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TOWARDS THE NUMERICAL MODELLING OF THE ADHESION BETWEEN PLANE STEEL SURFACES AND FINE-GRAINED SOILS

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Abstract: Adhesion or "stickiness" of cohesive soils is a huge concern in the context of tunnelling applications owing to the risk of significant clogging in tunnel boring machines (TBMs) passing through fine-grained soils. Separation tests can be used to quantify the adhesive strength of soil-steel interfaces. In this study, a finite element model was developed to predict the behaviour of soil-steel interface subjected to a separation load. Adopting an exponential traction separation law, the surface-based cohesive contact effectively replicated the separation response of the adhesive interface.

1. Introduction

Soil-structure interaction is a crucial phenomenon in geotechnical engineering with fundamental applications ranging from pile foundations to tunnelling [1]. The complex interaction between the steel surfaces of TBMs and clay result in significant clogging, which leads to reduction in efficiency, construction delays and an overall increase in the costs. Thus, a comprehensive understanding of the contact surface mechanics between a structure and the surrounding soil is essential. In the context of clayey soils, stickiness or adhesion at the soil-structure interface plays a significant role in the contact behaviour. One of the common ways to determine the adhesive strength is through separation tests, wherein the clay surface is compressed by a steel plate before being pulled away [2, 3]. Figure 1 shows the characteristic stress curve over time during a separation test, allowing for the measurement of adhesive stresses.

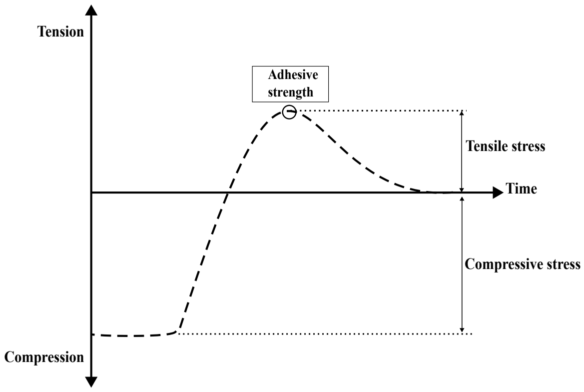

Figure 1. Exemplary progression of a separation test over time, as observed in [2]

The adhesive strength is then defined as the maximum tensile stress required to separate the soil from steel surface, given the failure occurs at the interface. It is dependent on the soil characteristics, including mineralogical composition and consistency of clay. Additionally, experimental factors such as interfacial roughness, rate of separation loading, temperature and contact time influence the adhesive properties. Numerical studies can provide detailed insights into this complex mechanism, given the adoption of appropriate constitutive models and contact laws. Limited studies exist which explicitly considered the adhesive interaction between soil and structural surfaces [4, 1]. Therefore, the current study focuses on investigating the usage of cohesive surfaces in a finite element model to simulate normal adhesion between a steel plate and clayey soil.

2. Finite element modelling of separation tests

A two-dimensional numerical model was developed using the finite element (FE) software, ABAQUS to simulate the normal separation test in clay. The adhesive behaviour of kaolinite is investigated in this study and the material properties are reported in Table 1.

Property	Value
Grain density (g/cm^3)	2.675
Liquid limit (%)	56.5
Plastic limit (%)	36.7
Compression Index, C_c	0.316
Swelling Index, C_s	0.025

Table 1. Basic geotechnical properties of kaolinite

The axisymmetric model, as depicted in Figure 2 consists of a clay sample with dimensions 30 mm x 15 mm along with a steel plate of dimensions 30 mm x 10 mm placed on the top of the clay surface. The clay is considered to be normally consolidated with an initial void ratio of 0.9. The steel plate is pressed onto the clay at a constant stress of 40 kPa, followed by a velocity controlled separation load at the rate of 0.75 mm/min. The boundary conditions were selected such that the base is restricted in the vertical direction whereas the sides are restricted in the lateral directions. The soil was discretised using four-noded axisymmetric pore pressure (CAX4P) elements.

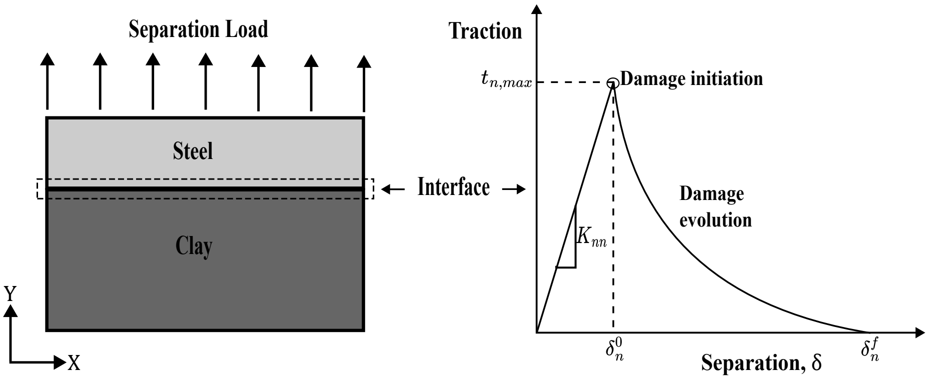

Figure 2. Simplified description of the FE model (left) and the traction-separation law employed at the interface [5] (right)

2.1. Constitutive and interface modelling

The elasto-plastic behaviour of clay was modelled using the Modified Cam Clay model. To implement this model, the material properties required are: the slopes of normal compression line

(NCL) and unloading-reloading lines (λ and κ) in the $e - \ln p'$ plane, where e is the void ratio and p' is the mean effective stress, the slope of the critical state line (M), a measure of the initial yield surface (a_0), a measure of the wet yield surface size (β) and the flow stress ratio (K). The values chosen based on experiments conducted on the clay are listed in Table 2. Further, the behaviour of steel plate is modelled as linear elastic, with a Young's modulus of 210 GPa and Poisson's ratio of 0.3.

Soil Parameter	*Elasticity*		*Plasticity*				
	κ	ν	λ	M	a_0	β	K
Value	0.018	0.28	0.137	0.93	20 kPa	1.0	1.0

Table 2. Modified Cam-Clay parameters for FE simulations

The interface was modelled using surface-based cohesive contact based on traction separation law which describes the relationship between stresses and relative displacements, as shown in Figure 2. It is widely used to model delamination at interfaces. The interface offers resistance against separation until a limiting separation distance beyond which the contact pressure falls to zero. The traction separation model initially exhibits a linear behaviour followed by initiation and evolution of damage. The elastic behaviour is defined by providing the cohesive contact stiffness value, K_{nn} of 2×10^4 kN/m^3 . The degradation and failure of the interface is enforced using a damage initiation criterion and a damage evolution law (Eq. 1). Damage initiation describes the beginning of degradation of the contact stiffness. This stage is reached when the separation reaches an effective critical value. A maximum stress criterion was used to initiate damage in the current study (Eq. 1; left). Damage evolution represents the rate of degradation of cohesive contact stiffness upon reaching the corresponding initiation criterion. It is defined using a scalar damage variable D, which ranges from 0 to 1 ($D = 0$ implies the undamaged state whereas $D = 1$ implies the fully damaged condition). The damage evolution law is defined using fracture energy (representing the area under the traction-separation curve) and the nature of the evolution of the damage variable.

$$\max\left\{\frac{\langle t_n\rangle}{t_n^o}, \frac{t_s}{t_s^o}, \frac{t_t}{t_t^o}\right\} = 1 \quad ; \quad D = 1 - \left\{\frac{\delta_n^o}{\delta_n^{\max}}\right\}\left\{1 - \frac{1 - \exp\left(-\alpha\left(\frac{\delta_n^{max} - \delta_n^o}{\delta_n^f - \delta_n^o}\right)\right)}{1 - \exp(-\alpha)}\right\} \tag{1}$$

Here, an exponential softening law (Eq. 1; right) was defined for the damage evolution, where δ_n^{max} refers to the maximum value of separation and α is a non-dimensional parameter to define the rate of damage evolution. To interpret the numerical results, the evolution of stress over time was plotted. The stresses which were initially compressive, decrease with time when subjected to separation load and reach a peak tensile stress (Figure 3), similar to the experimental trend illustrated in Figure 1. Here, the sign convention adopted is negative in compression and positive in tension.

2.2. *Inferences from the numerical model*

The numerical behaviour of the interface qualitatively mimics the experimental response. Prior to separation of steel base, the soil experiences compressive stress of about 40 kPa. The stress state progressively changes with time and the tensile stresses develop as the contact gap between the two surfaces increases. Further increase in the separation gap leads to yielding of the cohesive contact and as the interface gets damaged the peak contact stress drops to zero indicating complete damage of the adhesive bond. Thus, a proper choice of material as well as contact parameters is required to predict the interface response realistically. Further studies are to be conducted to study the influence of different parameters on the separation response of the clay-steel interface.

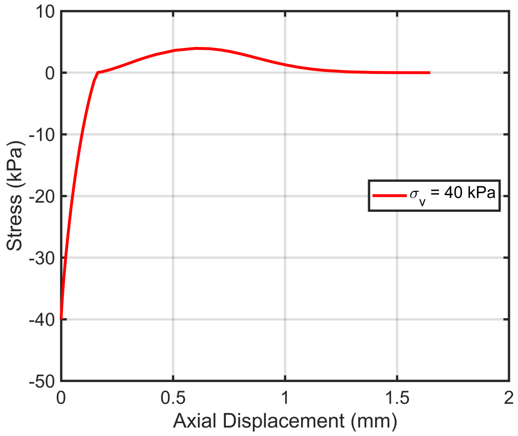

Figure 3. Stress evolution during the normal separation test obtained from FE simulation

3. Conclusions

A simple two-dimensional model was developed to predict the adhesive behaviour of clay in separation tests. A surface based cohesive contact law was used to model the interface. The results showed that the cohesive contact law could prove to be effective for modelling adhesion in soil-structure interaction applications. However, a major challenge would be to model the separation when the failure occurs within the soil, where adhesion and the internal shear strength of the soil would be mobilised in a combined manner. The contact model needs to be further enhanced to incorporate the tensile strength of the soil. Further, this model can be improved by developing a more intricate contact law capable of taking into account the effect of all the factors influencing adhesion, including the normal load, rate of separation, surface roughness and mechanical properties of clay.

4. Acknowledgements

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