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Enhancing Soil-Structure Interaction Analysis: A Comprehensive Study of Interface Contact Elements

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ABSTRACT: This paper investigates the behaviour of contact interfaces in soil-structure interaction zones using the finite element method. The current methods adopted in the literature and in commercial software are discussed, highlighting the need for comprehensive guidelines for interface modelling in various types of analyses. Oasys Gofer was utilised in the study to explore the state-of-the-art features of zero thickness interface elements to model the interaction between soil and structures with high fidelity. The paper highlights the critical role of selecting appropriate modelling assumptions for interface elements in drained and undrained analyses. Key considerations include the impact of allowing true gap creation between soil and structural components, the influence of interface specific suction limits in undrained analysis, the impact of tension limits in the interface zone, and the effect of virtual thickness on stiffness calculations, convergence, and accuracy. Through sensitivity analyses, different assumptions for the soil-structure interface zone are examined, comparing the results to identify key impacts on the overall behaviour. The findings demonstrate the significant influence these assumptions can have on ground and structural movements and forces, the accuracy of the modelling, and therefore the overall project outcome. The paper provides practical insights for any engineer involved in design or assessment of soil-structure interaction problems using the finite element method, helping to bridge the current gap in the literature. A robust framework for modelling soil-structure interaction is discussed, ultimately enhancing the accuracy, reliability, and safety of engineering analyses.

KEYWORDS: Soil-structure interaction, finite element modelling, zero thickness interface elements, undrained analysis.

1 INTRODUCTION

Accurate modelling of soil-structure interaction (SSI) is essential in geotechnical engineering, particularly for embedded retaining walls and foundation systems. The interface between soil and structure governs load transfer (i.e. transfer of normal and shear stresses) and deformation. Its behaviour is often nonlinear and discontinuous, and must be realistically captured in finite element (FE) analysis.

In geotechnical numerical modelling, two main approaches are commonly used to represent the soil–structure interaction (SSI) zone. The first approach involves zero thickness interface elements, as demonstrated in studies by Day & Potts 1994; Kaliakin & Li 1995; Coutinho et al., 2003; Lei, 2001. The second approach uses thin layer elements, as seen in the work of Desai et al., 1984; Sharma & Desai 1992; Dhahse et al., 2024. Certain commercial software packages provide built-in tools for implementing these interface elements. For example, Plaxis and Midas GTX include options for zero thickness elements. Other platforms may require manual construction of thin layer elements. Additionally, some software allows for the modelling of slip, gap formation, stress redistribution, tension cut-off mechanisms, and control over virtual thickness.

Although there are various advanced tools, the assumptions and limitations of these tools are often under-documented. Moreover, the literature lacks unified guidelines for selecting appropriate interface parameters and formulations. Design guidance such as CIRIA C580 (2003) and C760 (2017) contains valuable guidelines that can aid SSI zones.

This paper investigates interface behaviour in SSI zones using Oasys Gofer, which is a cloud based FE method. Sensitivity analyses examine the impact of interface assumptions—such as gap creation, suction limits, and virtual thickness—on structural response and modelling accuracy. The study aims to support more reliable and guideline-compliant SSI modelling in geotechnical practice.

2 BACKGROUND AND PROBLEM STATEMENT

2.1 *Classical approach to model interfaces*

The modelling of interface zones in geotechnical analysis remains relatively imprecise, with outcomes often influenced by the user's level of expertise. Enhanced understanding and awareness are required, particularly when interface elements are applied across varying material types and analysis conditions. It is important for users to be familiar with the anticipated behaviour of interfaces under specific scenarios. Considerations such as gap formation, slip and frictional resistance, tension cut-off, and suction limits—especially in undrained analyses—play a critical role in accurately capturing soil–structure interaction. It is also important to consider the assumptions related to normal and shear stress transfer, as well as the influence of pore pressure when a gap forms between the soil and the structure. Despite their significance, many commercial software packages offer limited guidance on the implementation and interpretation of these features.

2.2 *Design guidelines*

Design guidance documents such as CIRIA C580 (2003) and C760 (2017) provide clear recommendations on the behaviour of soil–structure interfaces under undrained conditions, particularly in the context of embedded cantilever retaining walls. These documents emphasize that tension cracks should usually be permitted to open behind the wall rather than assuming any tensile stresses develop across the soil/wall interface.

These principles have direct implications for finite element modelling of soil–structure interfaces, especially when employing zero thickness interface elements. In undrained analyses, interface elements should be configured to allow loss of contact and gap formation, rather than artificially maintaining tensile resistance through suction-based assumptions. The application of tension cut-off within the interface zone is also recommended, as it facilitates realistic gap formation and prevents the introduction of non-physical tensile forces.

3 OVERVIEW OF THE PROPOSED APPROACH

3.1 *Application of contact interfaces in Gofer*

Gofer adopts user friendly approach when generating interfaces in such a way that it automatically detects all the structural items and generates interface zones surrounding it. This avoids the need for the user to manually draw the interface zone around structural elements, thereby reducing modelling effort. The interface properties contain advanced features (gap definitions, tension and suction cut-off definitions, normal/shear stress transfer definitions) so that users have more flexibility to extend for various scenarios.

3.2 *Zero thickness elements*

Gofer uses zero thickness elements with Newton-Cotes integration where the Newton-Cotes stress point coincides with the coincident nodes in the 2D element and structural element. Figure 1 shows the definition of contact interface elements in Gofer; the finite thickness is shown only for visualization purposes only.

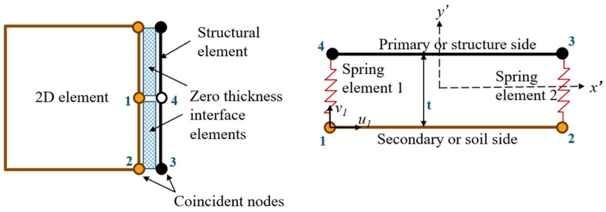

Figure 1. Contact interface elements in Gofer.

The interface is governed by the Coulomb frictional law. Its properties are automatically inherited from the adjacent soil element material. The primary parameter controlling both strength and stiffness is the interface reduction factor R_i, which modifies the relevant properties as follows:

$$G_i = R_i G \tag{1}$$

$$c_i = R_i c \tag{2}$$

$$\phi_i = \tan^{-1}(R_i \tan(\phi)) \tag{3}$$

where G is the shear modulus, c is the cohesion or the undrained shear strength in undrained calculations, ϕ friction angle of soil. A constant value of 0.45 is used as the Poisson's ratio v_i for the interface material.

3.3 *User controls*

Users can define a limiting tensile strength, $f_{t,lim}$ corresponding to that of the adjacent soil. When this limit is reached, Gofer applies a default gap formulation consistent with CIRIA C760 (2017) guidelines (i.e., shear and tensile stresses are not transferred across the interface once a gap has opened). However, users can override this default behaviour and permit stress transfer across the gap to match the behaviour of other software packages.

Users can also specify a suction cut-off value, $f_{s,lim}$ within the interface zone. By default, Gofer assumes a zero suction cut-off, in accordance with CIRIA C760 (2017) guidelines. This prevents the transfer of tensile stresses induced by suction into the structure, which could otherwise lead to dangerous stability predictions. However, users may override this default by defining a higher suction cut-off value.

Interface elements incorporate a virtual thickness value t_i, which should be sufficiently small to induce minimal elastic deformation. However, excessively small values of t_i may lead to convergence issues due to numerical ill-conditioning. The virtual thickness t_i is calculated as the product of a virtual thickness factor and the global element size - defined as the largest element length along the structure. Users can modify the default virtual thickness factor, which is set to 0.25.

The stiffness of the interface element is computed using Newton Cotes integration rule:

$$k_n = (\lambda_i + 2G_i) l_i / 2t_i \tag{4}$$

$$k_t = G_i l_i / 2t_i \tag{5}$$

where $\lambda_i + 2G_i$is the compression modulus, l_i is the interface length, λ_i is the Lamé constant (=$2G_i v_i/(1 - v_i)$).

3.4 *Internal forces in the interface elements*

Internal forces are computed using the Isoparametric formulation, similar to standard finite elements. Since the actual interface thickness is zero along the element length, nodal displacements are directly used to calculate internal forces in accordance with the Newton-Cotes integration scheme.

Normal and tangential/shear forces in spring element 1 are computed using:

$$f_{n,1} = k_n(v_4 - v_1) \tag{6}$$

$$f_{t,1} = k_t(u_4 - u_1) \tag{7}$$

Coulomb-Friction law is applied to limit the tangent/sliding force to a maximum allowable resistance. The following algorithm shown in Figure 2 is used to update normal force, $f_{n,j}$ and tangent force, $f_{t,j}$; where $j = 1,2$ corresponding to end 1 and end 2.

```
If $f_{n,j} > f_{t,lim}$:
  If $AllowGap = True$:
      $f_{n,j} = 0$
      $f_{t,j} = 0$
  If $AllowGap = False$:
      $f_{n,j} = f_{t,lim}$
      $f_{t,j} = sign(f_{t,j})\min(abs(f_{t,j}), \max(c_i l_i/2 - f_{t,j}\tan(\phi_i), 0))$
Else:
    $f_{t,j} = sign(f_{t,j})\min(abs(f_{t,j}), \max(c_i l_i/2 - f_{t,j}\tan(\phi_i), 0))$

$p_{w,j} = p_{excess,j} + p_{steady,j}$
If $f_{s,lim} = True$:
    $f_{n,j} = f_{n,j} + \min(p_{w,j}, f_{s,lim}) l_i$
Else:
    $f_{n,j} = f_{n,j} + p_{w,j} l_i$
```

Figure 2. Contact interface algorithm in Gofer

In the above algorithm, the total pore pressure value $p_{w,j}$ in the interface is directly obtained by the adjacent soil node using the excess pore pressure, $p_{excess,j}$ and steady state pore pressure, $p_{steady,j}$.

The contact interface algorithm implemented in Gofer is used to do a sensitivity analysis to further understand the interface behaviour on structural results.

4 SENSITIVITY ANALYSIS

The contact interface algorithm implemented in Gofer is used to do a sensitivity analysis to further understand the interface behaviour on structural results.

A baseline model was created as displayed below in Figure 3.

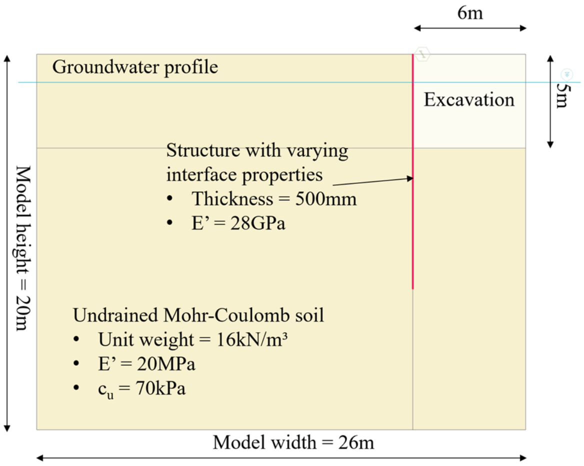

Figure 3. Baseline Gofer model geometry.

This simple model was used to demonstrate the impact of the various interface settings discussed. A simple staged construction comprising stress initialization, wall installation, and then an undrained and dewatered excavation.

4.1 *Effect of interface tension and gap settings on a cantilevered retained excavation*

Three comparison models were analysed:

1. An interface formation which prevented tension and suction forces, and gap settings which prevent any transfer of shear or tension across the gap once formed (i.e. behaviour in line with CIRIA C760)
2. An interface formulation which prevented tension and suction forces, but with gap settings which permit transfer of shear and tension across the gap once formed.
3. An interface formulation which permitted transfer of tension (i.e. prevented a gap forming)

The gap formation is evident from the displaced mesh output shown in Figure 4 and Figure 5.

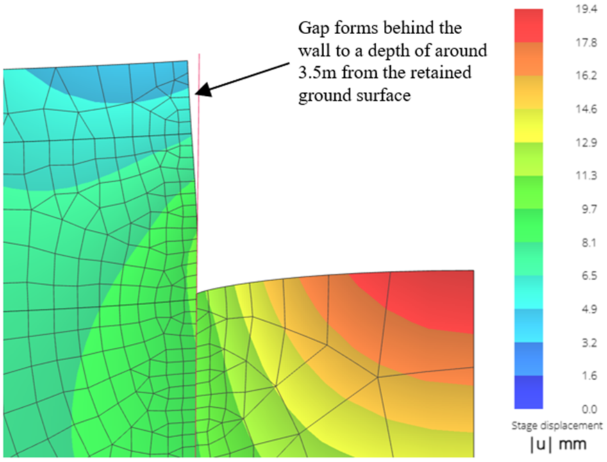
Gap forms behind the wall to a depth of around 3.5m from the retained ground surface

Figure 4. Stage displacement results for Model 1.

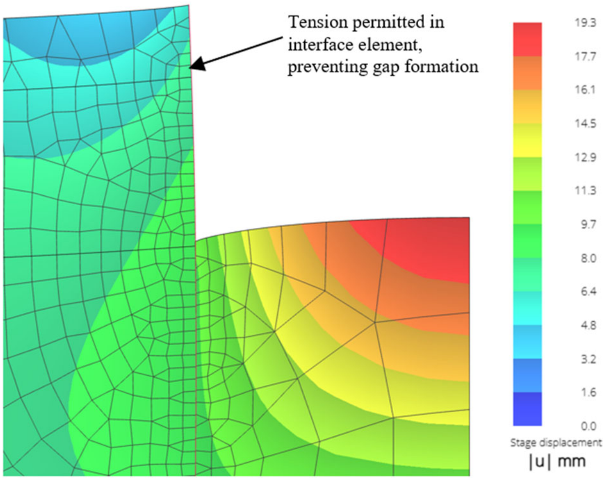
Tension permitted in interface element, preventing gap formation

Figure 5. Stage displacement results for Model 3.

Output of the structural element itself for the 3 different interface settings is presented in Figure 6.

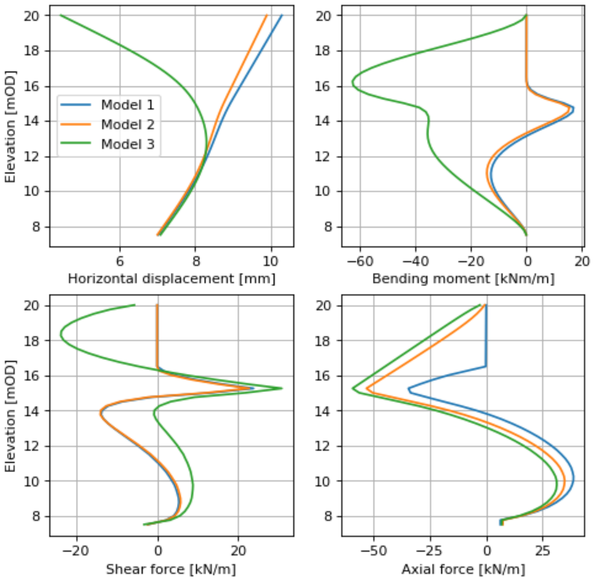

Figure 6. Wall displacement, moment, and force moment comparison for different interface definitions and a cantilever retaining wall.

The horizontal displacement for models 1 and 2 are similar. Although model 2 permits transfer of shear and tension across the gap, the tension is limited to zero and the shear only has a small impact on the deflected shape. The horizontal deflection for model 3 is quite different as the wall is held back against the soil due to tensile stresses.

The same applies for the bending moment and shear force in the structure. Higher bending moments and shear forces are induced when shear transfer is permitted in the interface elements.

However, when considering axial force, significant differences are observed, with model 2 behaving more similarly to model 3 despite the gap formation. This is intuitive, as although a gap has formed, shear transfer is permitted in the same way for both models. Model 1 shows zero shear in the wall over the gap depth.

4.2 *Effect of interface tension and gap settings on a propped excavation*

A prop was added to the base model described in Figure 3, supporting the top of the wall. The same three sets of interface options were re-analysed with this propped arrangement, and the results presented in Figure 7. The presence of the prop at the top of the wall prevents a gap forming, and hence all three models behave the same.

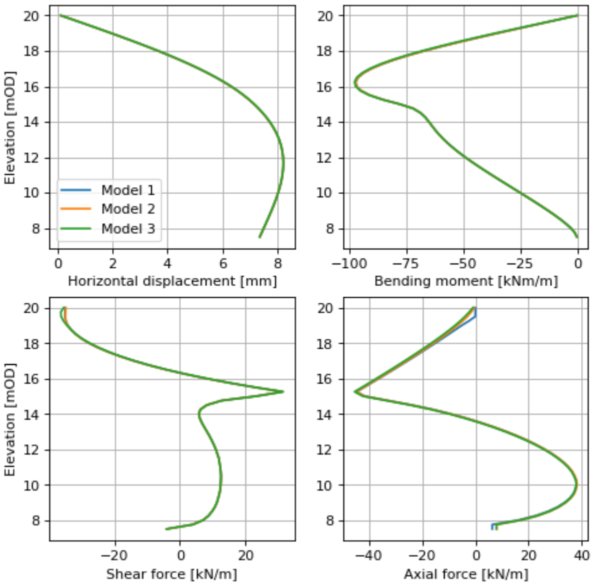

Figure 7. Wall displacement, moment, and force moment comparison for different interface definitions and a propped retaining wall.

4.3 *Effect of interface suction cut-off*

This has the same effect as allowing tension, as observed in Model 3 in Figure 6.

4.4 *Effect of interface thickness*

The effect of the virtual interface thickness factor has been investigated using the cantilevered base model from Figure 3 and the results on forces and displacements of the retaining structure are presented in Figure 8.

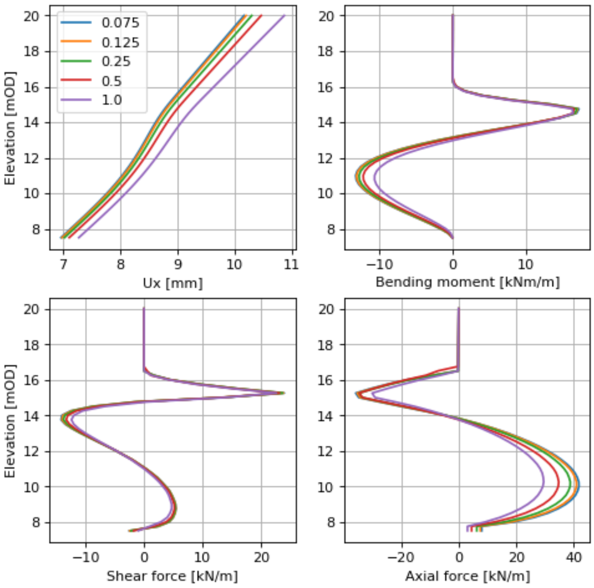

Figure 8. Wall displacement, moment, and force moment comparison for different interface virtual thickness factors between 0.075 and 1.0.

As the thickness of the interface increases, so do the horizontal displacements as would be expected when considering equations (4) and (5). Bending moment, axial force, and shear force all increase with decreasing interface thickness. However, there is a balance between thickness and computation effort as illustrated in Figure 9. A default value of 0.25 has been selected in Gofer as an appropriate balance between accuracy and computation cost.

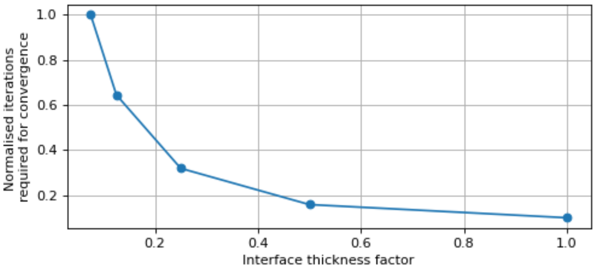

Figure 9. Normalised number of iterations required for convergence with different interface thickness factors.

5 CONCLUSIONS

This study highlights the importance of accurate interface modelling in soil–structure interaction (SSI) analyses. Sensitivity tests using Oasys Gofer show that assumptions around tension limits, suction cut-off, gap formation, and virtual thickness significantly affect structural behaviour and modelling accuracy. Aligning interface settings with design guidance such as CIRIA C760 - especially in undrained conditions - is essential for realistic and safe outcomes. The ability to control interface parameters allows engineers to tailor models to specific site conditions. By clarifying the impact of interface assumptions and offering a practical modelling framework, this work supports more reliable and guideline-compliant SSI analysis in geotechnical engineering.

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