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THE INFLUENCE OF INTERFACE ROUGHNESS ON PROBLEMS OF AXISYMMETRIC SOIL/STRUCTURE INTERACTION

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ABSTRACT

Modelling of soil/structure interaction using finite element analysis often requires the use of 'interface' elements. Much discussion can centre around the best type of element to use and the constitutive behaviour to be employed (e.g. rigid plastic, elasto-plastic, adhesive, frictional). Even when a decision is reached, the implementation of such elements is at best inconvenient and at worst can lead to numerical difficulties. This paper discusses methods of modelling slip without actually using specialised elements. Perfectly smooth conditions are achieved by uncoupling and orientating the freedoms parallel to the proposed interface direction. Perfectly rough conditions can also be modelled using the same mesh provided it is sufficiently refined. This leads to upper and lower bounds on the actual behaviour corresponding to a finite amount of adhesion or friction. Two rather confined axisymmetric problems are considered to demonstrate the method. Firstly, a cone and, secondly, a laterally loaded disc are both pushed until ultimate conditions are reached. The latter example involves Fourier expansions in the tangential direction. Results obtained from both cases are compared with existing 'analytical' solutions.

INTRODUCTION

Numerical modelling of problems in which interface behaviour is considered important involves the use of specialised thin elements (e.g. Ghaboussi et al [1], Katona [2], Desai et al [3]). Several different kinds of interface elements have been proposed and tested successfully in boundary value problems. Other authors (e.g. Pande and Sharma [4], Griffiths [5]) have shown that even the familiar 8-node quadratic element with reduced integration, performs well as an interface up to quite high aspect ratios. A feature common to many problems involving surface roughness in foundation engineering (e.g. retaining walls, footings, culverts and buried structures) is that the range of solutions going from perfectly rough to perfectly smooth is not very great. This is particularly true of 'adhesive' types of slippage appropriate to soil/structure interaction involving undrained clays.

The magnitude of passive earth pressure for varying roughness illustrates this point well - for an undrained clay ($\phi_u = 0$), the rough value is 30% higher than the 'smooth' value, whereas for a cohesionless soil with $\phi' = 40^\circ$ say, the increase is greater than 150% [6]. Clearly, correct modelling of interface effects is more important in the latter case. The fact remains, however that accurate measurements of the adhesion or friction angle between soil and structure is difficult in practice. Furthermore, the effects of progressivity and the varying levels of mobilisation of the friction or adhesion at different locations along the interface add to the uncertainty.

This paper proposes that the range of possible solutions for interface problems should firstly be established by considering perfectly rough and perfectly smooth conditions in a numerical model. The results given by these two analyses then represent the upper and lower bounds within which all actual results must lie. Provided this range is not too great, further examination with specialised elements should prove unnecessary.

Rough conditions are modelled using a conventional finite element analysis in which soil and structure are 'tied' together at the nodes. Provided the mesh is reasonably refined, failure along the 'interface' can then be detected using a conventional plasticity algorithm along the row of Gauss-points within the soil closest to the structure. Smooth conditions are modelled by uncoupling one of the freedoms on each side of the interface (for 2-D problems) and if necessary, re-orientating them to be parallel to the proposed interface direction.

UNCOUPLING AND REORIENTATION OF FREEDOMS

The method is directly analogous to that adopted in simple structural analysis when an internal pin is placed within a loaded frame (Smith and Griffiths [7]). In such a case, different amounts of rotation for each member attached to the pin are allowed to occur. A perfectly smooth pin is modelled by this method, and no moment can develop on either side. Extrapolating this approach to 2-D continuum analyses implies that in order to reproduce a smooth interface in the example shown in Figure 1, freedoms parallel to the interface direction must be uncoupled whereas freedoms normal to the interface are 'tied' in the conventional way. No shear stresses will be able to develop along the 'interface' thus smooth conditions are reproduced, but separation is not allowed. A more detailed discussion of this method, and a subroutine for performing the transformation is provided by Griffiths [8].

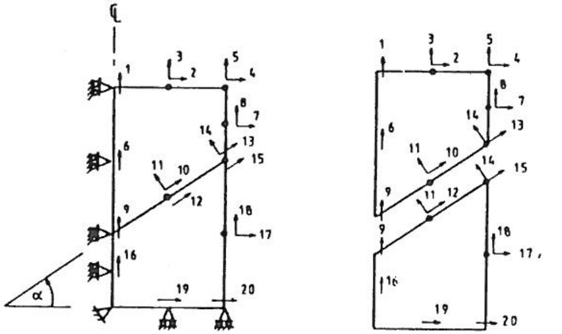

Fig.1 Freedom numbering for inclined interface

SMOOTH CONE PUSHED INTO COHESIVE SOIL

The mesh shown in Figure 2 is the same as that adopted for plane strain analysis by Griffiths [8] and uses 8-node quadratic elements with 'reduced' integration. Freedoms at nodes along the cone/soil interface were uncoupled and transformed in a similar way to that shown in Figure 1.

The cone was displaced vertically into the soil, which was assumed to behave as an elastic-perfectly plastic (Tresca) material. At convergence after each displacement increment, the reactions at the displaced nodes were back-figured from the equilibrium stress state. The reactions (T) were converted into a dimensionless factor N_c as follows -

$$N_c = \frac{T}{\pi R^2 c_u} \tag{1}$$

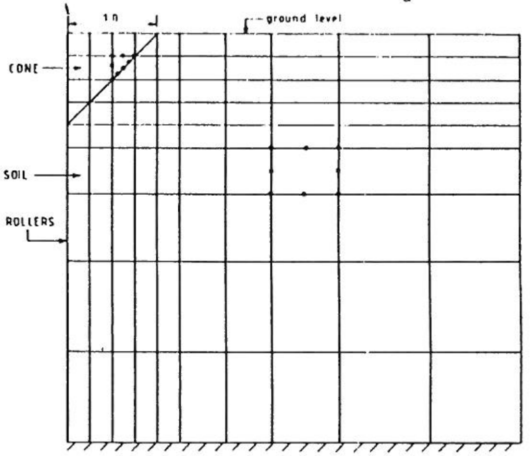

Fig. 2 Mesh used for cone analysis

where R = cone radius
c_u = undrained strength of soil

The estimated N_c value at failure for each case is shown plotted against cone angle in Figure 3. Also shown on this figure is a proposed closed - form solution [9] which indicates a minimum value of N_c corresponding to a cone angle of 52.6°. This minimum is not observed by the finite element solution presented here, neither was it detected by Willson [10] using genuine interface elements.

Displacement vectors at failure for both a rough and smooth 90° cone are given in Figure 4. The mechanisms are clearly quite different. In the smooth case, the soil is pushed away from the cone at right-angles from its surface, whereas in the rough case the soil is dragged down vertically with the cone.

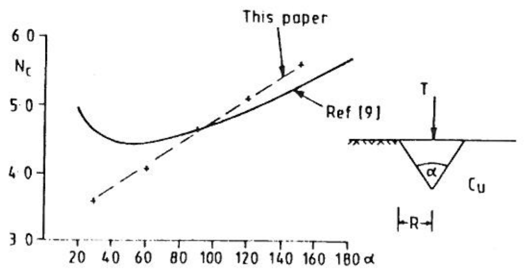

Fig.3 N_c at failure vs. cone angle

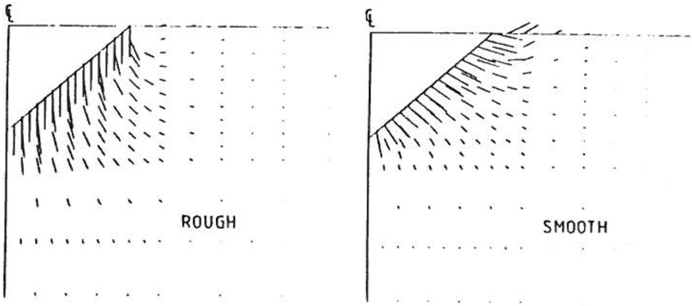

Fig.4 Rough and smooth displacement vectors at failure (90° cone)

AXISYMMETRIC BODIES SUBJECTED TO NON-AXISYMMETRIC LOADING

The second example involved a stiff disc pushed laterally into cohesive material. Although the particular case considered in this paper amounted to plane strain conditions with only radial and tangential movement permitted, a different algorithm was used involving Fourier expansions in the tangential directions.

The algorithm is suitable for axisymmetric bodies subjected to non-axisymmetric loading, and in many cases will be cheaper to run than a full 3-D analysis. For elastic analysis, applications to structural configuration were described by Wilson [11] and later by Zienkiewicz [12]. Still in the elastic domain, analyses of laterally loaded piles were considered by Suen [13] and Randolph [14]. An elastic program to solve problems of this type has been published by Smith and Griffiths [7].

Non-linear analyses using the Fourier approach were described by Meissner [15], but the first attempt to explain the workings of the algorithm was made by Winnicki and Zienkiewicz [16] in the context of viscoplasticity. Further development of this latter approach was reported by Barton and Pande [17]. More recently, a modular program for Fourier analysis of elasto-viscoplastic materials has been developed by Griffiths [18] and implemented in a laterally loaded foundation problem [5].

For problems involving $\phi_u = 0$ materials, a considerable saving can be made in computer time and storage due to (anti-) symmetry of all the displacement component distributions about the 90° axis. It was shown [18] that the number of harmonics required for such materials depends on the number of angular sampling points in the range $0 < \Theta < 180°$.

If the number of angular sampling points is NANG (odd), then the number of harmonics NHAR is given by -

$$\text{NHAR} = \frac{\text{NANG} - 1}{2} \qquad (2)$$

Using odd-numbered harmonics only, this reults in a Fourier series function that passes exactly through the discrete values at the NANG locations. This only occurs [18] if amplitudes a_i are found using the Repeated Trapezium Rule to evaluate integrals of the type -

$$a_i = \frac{2}{\pi} \int_0^{\pi} f(\Theta) \cos i\Theta d\Theta \qquad (3)$$

For Mohr-Coulomb materials, or materials in which no tension is allowed to develop, even numbered harmonics must be incorporated (including 'zero'). Analyses involving these types of materials will form the basis of a later publication.

LATERALLY LOADED DISC IN COHESIVE MATERIAL

An elastic analysis of this problem was performed initially for comparison with closed form solutions (e.g. Baguelin et al [19]). The mesh at the top of Figure 5 represents a radial plane of the problem under consideration for a 'rough' interface. The disc was displaced radially on a 1st harmonic into the soil medium and the displacement profile in front of the disc at increasing radial distances is shown. The closed form

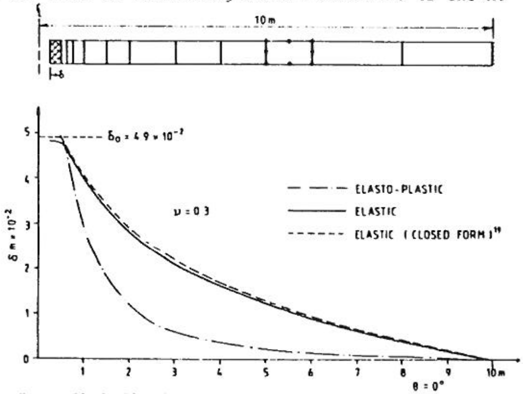

Fig.5 Radial displacements in front of rough disc

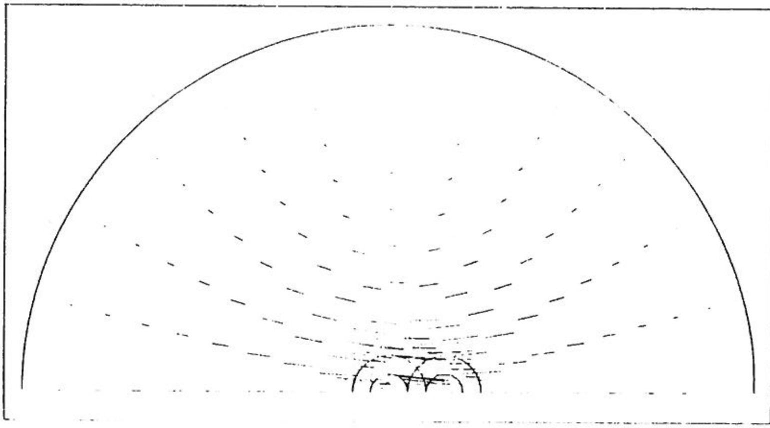

Fig.6 Elastic displacement vectors (rough disc)

solution [19] is also included in this figure for comparison and all elastic properties are given in Figure 7. Unfortunately the elastic response of this configuration is a function of the radial distance of the rigid boundary. As this radial distance increases towards infinity, the reactions (T) that would be computed for a given displacement tend to zero. The displacement vectors generated in the elastic soil by movement of the disc are shown in Figure 6 and the effects of the boundary are clearly seen.

The response changes dramatically when the soil is assumed to behave as an elastic/Tresca material as noted by Lane [20]. The disc is displaced incrementally into the soil and the reactive forces back-figured from the converged stress state. After some parametric studies, it was decided that NANG = 5 (NHAR = 2) gave sufficiently accurate solution for 'Tresca' materials. Failure was indicated by a levelling-off of the reactive forces. The attenuation of radial displacements in front of the disc for the elasto plastic solution is clearly seen in Figure 5.

	E	C_u	ν
SOIL	1.E5	1E2	·3, ·49
PILE	6.E7	1.E10	·3

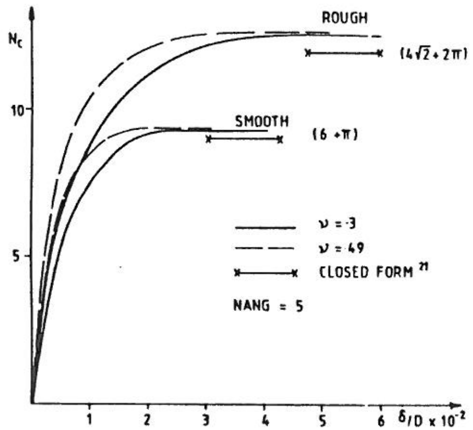

Fig. 7 Load/displacement response

The 'smooth' case was easily implemented by uncoupling the tangential displacement components correspnding to the soil and disc at nodes along the interface. The complete load/displacement response computed for both the rough and smooth cases is given in Figure 7. The agreement with the characteristics solution of Randolph and Houlsby [21] is seen to be quite acceptable. The solution obtained for the rough case could probably be improved further by refining the mesh close to the interface.

The displacement vectors at failure given in Figure 8 for both the rough and smooth cases [20] show very well the rotational nature of the plastic flow. As would be expected, the 'rough' mechanism is the more extensive of the two, but in both cases, the attenuation of displacements is such that a highly localised mechanism is visible.

CONCLUSIONS

Finite element analyses of smooth interface behaviour have been performed on two axisymmetric problems of soil/structure interaction. The first example involved a cone pushed into a cohesive soil and required a transformation of freedoms to be parallel and perpendicular to the interface direction [8]. The computed peak resistance of the soil for a variety of cone angles did not reproduce a minimum predicted by a 'closed form' solution [9]. The reason for the discrepancy is not clear, but it is suggested that the closed form solution may be physically unrealistic for small cone angles.

The second example involved a disc pushed laterally into a cohesive soil. This analysis was performed using a finite element discretisation in radial planes only, with tangential variations modelled using Fourier series expansions. The smooth case was easily reproduced in this case by uncoupling tangential freedoms along the interface. Close agreement with closed form solutions [21] for both rough and smooth conditions was achieved using 2 harmonics with 5 angular sampling points. Plots of displacement vectors at failure showed highly localised mechanisms, hence the collapse loads were insensitive to the finite element boundary proximity.

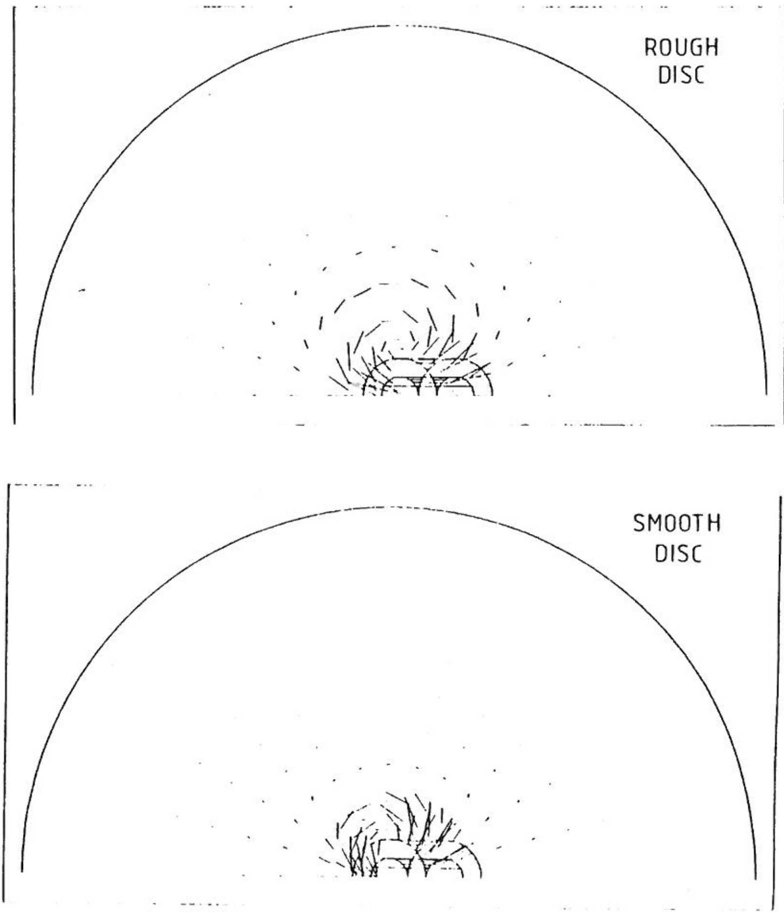

Fig. 8 Displacement vectors at failure ($\phi_u = 0$)

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