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Performance of Buried Pipelines Subjected to Surface Explosion

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ABSTRACT: In the global pursuit of net-zero energy solutions and sustainable practices, pipelines play a crucial role across various sectors, particularly in hydrogen transport, thermal energy storage (TES) and district heating and cooling (DHC) systems. The blast load is one of the primary causes of pipeline failure. Construction sites that require blasting or terrorist attacks are the main sources of explosions. Terrorist attacks and accidental explosions have become common in recent years. To address this issue, the present study aims to investigate the performance of buried pipeline subjected to surface explosion. To perform the analysis finite element method (FEM) based program Abaqus CAE is used. The subsurface is considered as soil layer and the pipe as continuous steel material. Coupled Eulerian-Lagrangian (CEL) technique is adopted to simulate the proposed large deformation problem. Soil is modelled using conventional Lagrangian elements. Whereas, air and blast domain is modelled using Eulerian elements. The TNT (trinitrotoluene) explosive material has been simulated using JWL (Jones-Wilkins-Lee) equation of state and an equation of state of type "Us-Up" is used to model air. The elasto plastic stress-strain behaviour of the steel pipe and the geometric non-linearity of the whole system have been incorporated in the analysis. The top of the air is treated as a free surface and to prevent any reflection of the waves produced by the blast loads all other outer surfaces is modelled as non-reflecting boundaries. From the present analysis, it has been observed that pipe stability against blast load increases with higher steel grades and internal pressure. The outcomes of the study will be useful during design or decision making of buried pipeline against such blast scenarios.

KEYWORDS: Buried pipelines, Coupled Eulerian Lagrangian, FEM, Blast load, Pipe-soil interaction.

1 INTRODUCTION

The demand for buried pipelines has increased significantly in recent years due to their efficiency in transporting energy, oil, and gas. Additionally, with the rapid growth of urban infrastructure and the expansion of pipeline networks, buried pipelines are generally more preferable over above-ground pipelines to minimise surface disturbance. Pipelines are vulnerable to blast loading, which may occur accidentally or intentionally such as during nearby construction that requires blasting, accidental vehicle explosions, or terrorist attacks (Mokhtari and Alavi 2015). The duration of a blast load is much shorter than that of an earthquake load, but its magnitude is manifold. Hence, there is a high risk of potential failure of buried pipes due to blast loading. If a pipe fails, it may contaminate the ecosystem, cause leakage, result in energy loss, and potentially lead to a disaster. Hence, it is essential to understand the failure mechanism of pipes under blast load scenarios.

Works have been carried out in the area of underground utilities subjected to blast loads which includes surface explosion, subsurface explosion, and internal explosion (Mandal et al. 2021). Khan et al. 2025 found that the deformation of tunnel in silty clay is low because of its high modulus of elasticity, which increases the resistance to surface blast loading. With the increase in the buried depth of the pipeline, the resistance of the pipeline to the blast loading increases (Wang et al. 2023). The increase in the TNT magnitude and decrease in the wall thickness of the buried pipe, the deformations of the pipe is increased (Zhang et al. 2016). The stress, strain, and displacements of pipelines buried in unsaturated soils are little higher compared to the pipeline in saturated soils (Patnaik and Rajput 2023). Analytical works are better for obtaining a quick response of the pipe as they are cost-effective and less time-consuming (Chaudhuri and Choudhury 2022, Choudhury and Chaudhuri 2023). However, in most cases, such analytical solutions provide approximate outputs due to the various simplified assumptions made while formulating them. On the other hand, laboratory experiments or field tests are very challenging because of the involvement of TNT explosives. However, 3D numerical analysis can accurately capture the pipe response without much compromise in the modelling aspects. It should be noted that such numerical analysis is case-specific and time-consuming. In this context, the current study makes an effort to investigate the failure mechanism of a buried pipe subjected to a surface blast through a 3D FE-based numerical analysis in Abaqus Explicit. The Coupled Eulerian–Lagrangian (CEL) technique is adopted to simulate such a large deformation problem. Pipe responses are recorded for different steel grades available in the market. Furthermore, the impact of internal pressure on the pipe response is also investigated.

2 FINITE ELEMENT MODELLING

The three-dimensional numerical analysis has been conducted using FE-based programme Abaqus CAE (2018). The deformation induced by the blast load is relatively high compared to seismic load. Hence, to accurately capture the propagation of waves and the outcomes of the study, the blast load has been simulated in dynamic explicit step and the CEL technique is adopted for modelling. The soil is modelled as Lagrangian domain with Mohr-Coulomb constitutive model. On the other side the air along with TNT have been modelled using Eulerian elements. The pipe is considered as steel material and modelled as shell structure with elastic-plastic material behaviour; this is to take care of plastic deformations that are induced in the pipe during blasting.

The TNT properties are defined using JWL EOS as per equation 1 (Mokhtari and Alavi 2015).and the corresponding parameters for TNT are mentioned in Table 1.

$$P = A(1 - \frac{\omega}{R_1 V_1})e^{-R_1 V_1} + B(1 - \frac{\omega}{R_2 V_1})e^{-R_2 V_1} + \frac{\omega E_1}{V_1} \qquad (1)$$

Where, p represents pressure, E_1 denotes the internal energy per unit volume of TNT, and V_1 signifies the relative volume of TNT. The constants A, B, R_1, R_2, and ω have been established through dynamic experiments for a variety of common explosives. The parameters of TNT EOS are given in Table.1. The air properties follow the Us-Up EOS and the corresponding parameters for this equation of state is given in Table.2 (Zhang et al. 2018). To avoid wave reflection, absorbing boundaries are applied to the side and bottom surfaces of the soil domain. For the air domain, non-reflecting boundaries are assigned to the side surfaces, while the top surface is modelled as free. Figure 1 depicts the typical three-dimensional view of buried pipe subjected to surface blast considering air domain along with the absorbing boundaries.

Table.1. JWL EOS parameters for TNT explosive.

Density, ρ (kg/m^3)	1640
Wave speed of detonation, V_0(m/s)	6930
Wave pressure of detonation, P_{CJ}(GPa)	27
A(GPa)	374
B(GPa)	3.23
R_1	4.15
R_2	0.95
ω	0.3

Table.2. Parameters for air and equation of state

ρ (kg/m^3)	c_0	c_1	c_2	c_3	c_4	c_5	c_6	E_2(J/m^3)	V_2
1.29	0	0	0	0	0.4	0.4	0	2.5×10^5	1

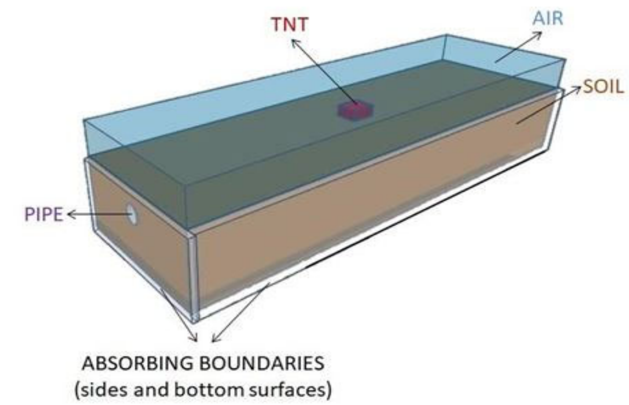


Figure 1. Schematic representation of soil-pipe-air-TNT system

3 VALIDATION

The present study is validated with the results obtained from Zhang et al. 2018. For validation purpose, the TNT is placed 0.3 m above the ground which is directly above the pipe crown. Figure 2 represents 2D view of the model which is considered for the validation study. X-70 grade of steel pipe is considered and the soil properties are listed in Table 3 (Zhang et al. 2018). The pipe deformation along the length of the pipe has been recorded and compared with the pattern obtained from Zhang et al. 2018 as shown in Figure 3. It can be seen that both the patterns are in good match which confirms the accuracy of the current numerical model. The peak deformation of 0.357 m is observed at the pipe mid-span (Figure 3). Figure 4 (a-b) shows cavity formation within the soil and pipe deformation after the surface explosion, respectively.

Table.3. Input soil properties (Zhang et al. 2018)

ρ (kg/m^3)	E(MPa)	c(kPa)	μ	φ
1840	20	15	0.3	15°

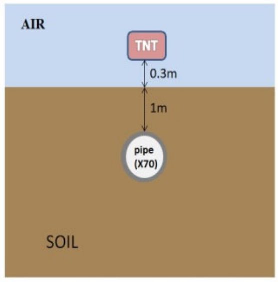


Figure 2. 2-D representation of buried pipe subjected to surface explosion (modified after Zhang et al. 2018)

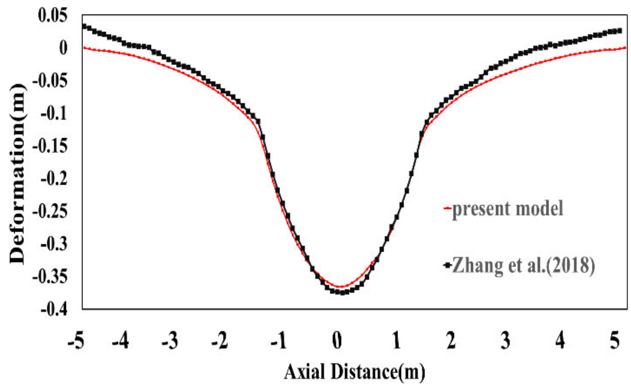
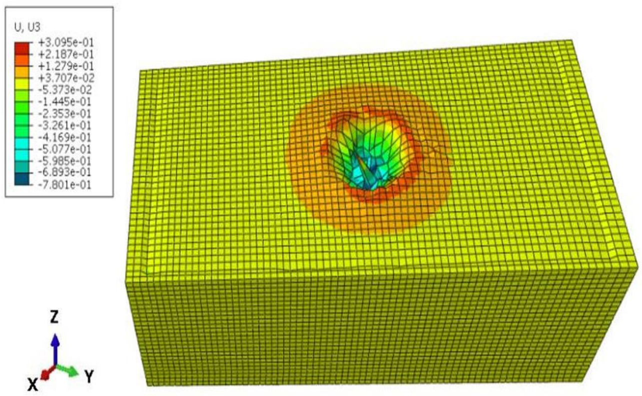
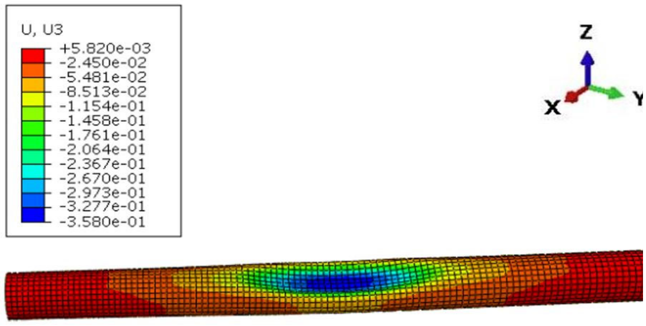


Figure 3. Comparison of pipe deformation profile along the length of pipe.



(a) Deformation of soil after explosion.



(b) Deformation of pipe after explosion.

Figure 4. Deformation of (a) soil and (b) pipe after the explosion.

4 RESULTS AND DISCUSSION

The numerical analysis is performed considering Toyoura sand (Chaudhuri et al. 2020). Various grades of steel pipe are considered in the current study. The pipe has a diameter-to-thickness ratio of 81.3, and the top of the pipeline is located 1 m below the ground surface. The TNT charge is placed 0.3m above the ground surface and aligned vertically with the buried pipeline (refer Figure 2). The soil and pipe properties used in the present analysis are provided in Table 4 and Table 5 respectively.

Table.4. Input soil properties of the present numerical model

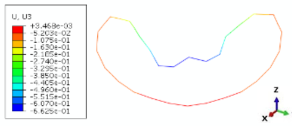
ρ (kg/m^3)	E(MPa)	c(kPa)	μ	φ
1630	40	10	0.3	31°

Table 5. Yield strength of different grades of steel pipe (Rigas, 2021)

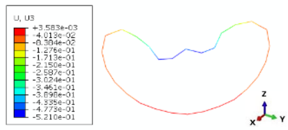
Grade of pipe	Yield strength (MPa)
A	207
X46	317
X60	413
X80	551

4.1 *Pipe Deformation*

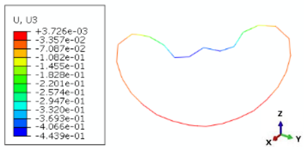
The deformations of the pipe with and without internal pressure were examined. The deformation of the pipe without internal pressure exhibits greater deformation under blast loading. Among different pipe grades, it has been observed that Grade A exhibits maximum deformation and Grade X80 experiences minimum deformation, irrespective of internal pressure (refer to Figures 5 to 7). Figures 5 and 6 depict dent formation at the pipe cross-section for various steel grades, considering cases without and with internal pressure, respectively. Whereas, the pipe deformation profiles along the length of the pipe considering cases with and without internal pressure for various grades of steel are shown in Figure7. The peak deformation of Grade A pipe with and without internal pressure is recorded as 0.215 m (Figure 6a) and 0.628 m (Figure 5a), respectively. Similarly, the peak deformation of Grade X80 pipe with and without internal pressure is recorded as 0.102 m (Figure 6d) and 0.373 m (Figure 5d), respectively. This demonstrates that higher steel grades improve blast resistance due to increased material yield strength. Furthermore, internal pressure also improves the resistance of pipe deformation against blast load. For better understanding the impact of pipe internal pressure on blast resistance for various steel grades of pipe the outcomes are presented in terms of percentage reduction in pipe deformation as shown in Table 6.



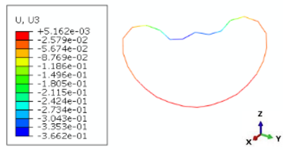
(a) A grade



(b) X46 grade

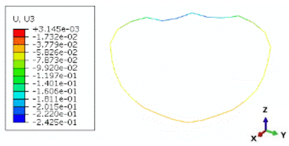


(c) X60 grade

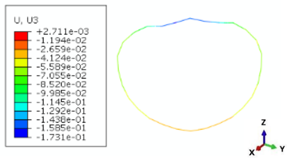


(d) X80 grade

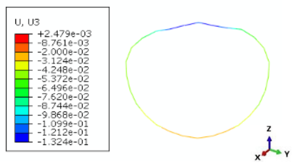
Figure 5. Deformations of pipe cross section at mid-span for different grade of steel (without internal pressure).



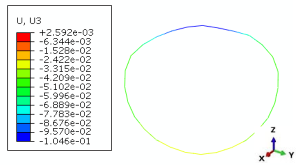
(a) A grade



(b) X46 grade



(c) X60 grade



(d) X80 grade

Figure 6. Deformations of pipe cross section at mid-span for different grade of steel (with internal pressure).

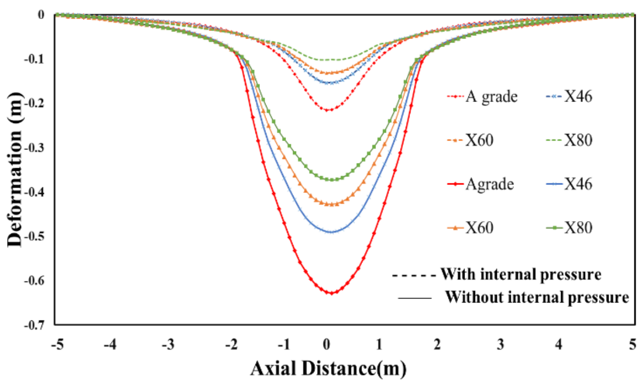


Figure 7. Pipe deformation profiles for different steel grades along the pipe length.

Table 6. Percentage reduction in pipe deformation

Pipe Grade	Peak Deformation (mm)		% Reduction
	Without internal pressure	With internal pressure	
A	628	215	65
X46	490	154	68
X60	427	124	71
X80	373	102	72

4.2 *Plastic Strain*

The development of plastic strain on the pipe over time is shown in Figure 8. At 0 s pipe is in intial stress free condition i.e., no sign of strain development. At 0.007 s strain start begins to develop and spreads along the pipe. At 0.012 s strain becomes more pronounced, and the maximum strain has developed at 0.03 s. After that no further strain development is observed. From Figure 8, it is evident that peak strain occurs at pipe crown, which is due to the surface blast directly above the pipe. Blast waves propagate through the soil and the first interaction occurs at the pipe crown. A maximum plastic strain of 12% is observed in the present case, indicating permanent failure of the pipe. These results highlight the importance of blast–soil–pipe interaction and the concentration and propagation of strain over time during an explosion.

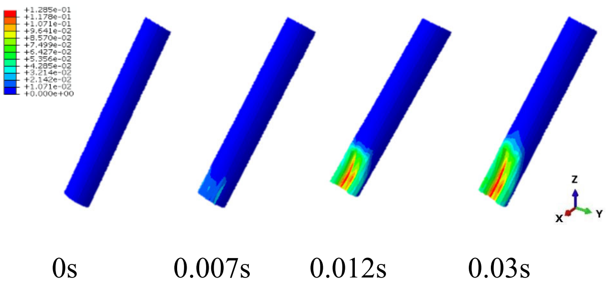


Figure 8. Plastic strain development on the pipe at various time steps.

5 CONCLUSIONS

In the present study three-dimensional finite element based numerical studies are conducted in Abaqus Explicit adopting the CEL technique to understand the failure mechanism of buried pipe subjected to surface blast. The following observations are drawn from the analysis:

- The comparative study confirms the accuracy of the present numerical approach.
- Peak pipe deformation recorded at the crown due to first interaction with blast waves.
- Higher steel grades significantly reduce blast-induced pipe deformation.
- Pipe internal pressure increase the resistance against deformation during explosion.
- The strain in the pipe initiates at the crown and then propagates along the pipe length and circumferentially towards the upper sides
- Maximum plastic strain (~12%) is recorded at the pipe crown which indicates permanent deformation and potential structural failure.

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