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Finite Element analysis of soil-pipeline interaction under lateral loading

Analyse par éléments finis de l'interaction sol-pipeline sous chargement latéral

M.Rouainia
School of Civil Engineering and Geosciences,University of Newcastle, Newcastle NE1 7RU, UK
A.C.H.Chan
School of Civil Engineering and Geosciences, University of Newcastle, Newcastle NE1 7RU, UK
P.F.C.Ng
Advantica, Ashby Road, Loughborough LE11 3GR, UK

ABSTRACT
In this paper, an elastoplastic model with a non-smooth friction mechanism and a volumetric mechanism is proposed to determine loads on pipes due to relative movements. The model requires the input of the stress-strain curves obtained directly from laboratory stress path on the particular soil studied, in the form of discrete data points. Various axisymmetric triaxial paths are simulated in order to demonstrate the good performance of the proposed model. In addition, several finite element analyses of soil-pipeline interaction under lateral loading have been carried out.

RÉSUMÉ
Dans cet article, un nouveau modèle constitutive avec deux mechanismes, l'un de frottement non-régulier, l'autre volumétrique, est proposé pour l'évaluation des forces appliquées sur les pipelines. Le modèle necessite les courbes deformations-contraintes des sols étudiés sous la forme de points discrets, obtenues au laboratoire en effectuant des essais à chemins de contraintes. En utilisant le nouveau modèle, des simulations numériques d'essais triaxiaux et des analyses par éléments finis de l'interaction sol-pipeline, ont été effectués. Ces résultats démontrent le potentiel du modèle proposé.

1 INTRODUCTION

The correct prediction of soil movement beneath a foundation, behind a retaining wall or around a buried pipeline requires the use of a suitably equipped constitutive model, which would enable the engineer to produce a safe and economical solution for the particular problem being analysed. The Advantica Linear Interpolation Model (ALIM) is such a model which satisfies the requirement of being a complex model in the sense that it is possible to reproduce relatively complex pattern of the mechanical behaviour of real soil, but it stands out from the other constitutive models because the common engineer will not have to face the difficult process of parametric identification. This in most cases is as important criteria for the model to be accepted in the engineering community.

ALIM is an elastoplastic model with a non-smooth friction mechanism and a volumetric mechanism. It requires the input of the stress-strain curves obtained directly from laboratory stress path on the particular soil studied, in the form of discrete data points. An accurate analysis of a geotechnical problem requires careful laboratory testing which covers the likely stress paths and the stress range to occur in the field. Extensive experimental studies have been made of the forces acting on pipelines due to relative movements (see e.g. Trautman and O'Rourke (1985), Paulin et al. (1998) among others). On the computational side, finite element studies of soil/pipeline interaction have been made for various boundary and loading conditions (see Popuscu et al. 2001, Yimsiri et al. 2004). In addition, effort has also been directed toward the development of more accurate theories for submarine pipes under combined vertical, horizontal and moment loading (Zhang et al. 2002).

This paper, axisymmetric triaxial paths are simulated and compared to triaxial laboratory results obtained for a dense sand in order to demonstrate the efficiency and good performance of the proposed model. In addition, several finite element analyses have been carried out to determine loads on pipes due to relative movement between soil and pipe. These numerical analyses include downward loading, upward loading and lateral loading. The type of soil in this study is dense sand. Comparison with the results from experimental program demonstrates the potential of the proposed model.

2 CONSTITUTIVE MODELLING

Sub-subheading, if used, are also automatically numbered, spaced, and set in italics. The ALIM incorporates a friction mechanism and a volumetric mechanism as observed in Figure 1. A brief description of the ALIM model is presented in the following section

2.1 The friction mechanism

The frictional mechanism is described mathematically by the following equation which defines a yield surface in the $(q,\,p)$ space as follows:

$$F_1 = q - R(\theta)\ \ Y + H\varepsilon_{ps} + (M_f + H'\varepsilon_{ps})p'\ \ = 0 \qquad (1)$$

where the function $R(\theta)$ is related to the lode angle θ and the reference friction angle ϕ_{ref}. The equivalent plastic strain ε_{ps} is defined in terms of deviatoric strain e^p_{kl} as:

$$\varepsilon_{ps} = [\frac{2}{3}\boldsymbol{e}^p : \boldsymbol{e}^p]^{\frac{1}{2}} \ \text{ with } \ \boldsymbol{e}^p = \frac{1}{3}\boldsymbol{\varepsilon}^p : \boldsymbol{I} \qquad (2)$$

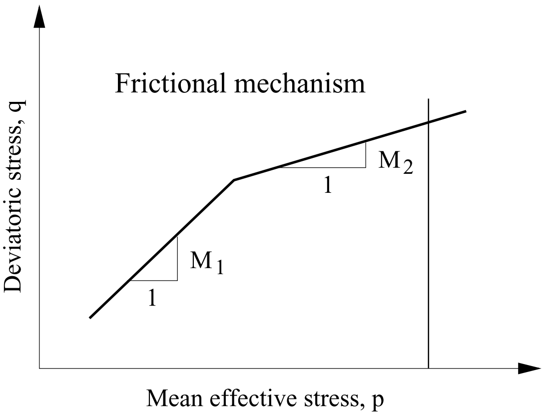

Figure 1: ALIM constitutive model: yield surface in $(p-q)$ plane.

where $\boldsymbol{I}$ is the identity tensor. Since a non-associative flow is assumed, the incremental plastic strain is obtained as:

$$d\boldsymbol{\varepsilon}^p = d\lambda \frac{\partial Q_1}{\partial \boldsymbol{\sigma}} \tag{3}$$

where $Q_1(p,q)$ is a von-Mises type plastic potential defined mathematically as:

$$Q_1 = q - Dp' - c_1 \tag{4}$$

The complete definition of the friction mechanism model requires the following six parameters: Y, H, Mf, H', ϕ_{ref} and D.

2.2 The volumetric mechanism

The yield surface corresponding to the volumetric mechanism is a straight vertical line in the $(q,\ p)$ space as seen in Figure 2.

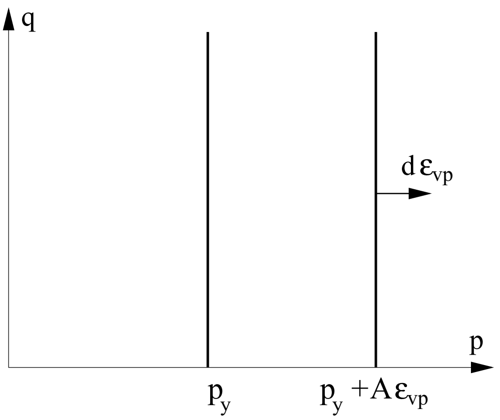

Figure 2: Volumetric mechanism with an associative flow rule.

The equation of the yield surface is expressed as:

$$F_2 = p - (p_y + A\varepsilon_v^p) \tag{5}$$

where p_y is the initial isotropic pressure below which the soil material is assumed to be elastic; ε_v^p is the plastic volumetric strain and the A is a material parameter defined as:

$$A^{-1} = \frac{\partial \varepsilon_v^p}{\partial p} \tag{6}$$

The increment of plastic volumetric strain is assumed to be associated to the yield surface (see Fig. 2).

2.3 Model parameters

The elasto-plastic model ALIM requires two elastic parameters: the bulk modulus K and the shear modulus G. The response associated with the elastic part is expressed in terms of K and G, which are assumed to depend on the mean pressure p' as follows:

$$G = G_{ref} \ {\frac{p'}{p_{ref}}}^{\alpha} \ , K = K_{ref} \ {\frac{p'}{p_{ref}}}^{\beta} \tag{7}$$

where G_{ref} and K_{ref} are the shear modulus and the bulk modulus defined at the mean stress reference, p_{pref}. The parameters α and β are constant taking values between 0 and 1.
The plastic material parameters for ALIM, introduced in the previous section, are easily related to A, B, C and M. The parameter A has been defined in equation 6 as the slope of (p, ε_v^p) curve obtained from an isotropic compression test. The parameters B, C and M are defined respectively as the slopes of curves (q, ε_v^p), (q, ε_v^p) and $(q,\ p)$. It should be noted that the (p, ε_v^p) relationship is unique and is represented by a single curve. The (q, ε_v^p), (q, ε_s^p), relationships are represented by a family of curves, each curve is obtained from a triaxial shear test at constant confinement pressure.
These non-linear stress-strain curves are represented by piecewise linear curves and the slopes between adjacent data points are assumed to be constant but vary over the range of the data. In Table 1, the model parameter are identified to parameters B, C and M; and the deviatoric stress under triaxial conditions q_c:

Table 1. Plastic parameters for ALIM model

$M_H + H\varepsilon_{ps} = M$
$H + H'p' = C$
D=-C/B
$Y + H\varepsilon_{ps} + M_H p' + H'p'\varepsilon_{ps} = q_c$

These parameters are obtained from interpolation between experimental data for a given stress state (q, p, ε_v^p, ε_s^p).
The numerical solution of the the stress-strain relation is advance based by adopting the backward Euler scheme, which is usually unconditionally stable. More detail about the integration algorithm are described in Chan (1999).

3 ELEMENT TESTS

ALIM has been implemented in the general purpose finite element code CRISP. In the following a conventional drained triaxial analysis is performed using CRISP. The soil material properties are obtained from interpolation using triaxial data. Three runs are performed for three different confining pressures p'=20kPa, 100kPa, 400kPa. The element test analyses are performed under controlled displacements to capture the post peak softening, using 100 increments.
Figure 3(a) shows the stress:strain responses for the drained tests up to a maximum shear strain of 18%. Results obtained using SM2D are also plotted. As observed the stress:strain curves from CRISP and SM2D match very well. The same can be said for the stress paths in the $p' - q$ plane plotted in Figure 3(b). It should be noted that the number of iterations to meet the tolerance is about 5-6 in all tests.

4 FINITE ELEMENT ANALYSIS

The finite element code CRISP has been used to determine the loads on pipes due to lateral loading in plane strain conditions (Ng et al. 2001, C-Core 1898). The initial stresses in the soil are generated using body loads corresponding to the bulk unit weight. Once the initial stresses are established the loading is performed

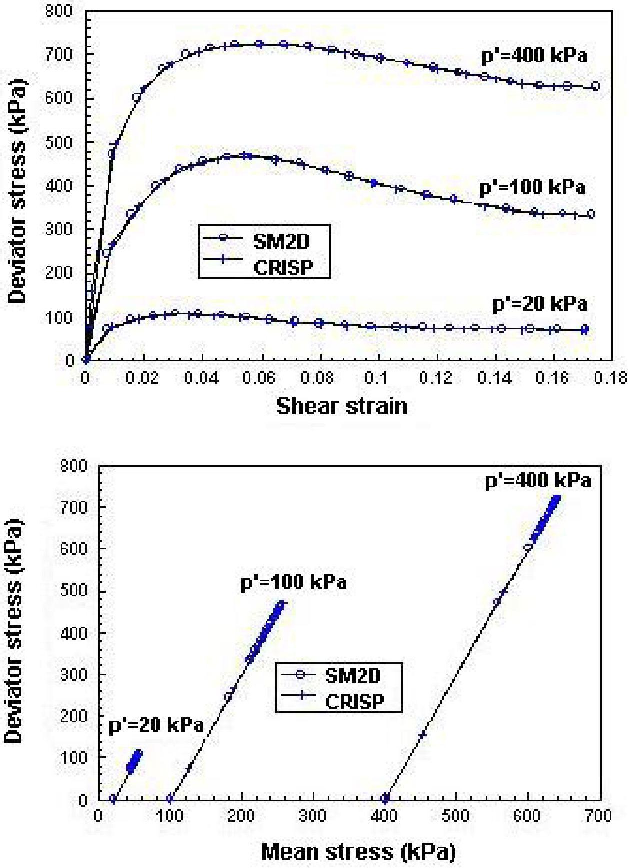

Figure 3: Drained triaxial analysis: comparaison of results from CRISP and SM2D (a) stress-strain response; (b) stress paths.

by imposing lateral displacements on all pipe nodes. The finite element idealisation consists of 136 and 32 six-noded elements for soil and pipe, respectively. The diameter of the pipe is 0.328 m, the base clearance is 0.2 m, the soil cover is 0.8 m and the width is 3 m. The distance from the left hand wall to the centre of the pipe is 0.65 m. It should be noted that interface elements are used to model the relative movement between soil and pipe.

Figure 4 shows the deformed mesh, deviatoric strain and deviatoric stress. The imposed lateral movement leads to a slight upward movement of the pipe due to the weak restraint on the surface. It can also be noticed that the localisation of the plastification, which takes place in front of the pipe, forms a precursor to failure (see Fig 4 (b)). A much steeper but weaker failure surface also develops behind the pipe. In general, if interface elements are used in the analysis, the soil heaves, both in front of and behind the pipe.

With the current reference data, the constitutive behaviour of ALIM dilates strongly when the deviatoric strain is high. But because of the drop in the mean effective stress (reflected in a much lower deviatoric stress zone) behind the pipe, the dilatancy is much less as the failure is due only to tension which develops and is accompanied by zero volume change.

Figure 5 shows the force displacement curves from the finite element analysis together with the experimental results. It can be observed that the simulation with interface elements gives lower load response than that performed without interface elements. The calculated peak load using interface elements is within 20%of the peak load of experiments BG7, LS04 and LS05. This is partly because the stiffness in the initial stage shown in the experiments is higher than that of the numerical simulations. The experimental results show a drop of 50% from the peak load to

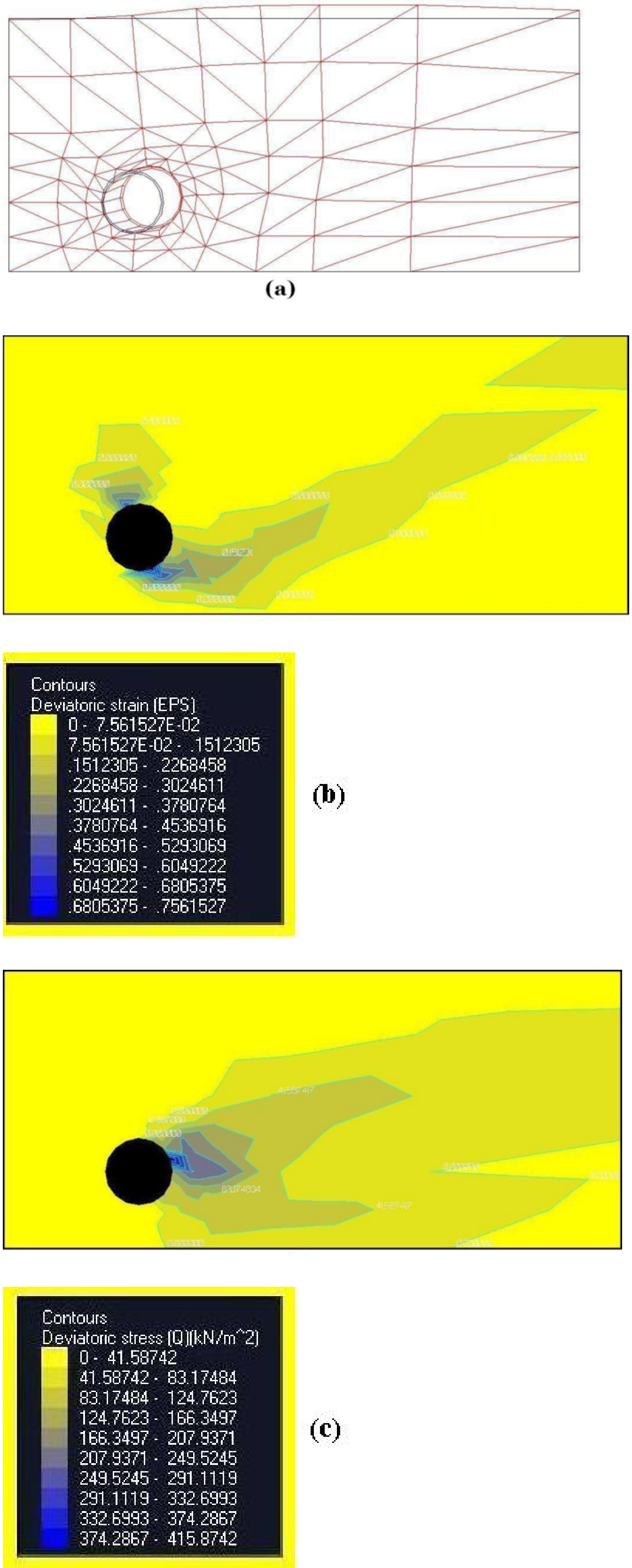

Figure 4: Lateral loading analysis in dense sand using ALIM model with and without interface (a) deformed mesh; (b) deviatoric strain; (c) deviatoric stress.

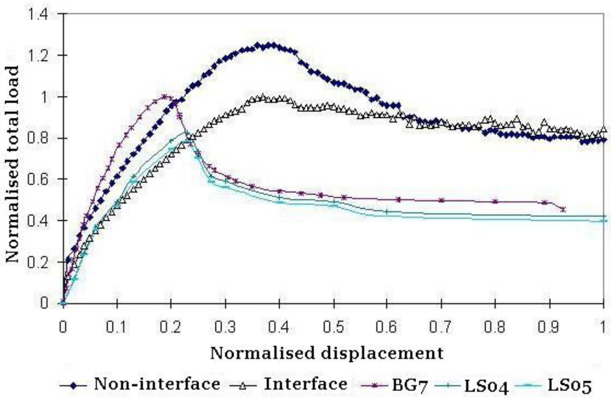

Figure 5: Lateral loading: load-displacement curves for analysis with and without interface elements.

the residual load. By contrast, the numerical results show only a drop of 20%, which is consistent with the amount of softening found in the reference data. The remaining 30% could be related to the formation of failure surfaces which are observed in the experiment.

5 CONCLUSIONS

The predictive capability of ALIM constitutive model of triaxial laboratory tests on sand and clay (not all reported in this paper) has been demonstrated for all range of confining pressures. Comparison of the predictions of a conventional triaxial test form CRISP and SM2D was in general excellent. The ability of the model to reproduce force-displacement responses observed in a number of different soil-pipeline loading conditions has also been demonstrated. The model results are much closer in general behaviour than the one obtained using other constitutive models such as Mohr-Coulomb. Using interface element, ALIM predicted a peak load within 20% of the experimental value. Further parametric studies should be performed to obtain a better fit of the experimental data.

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