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Sand–pipeline–trench lateral interaction effects for shallow buried pipelines

George P. Kouretzis *, Daichao Sheng, Scott W. Sloan

ARC Centre of Excellence for Geotechnical Science and Engineering, Faculty of Engineering and Built Environment, The University of Newcastle, Callaghan, NSW 2308, Australia

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ABSTRACT

A large-deformation numerical methodology is applied to simulate the interaction effects for a pipeline installed in a trench backfilled with loosely deposited dry sand, focusing on shallow buried pipelines subjected to lateral displacements relative to the surrounding soil. Based on the backfill–pipeline deformation mode under shallow embedment conditions, described in previous experimental studies, analyses are performed while considering only the critical state shear strength parameters of the backfill. The numerical methodology is validated against experimental full-scale test measurements from the literature, for pipelines buried in uniform dry loose and medium sand. Parametric analyses are performed to generate approximate formulas and charts for calculating (i) the maximum force on the pipeline and (ii) the minimum trench dimensions to eliminate interaction with the surrounding natural ground. Application of the proposed approach in the prediction of independent full-scale test results for a pipeline embedded in a shallow trench demonstrates its effectiveness, and underlines the effect of trench dimensioning on the response of the pipeline.

1. Introduction

Various experimental and numerical studies have been published on the quantification of soil-buried pipeline interaction effects due to the static movement of a pipeline relative to its surrounding soil. Such movements may result from seismic fault rupture, slope instability, ground subsidence due to underground works, or liquefaction [1], and will result in additional forces being applied on the pipeline. We focus our attention on horizontal relative movement, since this is generally most critical case for the integrity of a pipeline, as it tends to result in higher forces compared to axial or upward movement. Common practice for the calculation of the peak horizontal force per unit length is based on the following expression:

$$F = \gamma' H N_h D \qquad (1)$$

where γ' is the effective unit weight of the soil, H is the depth to the centerline of the pipe, D is the external pipeline diameter, and N_h is a dimensionless parameter depending on the soil friction angle, φ, and the embedment ratio, H/D. Calculation of the dimensionless parameter N_h is commonly based either on the nomograph proposed by Hanshen [2,3], or on a similar nomograph proposed in the benchmark experimental study by Trautmann and O'Rourke [1]. The latter was compiled from the results of a series of tests on pipelines in dry sand, for embedment ratios ranging from $H/D = 1.5$ to $H/D = 11$. More recent studies by Olson [4], O'Rourke [5], Yimsiri et al. [6], di Prisco and Galli [7], Turner [8], and Paulin et al. [9] deal with additional factors such as deep embedment conditions, the effect of sand water content, and the response under cyclic displacements.

Common construction practice for placed *in situ* buried pipelines includes installing the pipeline in a relatively shallow trench, which is subsequently backfilled with sand. The backfill material is loosely deposited since, in case of relative movement, higher backfill densities will result in higher forces applied to the pipeline (Eq. (1)). A rather conservative design approach of assuming medium-density sand for the calculation of the pipeline forces could be justified as, during the lifetime of the pipeline, the backfill could be unintentionally compacted due to traffic loads, nearby machine vibrations, seismic wave propagation, etc. The dimensions of the trench must be "adequate", so that the pipeline response will depend solely on the properties of the controlled backfill material, and not on the perhaps much stiffer surrounding soil, as stated in ASCE–ALA "*Guidelines for the design of buried steel pipe*" [3]. To the author's knowledge, however, there is no robust method for quantitatively predicting appropriate trench dimensions to meet this requirement. The relevant experimental studies [10] examine limited trench configurations, and do not propose design guidelines.

Apart from the above, existing studies on the force–displacement response of pipelines [1,5,6] treat a very wide range of

* Corresponding author. Address: EA Building, University of Newcastle, Callaghan, NSW 2308, Australia. Tel.: +61 2 4921 6449.
E-mail address: Georgios.Kouretzis@newcastle.edu.au (G.P. Kouretzis).

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embedment depths and backfill properties under a common assumption framework. It should be noted, however, that the kinematic mechanism under large relative displacements changes from a global "flow-type" failure under shallow embedment conditions, to a local shear soil failure under deep embedment conditions [6].

This paper focuses on the common case of buried pipelines embedded in shallow trenches (up to $H/D = 5.5$), where a "flow-type" failure is expected, for loose-to-medium dry sand backfills (as per construction practice where differential movements are expected). By employing a numerical model to replicate the experiments performed by Trautmann and O'Rourke [1] in uniform sand, new insight is provided on the parameters affecting the forces developed on the pipeline. Accordingly, a series of parametric analyses are performed to complement existing experimental data for additional embedment ratio cases. Interpretation of the results leads to a refined formula for calculating the dimensionless parameter in Eq. (1), specifically for shallow embedment ratios and loose-to-medium sands. Design charts are also developed for determining the minimum trench dimensions that will prevent interaction of the pipeline with the surrounding natural soil. The theoretical findings are compared with the independent experimental results given by Karimian et al. [10] for a pipeline moving horizontally in a uniform backfill inside a trench.

2. Description and verification of the numerical model

As the quasi-static relative movement of a pipeline can be of the order of the pipeline diameter, the numerical simulation of pipeline–backfill interaction effects must properly account for the development of large soil deformations. The numerical code ABAQUS/Explicit [11] is employed in the analyses for this purpose. ABAQUS/Explicit utilizes explicit integration to treat highly nonlinear problems, together with the Arbitrary-Lagrangian–Eulerian (ALE) remeshing technique to compensate for the inevitable mesh distortion. The problem is simulated dynamically, but the displacement on the pipeline is applied at a very slow rate of about 0.05 mm/s to avoid numerical instabilities. The simple Mohr–Coulomb constitutive model is used to model the backfill behavior for reasons explained later.

In the first stage of this study, eight (8) basic analyses are performed to replicate the pull tests performed by Trautmann and O'Rourke [1] for a pipeline with an external diameter of $D = 0.102$ m, buried in uniform loose ($\gamma = 14.8$ kN/m^3) and medium ($\gamma = 16.4$ kN/m^3) Cornell filter sand. These unit weight values correspond to relative densities of $D_r = 0\%$ and 45%, respectively. In the tests simulated, the pipeline is embedded at depths of $H/D = 1.5$, $H/D = 3.5$, $H/D = 5.5$, and $H/D = 11$.

According to Tratumann and O'Rourke [1], the abovementioned density states correspond to sand peak friction angles of $\varphi_{peak} = 31°$ and 36° for the loose and medium sand, respectively. Thus the critical friction angle of the sand used in the tests is set to $\varphi_{crit} = 31°$. Yimsiri et al. [6] estimated the dilatancy angle corresponding to the peak friction angle, ψ, from the expression $\varphi_{peak} = \varphi_{crit} + 0.8\psi$ [12]; which suggests that ψ increases from $\psi = 0°$ to $\psi = 5°$, as the density of the sand increases from $D_r = 0$–45%.

The abovementioned shear strength parameters were derived from direct shear (DS) tests. To be used in a 2-D plane strain numerical model with the Mohr–Coulomb failure surface, the equivalent plane-strain friction angle, φ_{PS}, must be estimated since the direct shear test peak stress state does not correspond to a point on the Mohr circle that is tangent to the failure surface [5]. Following Davis [13], the plane-strain friction angle can be estimated from the results of direct shear tests, assuming coaxiality of the stress and strain increments, using the following expression:

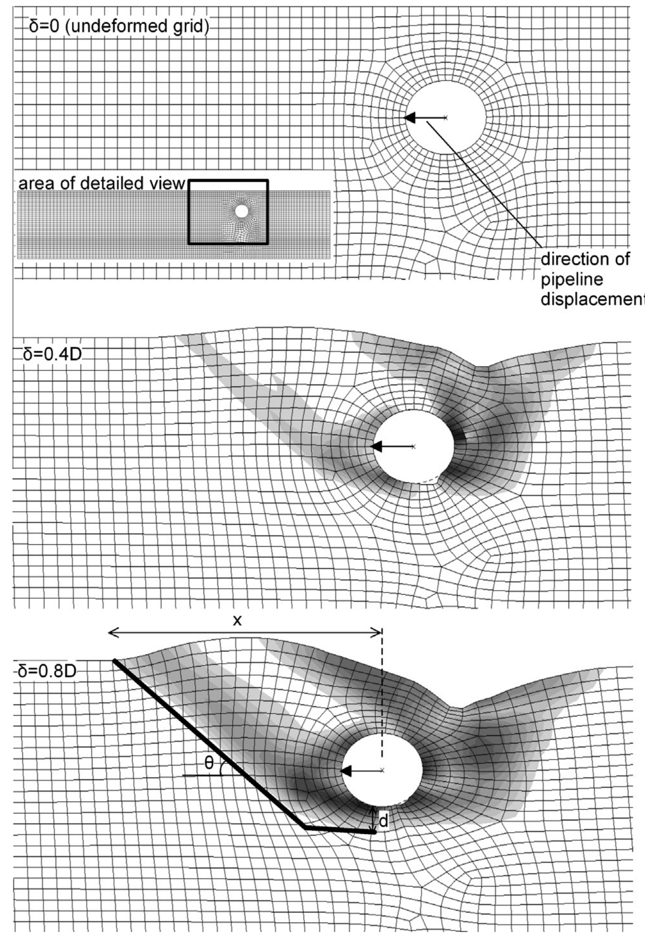

Fig. 1. Evolution of grid deformation and plastic strain contours with increasing pipeline–soil relative displacement. Embedment ratio $H/D = 1.5$ and loose sand (scale 1.0×, detail).

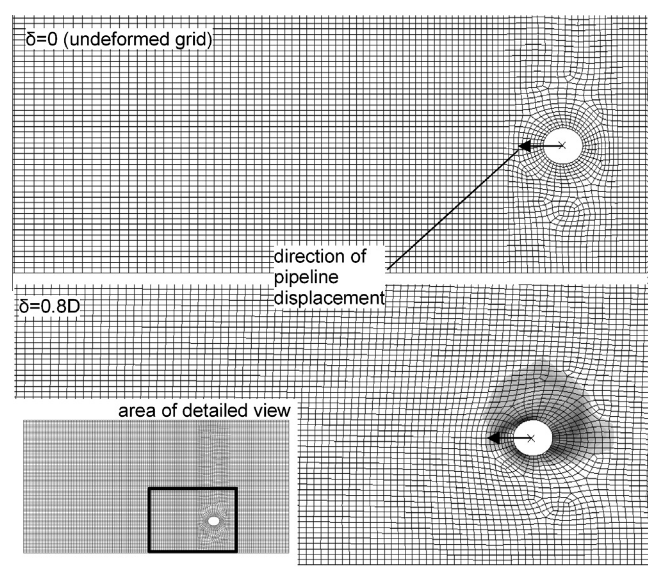

Fig. 2. Grid deformation and plastic strain contours at maximum pipeline–soil relative displacement. Embedment ratio $H/D = 11$ and loose sand (scale 1.0×, detail).

$$\tan \varphi_{DS} = \frac{\cos \psi \cdot \sin \varphi_{peak,PS}}{1 - \sin \psi \cdot \sin \varphi_{peak,PS}} \quad (2)$$