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Research Paper

Trench effects on lateral p-y relations for pipelines embedded in stiff soils and rocks

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ABSTRACT

Existing relationships for lateral backfill pressures on pipelines assume that the trench is adequately wide to contain the failure surface. This condition is commonly violated in design and construction practice, putting at risk the pipeline safety. In this context, size and shape effects for trenches excavated in stiff soils and rocks, are numerically investigated, through experimentally-calibrated parametric analyses. It is shown that, for narrow trenches, ultimate pressures and yield displacements may increase up to an order of magnitude compared to "infinite-trench" values, while excavation of inclined walls reduces the above detrimental effects. Simplified relations are developed to aid pipeline design.

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1. Introduction

It is widely acknowledged that trenches backfilled with loose to medium dense sand can drastically reduce design demands for buried pipelines subjected to permanent ground movement (e.g. fault rupture) in the core of stiff soil and rocky terrain. The reason is that the magnitude of soil pressures imposed to the pipeline is controlled by the properties of the backfill material and not by those of the much stiffer (in most cases) natural surrounding ground. Evidently, for the previous statement to be valid, the trench should be adequately large in order to fully contain the mobilized failure surface.

It is noteworthy that the potential effects of trench size are acknowledged in current design guidelines [1–5], but only in a qualitative way. For instance, according to ALA-ASCE [1], the backfill soil properties for the evaluation of soil pressures can only be used if the size of the trench is "*adequate*". Even though, and also despite the large number of studies dedicated to the response of buried pipelines [e.g. 6–14], research related to trench size effects remained limited until recently.

To fill this gap, Kouretzis et al. [15] and Chaloulos et al. [16] investigated systematically the extent of sand backfill failure for the case of laterally displaced pipelines (e.g. at strike-slip fault crossings), with the aid of experimentally calibrated linear elastic-perfectly plastic numerical analyses. It was thus shown that, common trench sections rarely ensure the unobstructed development of the failure surface inside the backfill sand. For instance, in the common case of a D = 30" (0.76 m) diameter pipeline embedded at H = 1.50 m average depth (i.e. $H/D \approx 2.0$), the required net half-width of the trench for free development of the failure surface within the sand backfill exceeds 3 m, not including the fault-induced displacement, as compared to the 0.2–0.5 m allowed in common practice. Under these conditions, the pipeline response is not controlled by the backfill, but by the much stiffer surrounding soil thus increasing both the pressures applied to the pipeline and the associated pipeline strains.

In light of the above, the present paper focuses upon the analytical computation of increased ultimate soil pressures and lateral yield displacements in the case of "narrow" and "shallow" trenches, i.e. when trench dimensions (width, depth and side wall inclination) are not adequate for un-hindered failure within the sand backfill. For this purpose, the numerical methodology that has been developed and verified in Chaloulos et al. [16] is now applied parametrically, for various backfill soil properties, pipeline diameters and embedment depths, in order to evaluate and

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incorporate trench boundary effects in the design of pipelines with the commonly applied "*beam on Winkler soil springs*" method. More specifically, the final output of the investigation is a set of equations that modify the Winkler soil spring characteristics according to the trench size and shape. To increase the application range of the proposed equations, trench size and shape effects are expressed in the form of correction factors which can be readily combined with existing relations for pipelines embedded in infinitely extending sand layers. To aid independent reading of the paper, Section 2 repeats briefly the numerical methodology that was used to simulate the problem, as well as the failure mechanism for laterally displaced pipes in uniform sand, obtained by Chaloulos et al. [16].

2. Outline of numerical analyses and results

2.1. Numerical methodology

Fig. 1 shows the finite difference mesh and the backfill sand that was used for the bulk of the parametric analyses: a cylindrical pipe section with diameter D is embedded at depth H, measured from the center of the pipeline, in an artificial trench backfilled with sand. The pipeline is displaced laterally to a maximum displacement $y = y_{max}$. The effect of trench geometry on the development of soil pressures was investigated by varying distances x and d, also shown in Fig. 1. More specifically, the horizontal distance x defines the semi-width of the trench in the direction of pipeline movement (left side in Fig. 1), and it is measured from the center of the pipeline (at its displaced position) to the lateral boundary. For the reference "infinite-trench" conditions, x was equal to 16D and was then step-by-step reduced to 0.75D for the most narrow trench conditions. Note that in the direction opposite to the pipeline movement (right side in Fig. 1), the semi-width of the trench was kept constant and equal to 6.5D throughout the parametric investigation, based on the results of sensitivity analyses which showed that the exact location of the wall at this side of the trench, even for the small lateral distances used in practice, does not affect the development of soil pressures. The vertical distance d is measured from the bottom of the pipeline to the base of the trench. Finally, in the majority of the parametric analyses, the trench has vertical side walls, while a number of parametric analyses is also performed for outwards inclined trench walls. In this trapezoidal trench geometry, the aforementioned horizontal dimensions refer to the horizontal plane passing through the pipeline axis.

All parametric analyses were performed with the finite difference code FLAC v7.0 [17]. The large strain formulation mode was activated, in combination with a mesh rezoning technique [16], in order to account for the large lateral displacement of the pipe section. Following sensitivity analyses, the mesh was discretized into square elements of size 0.1D. Special attention was placed regarding the selection of proper boundary constraints. Namely, for the simulation of the experiments, the selection was based on comparative analyses either with rollers or with hinges, which revealed that the latter provided a more consistent agreement between experimental results and numerical predictions. For the parametric study, the selection of proper boundary constraints was guided by the nature of the problem. Namely, as the analysis assumes that the natural soil is much stiffer than the backfill sand, it is reasonable to expect that the sides of the excavated trench will be rough and failure will take place within the backfill and not along the backfill-trench interface. Consequently, the side boundaries were considered as "rough" and simulated with hinges. It is also of interest to note that, parallel analyses performed for "smooth" side boundaries, i.e. with vertical rollers instead of hinges, have shown that application of hinges is more damaging for the pipeline (leads to larger spring reactions), suggesting that the selection of hinged boundary constraints is conservative.

The backfill material was given the characteristics of Cornell filter sand, i.e. the material of the model experiments that were used in order to calibrate the numerical methodology, with unit weight $\gamma = 14.8$ and $16.4\ kN/m^3$ for loose and medium density respectively [18]. Note that the use of dense sand backfill is not recommended by design codes, as it would unnecessarily increase soil pressures on the pipeline, and consequently it was not considered in this study. The analyses for both sand backfill densities were performed using the elastic-perfectly plastic Mohr-Coulomb model. The friction angle was computed from the critical state value $\varphi_{cr} = 31°$ that was obtained from direct shear tests on Cornell Sand [18] and was

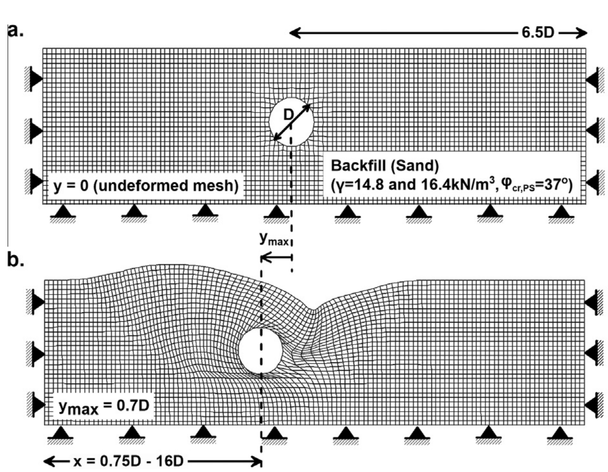

Fig. 1. Typical layout of the numerical model for "narrow" trench analysis: (a) before and (b) after application of lateral pipeline displacement $y = y_{max}$.

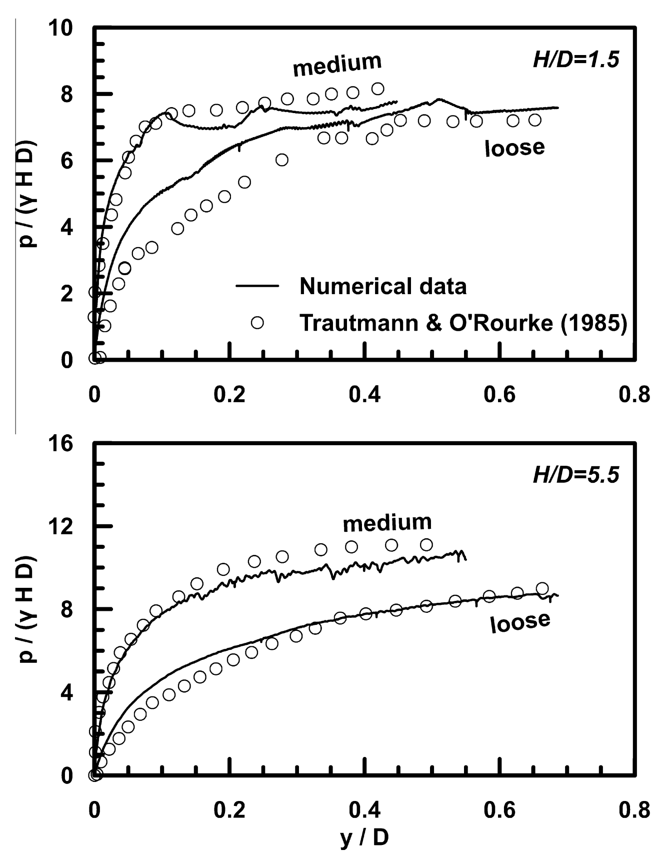

Fig. 2. Comparison of numerical results and experimental data for loose and medium dense sand and various embedment ratios.

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