

[5] Iftikhar, A.A. and Artati, H.K. 2024. Finite Element Modelling of Soil Nailing Inclination Effect on Slope Stability: Cibeureum Slope Case Study. *Teknisia*, 29(1): 14-23.

[6] Khoo, C.M., Lee, P.T., and Cheah, S.W. 2025. Evaluation of Finite Element Modelling Approaches for Soil Nailing in PLAXIS. *PLATFORM – A Journal of Engineering*, 9(3): 34-47.

[7] Lanzieri, D.R. and Avesani Neto, J.O. 2025. Finite Element Analysis of Soil-nailed Vertical Excavation in Fine-grained Soils in An Urban Area. *Soils and Rocks*, 48(1): e20250100523.

[8] Lee, P.T., Koo, K.S., Tan, Y.C., and Yeow A. 2011. Performance of Soil Nailed Wall and Ground Anchor as Retaining Structure for A Drill & Blast Tunnel Portal. In *Proceedings of International Conference & Exhibition on Tunnelling and Underground Space, Kuala Lumpur, Malaysia.*

[9] Liew, S.S., and Khoo, C.M. 2006. Soil Nail Stabilization for A 14.5m Deep Excavation at Uncontrolled Fill Ground. In Proceedings of the 10th International Conference on Piling and Deep Foundations, Amsterdam, The Netherlands.

[10] Maleki, M., and Hosseini, S.M.M.M. 2022. Assessment of the Pseudo-Static Seismic Behavior in the Soil Nail Walls Using Numerical Analysis. *Innovative Infrastructure Solutions*, 7: 262.

[11] Maleki, M., Mohammadnezhad, H. and Mir Mohammad Hosseini, S.M. 2025. A Numerical Study of Site Effect and Dynamic Response of Staged Excavation Supported by Soil Nail Walls. *Scientific Reports*, 15: 20521.

[12] Mohamed, M.H., Ahmed, M., Mallick, J., and AlQadhi, S. 2023. Finite Element Modeling of the Soil-Nailing Process in Nailed-Soil Slopes. *Applied Sciences*, 13(4): 2139.

[13] Schanz, T., Vermeer, P.A., and Bonnier, P.G. 1999. The Hardening Soil Model: Formulation and Verification. In Beyond 2000 in Computational Geotechnics, Rotterdam: Balkema.

[14] Singh, V.P. and Babu, G.L.S. 2010. 2D Numerical Simulations of Soil Nail Walls. *Geotechnical and Geological Engineering*, 28: 299–309.

[15] Tan, S.A., Cheang, W.W.L., Ooi, P.H., and Tan, D. 2004. Finite Element Analysis of A Soil Nailed Slope – Some Recent Experience. In Proceedings of the 3rd Asian Regional Conference on Geosynthetics.

[16] Tan, Y.C., and Chow, C.M. 2011. Deep Excavation for Basement via Soil Nailing Method. In CIE-HKIE-IEM Tripartite Seminar on Deep Excavation, Hong Kong.