Soil Constitutive Models to Simulate Pipeline-soil Interaction Behaviour

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ABSTRACT: At the present time, it is very common in practice (industry as well as in research) to utilise standard material models such as Mohr-Coulomb and Drucker-Prager to simulate the soil behaviour in the application of soil-structure interaction problems. These models are readily available in commercial finite element programs such as ABAQUS. The models are often chosen considering their simplicity, ease of use, reasonable computational time and the high level of understanding among the engineers. Furthermore, such models are widely popular in the community for modelling the behaviour of soils due to their relative simplicity and only requiring the basic soil properties (such as friction and dilation angles). The current study focuses on the application of such standard models to analyse laterally moving pipeline under plane strain condition. The results from the finite element analyses are compared with the large scale physical model test data. The results derived from user defined advanced constitutive soil models such as Nor-Sand and modified Mohr-Coulomb are also presented in comparison. Outcomes from the study revealed that Mohr-Coulomb model gives a better prediction of pipeline loads than from Drucker-Prager model, which however can be used to match with the Mohr-Coulomb response under plane strain condition. It is also shown that the advanced constitutive soil models give accurate prediction of pipeline loading in contrast to standard soil models due to their capability of modeling critical state behavior of soils. The performance of the standard models is also discussed using the available experimental results for friction angles in cohesionless soils.

1 INTRODUCTION

The development of numerical analysis and its application to geotechnical engineering problems over the past 20 years have provided geotechnical engineers with an extremely powerful analysis tool. The most recent research work conducted in the area of numerical modelling of soil-pipeline interaction problems has been able to highlight the development of proper numerical tools to capture the real behaviour of pipelines when subjected to lateral movements.

The accurate prediction of pipeline response during lateral soil displacement mainly depends on capturing the realistic soil behavior during its state change (such as void ratio) as well as at different mean normal stresses. The advanced constitutive models, such as Nor-Sand (Jefferies, 1993) and Cam-Clay (Schofield et al., 1968) are well equipped to capture such complexities in soil behaviour. However, these models are required to be calibrated using advanced soil testing programs. On the other hand, it is very common in practice to utilise standard material models such as Mohr-Coulomb (MC) and Drucker-Prager (DP) to simulate the soil behaviour in the application of soil-structure interaction problems. These models are readily available in commercial finite element programs such as ABAQUS. The models are often chosen considering its simplicity, ease of use, reasonable computational time and the high level of understanding among the engineers. Furthermore, such models are widely popular in the community for modelling the behaviour of soils due to their relative simplicity and only requiring the basic soil properties (such as friction and dilation angles). The current study focuses on the application of such standard models to analyse laterally moving pipeline under plane strain condition. The results from the finite element analyses are compared with the large scale physical model test data. The performance of the standard models is also discussed using the available experiment results for friction angles in cohesionless soils. Further, the results derived from advanced constitutive soil models such as Nor-Sand and modified Mohr-Coulomb are also presented in comparison.

2 STANDARD CONSTITUTIVE MODELS

2.1 *Mohr-Coulomb model*

Mohr-Coulomb model is a simple linear elastic-perfectly plastic model which is widely used for the design applications in geotechnical engineering to simulate material response under monotonic loading. The model is widely popular in the community for modelling the behaviour of soils due to its relative simplicity and the requirement of the basic soil properties (such as friction and dilation of soils).

The model behaves elastically and obeys Hooke's law until the onset of yielding which is determined by the Mohr-Coulomb yield criterion. In deviatoric stress space, the yield function plots as an irregular hexagonal cone (Fig. 1). The standard Mohr-Coulomb model possesses a perfectly plastic response upon yielding (i.e. no hardening/softening law incorporated).

The original Mohr-Coulomb model has been modified in this work to capture the strain softening behaviour of the material at large deformations. The softening behaviour has been captured by reducing the mobilized friction and dilation angle with an increase in plastic deviatoric shear strains. The calibration and validation of the model based on triaxial compression data, as well as mesh sensitivity effects can be found in Robert (2010).

2.2 *Drucker-Prager model*

Due to the singularities expected from the sharp corners associated with the Mohr-Coulomb yield function in deviatoric stress space, earlier pioneers of the field sought simplifications (Potts and Zdravkovic, 1999). One of the ways to overcome such corner problem is through Drucker-Prager model. The linear Drucker-Prager criterion plots the yield function as a cylindrical cone in deviatoric stress space (Fig. 1).

The Drucker-Prager model can be used to represent the behaviour of soil to match the Mohr-Coulomb yielding response in plane strain condition. Equations 1 & 2 (ABAQUS, 2011) can be used to derive Drucker-Prager parameters (β, ψ and d) under plane strain condition on the basis of Mohr-Coulomb parameters (ϕ, ψ and c).

$$\sin\phi = \frac{\tan\beta\sqrt{3(9-\tan^2\psi)}}{(9-\tan\beta\tan\psi)} \quad (1)$$

$$c\cos\phi = \frac{\sqrt{3(9-\tan^2\psi)}}{(9-\tan\beta\tan\psi)}d \quad (2)$$

2.3 *Model Behaviour*

Fig. 1 represents the yield surface representation of the Mohr-Coulomb and Drucker-Prager models in deviatoric stress plane at a mean pressure of 20 kPa. The model parameters used for Mohr- Coulomb model are a friction angle of 35º and zero cohesion.

The Mohr-Coulomb yield criteria is independent of the loading condition (i.e. uniform friction angle), whereas the Drucker-Prager yield criteria has varying equivalent MC friction with the change in load angle (θ).It can also be seen that Drucker-Prager yield criteria changes in size and shape with the change in 'K' value.

Due to the behavior of DP model which has varying friction angles with θ & K, the actual friction angles of sand subjected to various loading conditions can be compared with the DP model behavior. The Fig. 2 shows the experiment friction angles (Kulhavy and Mayne, 1990) and friction angle representation in Drucker-Prager model (the ranges of the experiment friction angles in Fig. 2 are denoted as 'top' and 'bottom'). It can be seen that the proximity of the DP model response to the experiment observation depends on the ratio K, which defines the ratio between yield stresses in triaxial extension (TE) and compression (TC). When 'K' is decreasing, the model gets flatter and tends to reach the experiment range of friction angle. However the model defined in FE program ABAQUS does not permit to lower the 'K' beyond 0.778 in order to keep the convex shape of the yield surface. Therefore the line K=0.778 in Fig. 2 represents the limiting representation of the model which is the closest possible approach to the experiment behaviour at TC friction angle 35^0. Here the maximum deviation of the model behaviour is within 14% of the experiment behaviour.

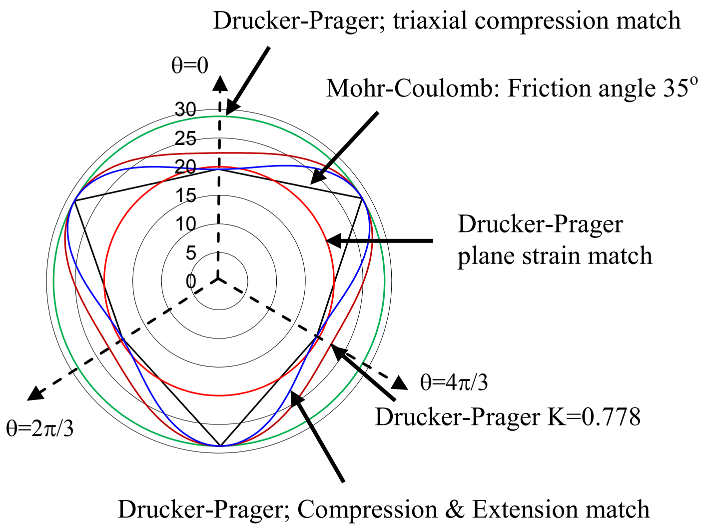


Fig. 1 Mohr-Coulomb and Drucker-Prager yield surfaces comparison in deviatoric stress space.

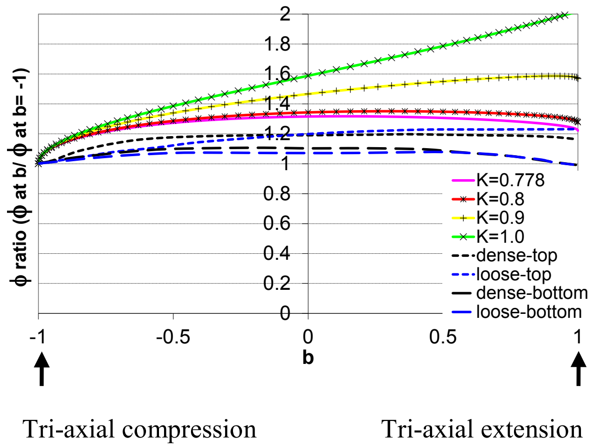


Fig. 2 Drucker-Prager friction angles vs experiment observation.

3 LARGE SCALE EXPERIMENTS

Large scale physical model tests were conducted at the Pipeline Engineering Research Laboratory (PERL), Tokyo Gas Co., Ltd, Japan, in order to investigate the effects of pipeline response under lateral soil deformation. The experimental facility was included a test compartment, a loading cell, an instrumentation and data acquisition system, displacement sensors, pressure sensors, a counter weight system and a soil handling equipment (overhead crane). Further details of testing such as test box apparatus, soil condition and preparation, and test procedures can be found in Robert, 2010.

In the current study, the response of a steel pipe (buried at 0.65m depth in a sand which has an initial dry density of 1.56g/cm^3) with a diameter of 114.6mm and thickness of 4.6mm, was studied to investigate the responses from standard and advanced constitutive soil models.

4 FINITE ELEMENT ANALYSIS

FE analyses were carried out using ABAQUS (ABAQUS, 2011) with geometric non-linearity and large strain formulation. The analyses were performed under plane strain conditions and the model uses soil and pipe elements with 4-noded bilinear, plane strain, reduced integration with hourglass control (CPE4R) elements. The wall boundaries were assumed to be smooth and supported only in the normal direction. The pipe was pulled laterally by imposing equal lateral displacement on all pipe nodes and was set to move freely in the vertical direction. Adaptive meshing has been incorporated in the analyses to control the mesh distortions that result from large deformations of the soil caused by lateral pipe displacements.

The behavior of pipe is assumed as a linear elastic material (ASTM A36) and the behavior of soil was modeled using Mohr-Coulomb and Drucker-Prager plasticity with the use of properties obtained from triaxial tests (Robert, 2010). The Drucker-Prager model parameters were derived to match the Mohr-Coulomb yielding response in plane strain condition. Analyses were also performed using modified Mohr-Coulomb model as well as Nor-Sand model. Table 1 shows the model parameters used in this study (Authors refer to Robert, 2010 for detailed calibration and validation of the models).

Table 1. Model parameters

Parameter	Units	Value
Mohr-Coulomb (MC) model parameters		
Young's Modulus	kPa	2300
Poisson's ration	-	0.3
Friction angle (ϕ)	Degrees	44.5
Dilation angle (ψ)	Degrees	11.6
Cohesion (c)	kPa	0.3
Drucker-Prager (DP) model parameters (plane strain)		
Young's Modulus	kPa	2300
Poisson's ration	-	0.3
Friction angle (β)	Degrees	49.8
Dilation angle (ψ)	Degrees	11.6
Cohesion (d)	kPa	0.36
Modified Mohr-Coulomb model (MMC)		
Same parameters as in MC model		
Critical state friction angle	Degrees	33
Plastic deviatoric shear strain at completion of the softening	-	0.3

5 RESULTS

The results from the FE analyses are shown in Fig. 3 & 4 for pipe load-displacement response and soil deformation mechanisms respectively. It can be seen from Fig. 3 that pipe loading response obtained from Mohr-Coulomb model closely matches with that from experiments, in contrast to Drucker-Prager model prediction which under-estimates the actual pipe loading. However, the Drucker-Prager model prediction based on plane strain response shows similar behavior when compared to Mohr-Coulomb model and experimental behaviour. This is because the model parameters were derived to match similar responses of stress-strain in plane strain loading condition. The deformation mechanism at peak pipe loading (Fig. 4) also dictates similar shearing modes between the Mohr-

Coulomb and plane strain Drucker-Prager models. Three shear bands were formed in both the models due to pipe lateral displacement. Shear bands 1 and 2 were occurred due to the upward soil displacement caused by the lateral pipe movement. Shear band 3 was formed by soil depression. Hence, both the Mohr-Coulomb and plane strain Drucker-Prager models are predicting similar loading responses and capable of capturing the approximate loading prediction when compared to data from large scale tests.

However, the models are unable to predict the accurate pipe loading, especially at large displacements due to lack of critical state modelling of soil behaviour. Modified Mohr-Coulomb model showed better loading predictions when compared to large scale test data. This reveals that the Mohr-Coulomb model which incorporates strain softening of soil, can predict the accurate pipeline loading if the model parameters are appropriately applied for a given stress and void ratio state. However, Nor-Sand model is superior because it can accurately predict the critical state behavior of soils and can be used for a given material without the effect of density and confining stress. Therefore, advanced constitutive models should be used to predict soil response in situations where large deformations are involved.

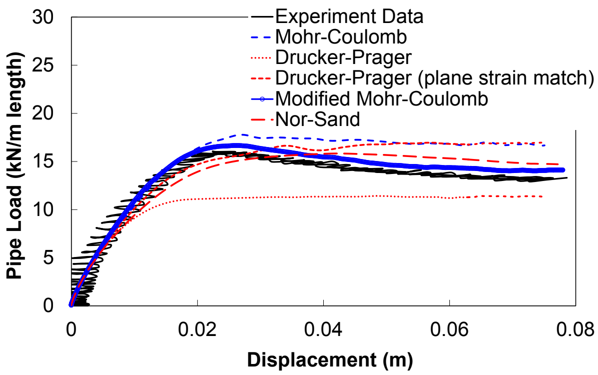
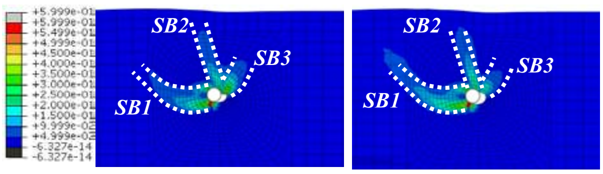


Fig. 3 *f*-*δ* response of the pipe



(a) DP model (plane strain) *(b) MC model*

Fig. 4 Model deformation mechanism (Plastic strains plotted)

6 SUMMARY AND CONCLUSIONS

The current study investigates the application of standard models such as Mohr-Coulomb and Drucker-Prager to simulate soil behavior in soil-pipeline interaction problems. The results from the finite element analyses are compared with the large scale physical model test data. The results derived from user defined advanced constitutive soil models such as Nor-Sand and modified Mohr-Coulomb are also presented in comparison.

The investigations revealed that the standard material models are capable enough in predicting approximate loading responses when compared to data from large scale tests under plane strain conditions. However, such models are unable to capture the accurate pipeline loading due to lack of critical state modeling of soil behavior. Mohr-Coulomb model which incorporates strain softening of soil, can predict accurate pipeline loading if the model parameters are appropriately applied for a given stress and void ratio state. However, Nor-Sand model is more appropriate because it can accurately predict the critical state behavior of soils and can be used for a given material without the effect of density and confining stress. Hence, it is recommended to utilize advanced constitutive models to represent soil in situations where large soil deformations are expected.

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