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Original Research Article

# A parametric study on the mechanical performance of buried X65 steel pipelines under subsurface detonation

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ABSTRACT

Existing studies on the response of buried steel pipelines to explosion generally concern finding safe distance of explosion where pipeline does not undergo plastic deformation while intentional explosions impose intense deformations on steel pipelines. In order to address this gap, the present investigation is carried out numerically dealing with the response of buried API 5L grade X65 pipelines to a nearby sever explosion due to sabotage or war. Furthermore, the effects of the pipeline diameter-to-thickness ratio and internal pressure on this response were investigated numerically. A combined Eulerian–Lagrangian (CEL) method was adopted to develop a full-coupled 3D finite element model. Employing simplified Johnson-Cook material model to simulate mechanical behavior of steel pipelines and considering air in the model increased the simulation accuracy. The results from present study were compared with those of recent investigations and good agreements were observed. The results show that, the amount of deformation and consequently the value of maximum equivalent strain of pipelines decrease with either increase in operating pressure or decrease in diameter-to-thickness ratio; however, the effect of pipeline internal pressure was far more than diameter-to-thickness ratio. The results obtained from the present study can be used for improvement in protective design of steel pipelines.

## 1. Introduction

Used for distribution of water, gas, oil, etc., buried pipelines are considered among the most important elements of lifelines. Buried pressurized gas pipelines are bound to be threatened by accidental explosions in process industries, explosives factories, open pit mines, quarries, public works or even intentional explosions near a pipeline (sabotage or terrorist attack) [1]. Terrorist attacks have unfortunately been increasing so that multiple explosions, in recent years, have taken place in the route of oil and gas transmission pipelines. Accordingly, blast loads and the design and the analysis of buried structures under destructive dynamic loads are particularly attended in recent years.

The first attempt to seismic design of buried pipelines likely be damaged by earthquakes or far explosions were carried out by Newmark [2] and Kuesel [3]. The expressions proposed by them

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are still used to seismic design of buried pipelines against earthquakes due to the fact that earthquakes induced by ground motions are seldom strong enough to affect steel pipelines [4]. Esparza et al. [5] performed a blasting research program conducted to develop simple procedures for predicting the maximum stresses and strains in steel pipelines induced by close-in subsurface explosions. These days, either the empirical relations proposed initially by Esparza et al. [5] and lately accepted by the ASCE-ALA guidelines [6] or analytical relations originally proposed for seismic waves with plane front and constant amplitude [7] are applied to design of pipelines against blasts. Application range of such relations, however, is circumscribed to circumstances similar to the conditions dominating the relevant experiments and the hypotheses taken into account to develop them [4]. Such a complex problem should generally be solved using numerical methods. The finite element method (FEM), the finite-difference method (FDM) or their combination are the most frequently applied methods [8–10].

Uncoupled and coupled methods, different types of numerical methods, have recently been used in order to investigate the response of buried structures to blast loads. Description about these methods can be found in Nagy et al. [11]. Many investigations deal with the numerical analysis of blast loaded buried structures [9,12–16]. In addition, there are found several investigations in the same field where mixed Eulerian–Lagrangian approach has been used [8,17–19].

Recently, the performance of pipes subjected to blast loads has been investigated. For instance, Malachowski et al. [20], applied the blast load to the pipes with and without protective cover using Arbitrary Lagrangian–Eulerian (ALE) method. However, literature on the response of buried pipelines to blast loads are scarce due to various constraints, of which most deal with estimation of safety distances of explosions in the vicinity of gas pipelines [1,4,5,21]. Thus, find literature on the mechanical behavior of buried steel pipelines under intense explosive loading causing to sever deformations (like those taking place in terrorist attacks and wars) is likely to be impossible. In addition, the effects of operating pressure and diameter-to-thickness ratio on the performance of foregoing pipelines are approximately unclear.

There are found several novelties in the present study. CEL method [22], adopted to develop a 3D finite element model, has not been employed to investigate the response of buried pipelines to explosive loading thus far. In addition, simplified Johnson-Cook model is employed for the first time to simulate the mechanical behavior of buried X65 steel pipelines using the results reported by El-Danaf et al. [23]. Furthermore, as mentioned earlier, the effect of internal pressure on the response of buried X65 steel pipeline under explosive loading is directly examined.

## 2. Finite element modeling and material models

In the present study, the mechanical performance of buried X65 continuous (welded) steel pipelines under subsurface detonation is studied numerically using nonlinear finite element code ABAQUS. Moreover, the effects of operating pressure and diameter-to-thickness ratio on the buried steel pipeline performance subjected to explosive loading are scrutinized. Development of the current finite element model is pithily presented in this section.

### 2.1. *Material models*

Various nonlinear material models and equations of state are utilized for modeling the behavior of materials involved in the problem, namely the API X65 steel, soil mass, the explosive charge and the air. These material models and equations of state are concisely explained in the following.

### 2.1.1. *Material model for X65 steel*

The material model used to simulate the material behavior of steel pipelines should consider strain rate due to the fact that explosive loading induces a high strain rate in the pipe's wall. The simplified Johnson-Cook material model, for this purpose, was applied to define the behavior of the pipeline material. The influence of strain hardening and strain rate on the flow stress ($\sigma_y$) of the material is considered in the model improving the accuracy of simulation. The simplified Johnson-Cook material model is defined as follows [23–26]:

$$\sigma_y = (A + B\bar{\varepsilon}^{P^n})(1 + C \ln \dot{\varepsilon}^*) \qquad (1)$$

where $A$, $B$, $C$, and $n$ are material constants; $\bar{\varepsilon}^P$ is the equivalent plastic strain; $\dot{\varepsilon}^* = \dot{\bar{\varepsilon}}^P / \dot{\varepsilon}_0$ is the dimensionless plastic strain rate; and $\dot{\varepsilon}_0$ is the reference strain rate. Table 1 presents material constants of the simplified Johnson-Cook material model for X65 steel.

### 2.1.2. *Modeling of soil mechanical behavior*

The site soil in the field tests performed by Ambrosini et al. [27], brown clay is assumed to be the surrounding soil of the steel pipelines in the current simulation. This type of soil is chosen in the current study to allow for comparison between the results of the present investigation and those of field tests performed by Ambrosini et al. [27]. In addition, such site conditions can be found where pipelines are laid across. Due to the fact that there is no time for drainage, soil mass can be considered as a single phase material under impact/explosive loading, and a total stress analysis can be performed [11,28,29]. Consequently, in order to simulate the behavior of soil in this research, a Drucker–Prager strength criterion with piecewise hardening and hydro tensile limit, equal to 100 kPa, was used based on the soil properties proposed by Luccioni et al. [30]. The full details of Drucker–Prager model comprising definition and derivation of all necessary parameters can be found in Drucker and Prager [31] and Chen and Mizuno [32].

**Table 1 – Material constants for the simplified Johnson-Cook model [23].**

| Material properties | API X65 steel |
|---|---|
| $E$ (GPa) | 210 |
| $A$ (MPa) | 500 |
| $B$ (MPa) | 857 |
| $n$ | 0.34257 |
| $C$ | 0.032604 |
| $\dot{\varepsilon}_0$ (s$^{-1}$) | 1 |