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Research Paper

Lateral soil–pipeline interaction in sand backfill: Effect of trench dimensions

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ABSTRACT

Current analytical methodologies for the evaluation of soil pressures on laterally displaced pipelines, as in the case of differential (e.g. fault-induced) permanent ground movements, allow the use of sand fill material properties under the condition that the size of the trench is adequate so that the failure surface develops fully within the sand fill (i.e. "free field" response). The accuracy of this assumption is investigated in this paper by means of numerical analyses, which employ a number of advanced features, such as pipe-backfill interface elements, large strain formulation and mesh rezoning. Following verification against well-documented experimental data, the analyses investigate: (a) the shape and size of the failure mechanism, as well as, (b) the potential trench effects on soil pressures and pipeline strains in the case of a strike-slip fault rupture. It is shown that for small embedment depths soil failure extends to the ground surface, in the form of a general shear failure mechanism, while for larger depths it becomes progressively localized and surrounds the pipeline. It is also shown that, for most cases of pipeline diameter and embedment depth, common trench dimensions cannot contain the "free field" failure surface dimensions. Finally, analyses for limited trench dimensions, reveal that the ultimate soil pressure increases exponentially with decreasing trench width, leading to high bending strains in pipelines subjected to differential lateral ground displacements.

1. Problem outline

The most common construction practice for fuel transmitting pipelines is burial into an artificial trench, excavated into the natural ground. To reduce the soil reaction and the associated pipeline strains, in the event of permanent ground displacements and stiff natural soil conditions, the trench is backfilled with loose to medium dense sand. It is realized that the efficiency of this technique lies on the assumption that the dimensions of the trench are large enough, so that the response of the pipeline depends solely on the properties of the backfill material and not of the much stiffer surrounding soil.

Nevertheless, current design guidelines (e.g. ALA-ASCE [1]; ASCE [2]; O'Rourke and Liu [3]; PRCI [4,5]) do not provide specific recommendations with regard to the appropriate trench dimensions for the case of sand backfill. For instance, the widely used ALA-ASCE "Guidelines for the design of buried steel pipes" [1] only include a qualitative reference to this aspect of the problem, stating that the calculation of lateral springs can be performed with the properties of the backfill soil only under the condition that the dimensions of the trench are "adequate". Furthermore, available methods for the estimation of ultimate soil reaction pressures (e.g. Trautmann and O'Rourke [6]) do not take directly or indirectly into account trench dimension effects, as they are based on experimental data and analyses where the distance between the pipeline and the wall of the backfill container was adequately large so that "infinite" free-field conditions were simulated.

Despite that a large number of studies has been dedicated on the response of pipelines under lateral loading [7–13], the attention on potential effects of trench dimensions is rather limited. An exception is the recent study of Kouretzis et al. [14] who published results from a series of numerical analyses which focus on the quantitative description of the shape and the size of the failure surface for the case of laterally displaced pipelines in loose and medium dense sandy backfills. The authors proposed design charts for the evaluation of the size of the failure surface, which may be indirectly used to specify the required trench geometry so that the effects of the surrounding natural soil are eliminated. It was thus revealed that the excavation of common trenches, without any provision for the

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anticipated permanent ground displacements, is in general insufficient for free development of the failure mechanism.

Nevertheless, the study of Kouretzis et al. [14] is limited to shallow embedded pipelines (i.e. $H/D \leqslant 5.5$, H is the depth of the pipeline axis and D is the pipe diameter), while no insight is provided to the potential effects of "inadequate" trench dimensions on the applied backfill pressures and the response of the pipeline. These practical design aspects are addressed herein. Namely, the numerical analyses are extended to large embedment ratios (i.e. $H/D = 16$), common for relatively small diameter pipelines and/or large embedment depths, as in the case of pipelines laid in urban areas or at crossings with traffic routes. Furthermore, to evaluate the practical importance of trench dimensions on the pipeline design, the ultimate soil pressures on the pipeline are computed for progressively decreasing trench width and they are consequently used to assess the associated pipeline strains in a typical case of differential ground displacement due to strike-slip fault rupture.

2. Numerical methodology

The numerical model that was used in the parametric analyses is shown in Fig. 1. A pipeline with external diameter D, is embedded at depth H (measured to the center of the pipeline) and is laterally displaced to a maximum distance y_{max}. The trench has vertical walls and its geometry is parametrically defined in terms of the final (at the end of any pipeline displacement) distances x and d of the pipeline wall from the vertical and horizontal trench boundaries respectively. Following a number of sensitivity analyses, the trench wall opposite to the direction of the pipeline movement, was set at an initial distance of 6.5D from the pipeline, so that it does not affect the computed response.

Similar to the analyses by Kouretzis et al. [14], it was assumed that the backfill consists of Cornell filter sand, i.e. the sand that was used in the experiments of Trautmann and O'Rourke [6] which are employed herein in order to calibrate the numerical methodology. Thus, the unit weight was set to $\gamma = 14.8$ and 16.4 kN/m^3 for the case of loose and medium sand respectively, while the Young modulus varied with vertical effective stress σ'_v as [8]:

$$E = 2 \cdot 10^{-13.97} \cdot (\gamma \cdot \sigma_v'^{0.0378})^{13.7} \tag{1}$$

The stress–strain response of the backfill sand was simulated with the widely used Mohr–Coulomb elasto-plastic constitutive model, while the shearing strength was computed in terms of the critical state (residual) friction angle of Cornell sand $\varphi_{cr} = 31°$ (Trautmann and O'Rourke [6]), in order to account for the large displacements associated with backfill failure. Note that this friction angle value was derived from direct shear (DS) tests and consequently it had to be adjusted to the plane strain conditions of the numerical analyses, according to the following expression [15]:

$$\sin \varphi_{cr,PS} = \tan \varphi_{cr,DS} \tag{2}$$

where $\varphi_{cr,DS}$ and $\varphi_{cr,PS}$ denote the residual friction angle under Direct Shear and Plane Strain conditions respectively. Thus, the friction angle of the soil was finally set equal to $\varphi_{cr,PS} = 37°$.

The numerical analyses were performed with the finite difference code FLAC v7.0 [16]. The mesh was discretized to square zones of size 0.1D, while hinges were considered at the vertical and horizontal trench boundaries. Note that, numerical predictions with rollers (instead of hinges) at the base boundary of the model were not equally satisfactory. As mentioned earlier, the problem involves development of large pipe and soil displacements, hence FLAC's large strain mode was activated, updating constantly the coordinates of each node. Following the observation that large straining resulted in excess element distortion, it was also found necessary to apply rezoning at large relative pipe-soil displacements, i.e. mesh reconstruction and replacement of excessively distorted elements, at the ever current deformed state of the pipeline and the ground surface.

The rezoning process is invoked every time a bad geometry error is issued and involves two main steps: (a) mesh re-generation based on the current displacement state and (b) re-mapping of the various model variables (e.g. stresses, displacements, velocities, material properties, state variables, etc.) from the old to the new mesh. In the present study, the first of the above steps is performed manually, through a user-defined function programmed in FLAC's inbuilt FISH language. In short, this function is executed in the following sequence:

<u>Step 1:</u> The x,y coordinates of the pipe and the ground surface are stored in two separate tables.

<u>Step 2:</u> The interface elements between the pipe and the soil are removed, as the rezoning process in FLAC v7.0 is not compatible with interface elements.

<u>Step 3:</u> The new mesh is generated based on the updated coordinates of the pipe and the ground surface, while the external size of the grid and the number of zones remain unchanged.

<u>Step 4:</u> Finally, interface elements between the pipe and the soil are re-installed.

Note that the above procedure yields a completely undistorted mesh, equivalent, in terms of regularity, to the one at the beginning of the analysis. The alternative would be the use of FLAC's inbuilt mesh smoothening techniques. In that case, however, the resulting

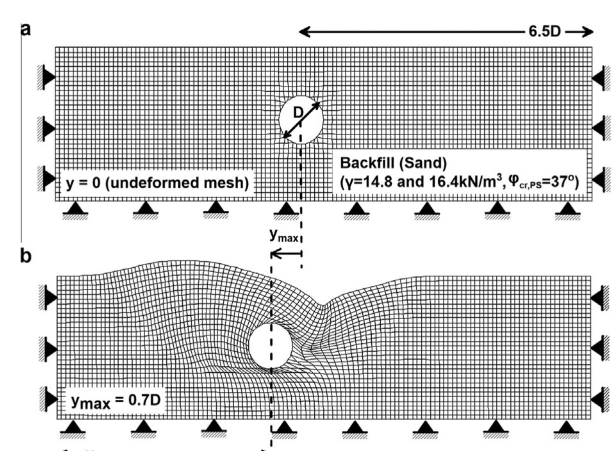

Fig. 1. Layout of the numerical model (a) before and (b) after application of pipeline lateral displacement $y = y_{max}$.

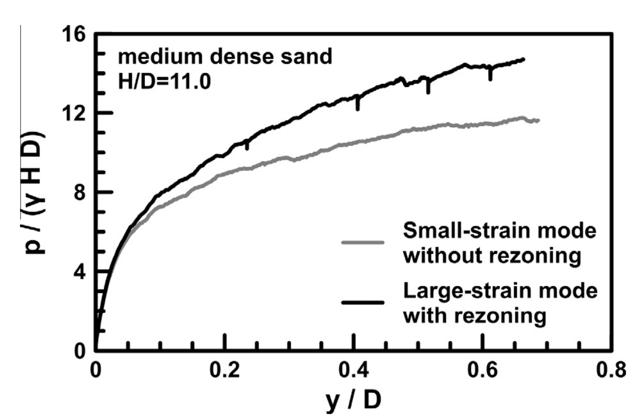

Fig. 2. Comparison of load–deformation curves for two analyses with and without rezoning techniques (medium dense sand, $H/D = 11$).