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Analysis of Soil-Pipeline Interaction using ABAQUS/Explicit

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Abstract

It is common in practice (industry as well as in research) to utilise the finite element method for obtaining a solution for pipe-soil interaction problem. There are different finite element methods (such as implicit & explicit) being employed to understand the behaviour of buried pipelines. Implicit finite element solutions, which are always unconditionally stable, are commonly used for soil-pipeline interaction problems. However, this consumes substantial time, memory, storage and in some cases severe convergence problems in reaching towards the final solution. In contrast, explicit finite element calculation is conditionally stable with the use of dynamic finite element formulation. It is more common to use implicit methods for soil-pipeline interaction analyses, but a number of benefits of explicit FE over implicit modelling for pipeline designs have been identified, such as faster simulation time and less numerical problems. To analyse soil-pipeline interaction problems under quasi-static conditions, it is important to conduct analysis with proper control on the stability limits/kinetic energy dissipation of the model. This paper describes how the explicit modelling can be utilised to investigate the behaviour of pipelines under dry as well as unsaturated conditions. In this study, advanced constitutive models that can effectively simulate dry and unsaturated sand behaviour have been implemented into both implicit and explicit solvers, and shown that similar behaviour can be predicted using both the codes. The current study uses the finite element package ABAQUS which has both implicit and explicit solvers inbuilt.

Keywords: Implicit finite elements, explicit finite elements, ABAQUS, soil-pipeline interaction, advanced constitutive models, dry sand behaviour, unsaturated sand behaviour

Introduction

Pipelines used for the transport of energy and services are very important lifelines to modern society. The vital role that they play in our present economy is reflected in the many kilometres of pipelines laid in onshore and offshore locations worldwide. As most of such pipelines are buried underground, the analysis between pipeline-soil interactions is of major importance for the role of pipeline designs. Failing to correctly predict the pipe-soil interaction could lead to failure of the pipeline resulting in devastating socio-economic consequences.

At present, it is common in practice (industry as well as in research) to utilise finite elements for obtaining a solution for pipe-soil interaction problem. There are different finite element methods (such as implicit & explicit) being employed to understand the behaviour of buried pipelines. Implicit finite element solutions, which are always unconditionally stable, are commonly used for soil-pipeline interaction problems. However, this consumes substantial time, memory, storage and in some cases severe convergence problems in reaching towards the final solution. In contrast, explicit finite element method is conditionally stable with the use of dynamic finite element formulation. There is a number of benefits in using explicit FE over implicit modelling for pipeline designs have been identified, such as faster simulation time and less numerical problems. To analyse soil-pipeline interaction problems under quasi-static conditions, however, it is necessary to apply proper control on the stability limits/kinetic energy dissipation of the model. This paper describes how the explicit modelling can be utilised to investigate the behaviour of pipelines under dry as well as unsaturated conditions. In this study, advanced constitutive models that can effectively simulate dry and unsaturated sand behaviour...
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**Implicit modelling of soil-pipeline interaction problems**

Implicit modelling has been in practice for many years to solve a wide range of linear and non-linear problems involving static, dynamic, thermal, and electrical response of structures. It is also highly popular in the use of soil-pipeline interaction research to handle diversified non-linearities arising from material, boundary condition and geometry [5,7,13,14].

In implicit modelling, the solution for a non-linear problem is found by applying the specified loads gradually and incrementally working towards the final solution. Therefore it breaks the simulation into a number of load increments and finds the approximate equilibrium at the end of each load increment. It often takes several iterations to determine an acceptable solution to a given load increment. Due to this solving mechanism, implicit models consume substantial time, memory and storage, and in some cases, it has convergence problems in reaching the ultimate solution.

**Explicit modelling of Soil-Pipeline Interaction Problems**

**General**

Explicit modelling can be often considered as a complimentary analysis to implicit modelling. Although the modelling in explicit is suitable for high speed dynamic events, it can effectively be used to analyse the soil-pipeline interaction by defining the problem as quasi-static. The challenge in explicit analysis is to perform a quasi-static analysis without any dynamic effects.

Explicit modelling uses a central difference rule to integrate the equations of motion explicitly through time, using the kinematic conditions at one increment to calculate the kinematic conditions at the next increment. Following the dynamic equilibrium, velocities and displacements are advanced *explicitly* through time after obtaining the accelerations at the beginning of each increment.

**Quasi-Static analysis**

The solution from an explicit analysis is based on a true dynamic procedure. Accordingly, out of balance forces propagate as stress waves between neighbouring elements while solving for a state of dynamic equilibrium. Most of the soil-pipeline interaction problems are to be analysed using static analyses due to the nature of the loading on pipe is static rather than dynamic (except cyclic loading scenarios). That is, when the pipeline is assumed to be moving slowly in a way that the inertial force development is negligibly small, then the problem can be solved by static analysis. Carrying out a static analysis (quasi-static) based on a dynamic procedure can be challenging in terms of time and cost. Explicit modelling in ABAQUS provides several strategies to reach for a static (quasi-static) solution within a reasonable computational time.

**Loading rate control**

A quasi-static process would produce accurate static results when the pipeline moves in such a way that the inertial forces would become minimum. In other words, the pipe should be moved in its natural time scale before reaching to its resonance stage. In order to achieve this, the pipe should be moved at a slow rate so as to avoid dynamic conditions. Explicit modelling in ABAQUS provides an efficient approach to control the smooth application of loading (i.e. smooth amplitude).

**Mass scaling**

Another approach to keep the inertial forces to a minimum is to move the pipeline very slowly. However, the drawback in terms of computation cost would be enormous due to small time step. Explicit modelling in ABAQUS adopts an efficient strategy called ‘mass scaling’ to reduce the CPU time, while providing the capability to move the pipe in its natural time scale which avoids the dynamic effects.

**Viscous pressure**

Application of a “viscous pressure” load to the model is another approach to damp out the low frequency dynamic effects, allowing the static equilibrium to be reached in a minimum number of
increments. In other words, the dynamic solution becomes asymptotic to the quasi-static solution much faster. Viscous pressure load in ABAQUS is applied as a distributed load [1].

Energy concept

Unlike in implicit modelling, it is of great importance to check the relevant energy quantities after carrying out an explicit analysis to ascertain whether the analysis has been carried out under quasi-static condition. As a general rule, the kinetic energy of the model should not exceed 5-10% of its internal energy throughout the process for a quasi-static analysis [1]. The energy dissipated by viscosity should be very small unless viscoelastic material and material damping are used. The energy dissipated from the frictional effects would be substantial for soil-pipeline interaction problems. Nevertheless, the work done by externally applied loads should be nearly equal to the internal energy of the model and the kinetic energy should be within 5-10% of the internal energy.

Explicit modelling of pipeline behaviour in dry sand

A 3-D explicit analysis was conducted to investigate the capability of explicit modelling of pipeline behaviour in dry sand. A quasi-static analysis has been conducted with the use of smooth load rate control. The effect of mass scaling has also been investigated to determine an appropriate mass scaling factor for pipeline-soil interaction analysis. Figure 1 shows the mesh discretisation of the FE model used to simulate the laterally loaded pipeline. The wall boundaries were assumed to be smooth and supported only in the normal direction. The pipe was pulled laterally at a constant speed by imposing equal lateral displacement on all pipe nodes and was set to move freely in the vertical direction. Soil behaviour was modelled using the Drucker-Prager model. Moreover, an equivalent analysis was carried out using Mohr-Coulomb yield criterion using implicit modelling. The Drucker-Prager friction and dilation angles were derived to match the plane strain response of the Mohr-Coulomb model so that the stress-strain response will become the same. The model parameters are listed in Table 1. The pipe, which was buried at H/D of 4 (H is the cover height to pipe centre and D is the pipe diameter), was modelled as a linear elastic material.

![Figure 1 3-D FE mesh used for lateral pipeline modelling in dry sand](image)

### Table 1 Model parameters for lateral pipeline analysis in dry sand

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
<th>Value 4</th>
<th>Value 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mohr-Coulomb</td>
<td>Density (kg/m³)</td>
<td>1640</td>
<td>1745</td>
<td>0.3</td>
<td>0.3</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Young's modulus (kPa)</td>
<td>1640</td>
<td>1745</td>
<td>0.3</td>
<td>0.42</td>
<td>44.5</td>
</tr>
</tbody>
</table>

The computing power utilised for this work was comprised with a computer of 2 GB of physical memory with the processor speed of 2.4GHz. The pipe was imposed a lateral displacement of 60mm within one second. Table 2 summarises the effect of mass scaling on the CPU time. It can be clearly seen that mass scaling has the ability to cut down the simulation time drastically. A mass scaling factor of 100 has cut down the simulation time by 68% from the case of 'no mass scaling explicit analysis', 80% from the case of standard analysis with Drucker-Prager model and 86% from the case of standard analysis with Mohr-Coulomb model.
Figure 2 shows that the load on the pipeline remains almost at its datum position (implicit or standard analysis output) if the mass scaling factor is less than 100. For occasions where mass scaling is more than 100, the pipe load was increased dramatically. This is because higher mass scaling increases the dynamic effects in the model, which in turn causes to yield unrealistic pipeline response, i.e. the maximum kinetic energy (KE) and internal energy (IE) of the model at mass scaling of 500 is approximately 0.02kPa and 0.08kPa respectively (KE > 5% of IE). However, for cases where the mass scaling is less than 100, the maximum KE is substantially lower in comparison with IE (for instance, at mass scaling of 100, the maximum KE is less than 0.005kPa and hence KE < 5% of IE in the model). Therefore, it can be seen that the application of mass scaling along with proper load controls (such as smooth amplitude loading) into the pipeline-soil interaction analysis has produced similar pipe response as obtained from equivalent implicit analysis, while substantially minimising the CPU time in contrast with implicit modelling.

<table>
<thead>
<tr>
<th>Mass scaling factor</th>
<th>CPU time</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>2h 58mins</td>
</tr>
<tr>
<td>75</td>
<td>3h 27mins</td>
</tr>
<tr>
<td>50</td>
<td>4h 10mins</td>
</tr>
<tr>
<td>40</td>
<td>4h 39mins</td>
</tr>
<tr>
<td>30</td>
<td>5h 27mins</td>
</tr>
<tr>
<td>20</td>
<td>6h 43mins</td>
</tr>
<tr>
<td>10</td>
<td>8h 09mins</td>
</tr>
<tr>
<td>No mass scaling</td>
<td>9h 31mins</td>
</tr>
<tr>
<td>Implicit modelling-MC</td>
<td>21h 30mins</td>
</tr>
<tr>
<td>Implicit modelling-DP</td>
<td>15h 36mins</td>
</tr>
</tbody>
</table>

Table 2 Effect of mass scaling on CPU time

Further studies have been conducted to investigate the capability of simulating advanced soil behaviour using explicit modelling. The user would need to implement an external (i.e. advanced) soil model into the explicit or implicit FE platforms to investigate the realistic behaviour of pipes buried in soils which could depict unique or complicated behaviour. In the current study, two material models (Mohr-Coulomb model & Nor-sand model) have been implemented into both implicit as well as explicit platforms. The results from each model are compared between implicit and explicit models to identify advantages associated with the explicit modelling.
Mohr-Coulomb model

The Mohr-Coulomb model, which has been developed to run in implicit as well as explicit platforms in ABAQUS, is a common model which is highly utilised in practise to simulate the behaviour of soils. However, if the user wishes to have more control over the mechanical constitutive behaviour of the material as was required by Robert [11] and Robert & Soga [12], a complete model has to be implemented. In the current study, the Mohr-Coulomb model has been developed and implemented to run in both implicit as well as explicit platforms using external subroutines. The elastic behaviour is modelled assuming linear isotropic elasticity and the stress state of the material after yielding was modelled as outlined in Robert [11] & Menetrey [10].

In order to validate the implemented Mohr-Coulomb model for dry sand, single element tests (triaxial compression, triaxial extension and plane strain) was performed in both implicit and in explicit models, and compared with the inbuilt Mohr-Coulomb model test results. Model parameters have been defined in Table 3. Initially an all-around compressive pressure of 10kPa was applied to the sample.

Table 3 Mohr-Coulomb model parameters for the element tests to validate the implemented UMAT & VUMAT

<table>
<thead>
<tr>
<th>Density (kg/m^3)</th>
<th>Young’s modulus (kPa)</th>
<th>Poisson’s ratio</th>
<th>Cohesion yield stress (kPa)</th>
<th>Friction angle (degrees)</th>
<th>Dilation angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1650</td>
<td>2000</td>
<td>0.3</td>
<td>0.5</td>
<td>40</td>
<td>8.75</td>
</tr>
</tbody>
</table>

Figure 3a shows the plane strain test results using implicit subroutine (UMAT) and explicit subroutine (VUMAT) in comparison with the inbuilt Mohr-Coulomb model (Results of other tests can be found in Robert [11]). As it can be seen, the model responses from both the UMAT & VUMAT are identical to that with the in-built material model.

Nor-sand model

The second soil model, which was tested for the explicit capability, is Nor-Sand. The original Nor-Sand model was proposed by Jefferies [8] and was implemented into implicit FE by Dasari and Soga [6]. In order to enhance the model performance, three modifications were made by Cheong [5]. They include (i) a new definition for the critical state (using Bolton [4]) (ii) lode angle dependency on the critical state parameter (using Matsuoka [9]) and (iii) the evolution of yield surface with respect to plastic shear strain.

Nor-Sand model is a generalised Cambridge-Type constitutive model for sand, which is based on the critical state theory. It uses the state parameter concept by Been & Jefferys [2], and attempts to accurately reproduce dilation and softening on the dry side of the critical state. This is achieved by postulating infinite isotropic normal consolidation loci (NCL), which allows a separation of the intrinsic state from the over-consolidation state. A main feature of Nor-Sand model is the use of rate-based hardening using the state parameter, to size the yield surface. Nor-Sand model adopts the associated flow rule yet predicts realistic dilation. In the current study, the Nor-Sand model was implemented to run in explicit platform.

In order to validate the implemented Nor-Sand code in explicit, a series of single element test simulations including triaxial compression, triaxial extension and plane strain in both 2-D and 3-D elements were performed and the results were compared with the identical implicit modeling data. The model parameters are used in accordance with Table 4. Figure 3b shows the deviatoric stress vs. deviatoric strain for triaxial compression tests, and the other test results can be found in Robert [11].

Table 4 Nor-Sand parameters used for 2-D & 3-D element tests

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear modulus constant (A)</td>
<td>300</td>
</tr>
<tr>
<td>Pressure exponent (n)</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Explicit modelling to simulate the pipeline behaviour in unsaturated soils

Studies have also been performed to investigate how the explicit modeling can be used to simulate the behavior of unsaturated soils. Explicit modeling in ABAQUS cannot perform coupled pore fluid diffusion/stress analysis and therefore the analysis should be either undrained or drained. In this study, considering the fast pipeline loading in low permeability unsaturated soils, it has been shown that explicit modeling can be used to simulate the pipeline behavior in undrained conditions (i.e. the volume of water remains constant).

In explicit modeling of unsaturated soils behavior, change in saturation can be obtained on the basis of the changes in volumetric strains in accordance with the following criteria, and the suctions are derived through soil moisture relations obtained from experiments.

\[ dS_w = \frac{S_{sat} \cdot d\varepsilon_{vol}^{\text{vol}}}{n_1 - d\varepsilon_{vol}^{\text{vol}}} \]

where \( S_{sat} \) and \( n_1 \) are the initial saturation and porosity respectively and \( d\varepsilon_{vol}^{\text{vol}} \) is the change in volumetric strain during a load increment.

The proposed methodology for unsaturated soil modelling under explicit algorithm has been proved to yield similar response to that with the pore pressure coupled analysis in conjunction with the generalized Bishop’s effective stress framework as shown by Robert [11]. Pore pressure-soil deformation coupled analyses were performed using modified Mohr-Coulomb UMAT [11] as well as Nor-Sand UMAT considering triaxial compression (TC), triaxial extension (TE) and plane strain compression tests and the results were compared with the identical undrained VUMAT model results. Model parameters were the same as defined in Table 3 & 4 for Mohr-Coulomb and Nor-sand models.

**Figure 3** Results of single element tests to validate the implemented explicit dry sand models

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poisson’s ratio (( \nu ))</td>
<td>0.2</td>
</tr>
<tr>
<td>Critical state ratio (( M ))</td>
<td>1.27</td>
</tr>
<tr>
<td>Maximum void ratio (( e_{\text{max}} ))</td>
<td>0.851</td>
</tr>
<tr>
<td>Minimum void ratio (( e_{\text{min}} ))</td>
<td>0.497</td>
</tr>
<tr>
<td>‘( \gamma )’ value in flow rule</td>
<td>0.2</td>
</tr>
<tr>
<td>Hardening parameter (( h ))</td>
<td>200</td>
</tr>
<tr>
<td>Maximum dilatancy coefficient (( \chi ))</td>
<td>3.5</td>
</tr>
<tr>
<td>Switch to use constant or exp ( H )</td>
<td>0.0 (exp)</td>
</tr>
<tr>
<td>Tolerance (TOL)</td>
<td>0.001</td>
</tr>
</tbody>
</table>
respectively. Initial water saturation of 60% and matric suction of 5 kPa were assumed for all the analyses. An initial net confining pressure of 10 kPa was applied all around the sample. Figures 4a & 4b show the results of triaxial compression test on modified Mohr-Coulomb and Nor-sand models respectively. The other validation results can be found in Robert [11]. As it can be seen, the model responses are identical between the two analyses validating the implementation of the unsaturated explicit model to simulate the behaviour of unsaturated soils under undrained condition.

![Figure 4 Validation of the explicit undrained model for 3-D plane strain element test](image)

(a) Modified Mohr-Coulomb model outputs - Effective Stress, \(\sigma'\) vs Axial Strain, \(\varepsilon_1\) & Total Stress, \(\sigma\) vs \(\varepsilon_1\)

(b) Nor-sand model outputs - Total stress, \(\sigma\) vs Axial strain, \(\varepsilon_1\) & Effective stress, \(\sigma'\) vs \(\varepsilon_1\)

The implemented undrained codes were used to analyse a soil-pipeline interaction of a laterally loaded pipeline tested at Pipeline Engineering Research Laboratory, Tokyo Gas, Japan [Pipe (diameter=0.1146m), which was buried at 0.6m depth in sand having initial moisture content of 17.3% and bulk density of 1780 kg/m³, was moved laterally at a speed of 0.01 m/s]. For the purpose of validating, the results were compared with the implicit pore pressure-coupled analysis and with the experimental results. The soil and the pipe were modeled using 4-node bilinear, reduced integration with hourglass control (CPE4R) elements. For the coupled analysis, the soil was modeled using 4-node bilinear displacement and pore pressure, reduced integration with hourglass control elements (CPE4RP). The sand was modeled using Mohr-Coulomb model, whereas the pipe was assumed to be a linear elastic material (ASTM Grade A-36 steel). The pipe in the coupled analyses was displaced at the same rate as defined in the experiment while the rate defined in the undrained model is slow enough to avoid the dynamic effects of the explicit analysis.

The mechanical behaviour of the sand was modeled using Mohr-Coulomb model. Three different simulation series were performed. In the first series, coupled analysis (MC_Coupled) and undrained analysis (MC_Undrained) were compared under implicit modelling conditions using conventional built in Mohr-Coulomb model. In the second series, coupled analysis (MMC_Coupled) and undrained (MMC_Undrained) analysis were performed using the modified Mohr-Coulomb code, which was developed considering the effect of plastic strains on friction, dilation and apparent cohesion (MMC-USDFLD, [11]). MMC-USDFLD code developed within an implicit framework, was used for the coupled analysis, whereas MMC code in explicit framework was used for the undrained analysis. In the third series, the problem was analysed using the unsaturated Mohr-Coulomb model under explicit modelling (MMC_Final), which considers the water saturation effect on apparent cohesion and dilation, in addition to the plastic strain effect [12].

Figure 5a-c shows the shear strain distribution contours at the dimensionless displacement of 0.7, computed by MMC_Final, MC_Coupled and MC_Undrained cases, respectively. In all three cases, two distinct shear bands are formed. The shear band formation of the MC_Coupled and MC_Undrained cases are similar demonstrating that the analysis is essentially in undrained conditions (similar pipeline loading was derived as shown in Fig.6). The deformation mechanism SB1 is more localized in the MMC_Final case than in the MC_Coupled and the MC_Undrained cases due to the
softening induced by the progressive development of plastic shear strains as well as changes in water saturation (see Fig. 6).

Therefore, the outcomes of the modeling revealed that the proper explicit modeling (such as in MMC_Final) which incorporates the behavior of unsaturated soils under undrained conditions is capable of reproducing the realistic pipeline response observed in the large scale physical model experiments.

Figure 5 Mechanism of shear band development in FE analyses

Figure 6 Load-displacement plots for the comparison of coupled and undrained analyses considering the behaviour of soil using Mohr-Coulomb model
Summary and Conclusion

The development of numerical analysis and its application to geotechnical engineering problems such as in soil-pipeline interaction over the past decade have provided geotechnical engineers with an extremely powerful analysis tool. Among such numerical tools, it is common in practice (industry as well as in research) to utilise the finite element method for obtaining a solution for pipe-soil interaction problems. There are different finite element methods (such as implicit & explicit) being employed at present, to understand the behaviour of buried pipelines. Implicit finite element solutions, which are always unconditionally stable, are more common to use for soil-pipeline interaction problems. However, this consumes substantial time, memory, storage and in some cases severe convergence problems in reaching towards the final solution. In contrast, explicit finite element method is conditionally stable with the use of dynamic finite element formulation, but it can be used effectively to analyse soil-pipeline interaction problems under quasi-static conditions with the proper controls on the stability limits/kinetic energy dissipation of the model. Although it is more common to use implicit methods for soil-pipeline interaction analyses, a number of benefits of using explicit modelling over implicit methods for pipeline designs have been identified, such as faster simulation time and less numerical problems. This paper describes how the explicit modelling can be used to simulate the behaviour of pipelines in dry as well as unsaturated soil conditions within quasi-static framework. It has also been shown that advanced constitutive models that can effectively simulate dry as well as unsaturated sand behaviour can be implemented into explicit FE, giving similar responses in comparison with implicit FE. Hence, it is highly advantageous to utilise explicit FE to simulate the buried pipeline response in complex soil environments for both dry as well as partially saturated conditions. One of the disadvantages of using explicit modelling in ABAQUS is that it cannot perform pore water pressure generation and dissipation response. Hence, either drained or undrained problems can only be solved in explicit modelling, not transient problems.

References