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Verification of the Pipe Depth Dependent Model using a finite element analysis

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ABSTRACT

Characterizing a dilation angle in terms of a single effective vertical stress at a pipe centerline is a simplification that does not account for a variable dilation angle and peak plane strain friction angle with depth. The current research is to evaluate the effects of more comprehensive characterization of soil strength. To accomplish the goal, finite element simulations for soil-pipe interaction were performed for layered soil conditions in which the dilation angle and peak plane strain friction angle were varied with depth and normal stress was estimated with greater accuracy. Finite element simulations using dilation angle and peak plane strain friction angle linked to a single effective vertical stress were performed for comparison. The results of soil-pipe interaction were converted into dimensionless force vs. dimensionless displacement curve for both simulations were compared. Because the comparisons of layered soil conditions and the single soil layer model show little difference in the results, the single soil layer model can be replaced with the layered soil conditions model, which is a simpler and straight forward characterization of dilation angle and peak plane strain friction angle. The predicted force of the effective vertical stress model is slightly higher than that of the normal stress model, and thus tends to produce conservative estimates for the analysis of pipeline deformation in the ground. Because the comparisons show very small difference in the results, the more simple and straightforward characterization of friction angle relative to the effective vertical stress at the pipe centerline can be used in the numerical simulations to predict the soil-pipe behavior.

1. Introduction

Research and engineering practice for the earthquake response of underground pipelines has focused on permanent ground deformation (PGD) and transient ground deformation (TGD) effects, with the recognition that PGD often causes the most serious local damage in buried pipeline networks (Hamada and O'Rourke, 1992; O'Rourke, 1998; 2010; Jung and Zhang, 2011). Many previous studies have addressed PGD and developed force vs. displacement models for soil-pipeline interaction (ASCE, 1984; Honegger and Nyman, 2004; American Lifelines Alliance, 2005). More recently, Jung and Zhang (2011) applied continuum models to account for the stresses and deformation in the soil.

Many previous research used finite element simulations (e.g., O'Rourke and Liu, 1999; Yoshishaki et al, 2001; Eidinger et al, 2002; Tutuncu and O'Rourke, 2006; O'Rourke et al., 2008; Jung and Zhang, 2011) to investigate soil-pipe interaction. The previous finite element simulations characterized a peak dilation angle (ψ_p) and a peak plane strain friction angle $\left(\phi'_{ps-p}\right)$ in terms of a single effective vertical stress at a pipe centerline (σ'_{vc}) due to its simplicity (See Fig. 1a). This is a simplification that does not account for a variable ψ_p and $\left(\phi'_{ps-p}\right)$ with pipe depth, as shown in Fig. 1b, and soil strength characteristics are not linked with appropriate normal stress (σ'_N), as illustrated in Fig. 1c.

The research described in this paper was undertaken to evaluate the effects of more comprehensive characterization of soil strength. The force vs. displacement relationships between soil and pipe under plane strain conditions were investigated with elasto-plastic constitutive laws and a Mohr–Coulomb (MC) yield criterion. To evaluate the effects of more comprehensive characterization of soil strength, finite element simulations were performed for layered soil conditions in which ψ_p and ϕ'_{ps-p} were varied with depth and the accurately estimated σ'_N. The former simulation, illustrated in Fig. 1b, is referred to as the 'Depth Dependent Model', whereas the latter, illustrated in Fig. 1c, is referred to as the 'σ'_N Reference Stress Model'. The finite element simulations using ψ_p and ϕ'_{ps-p} linked to a single σ'_{vc}, illustrated in Fig. 1a, is referred to as the 'Pipe Depth Dependent Model'. In the Pipe Depth Dependent Model, σ'_{vc}

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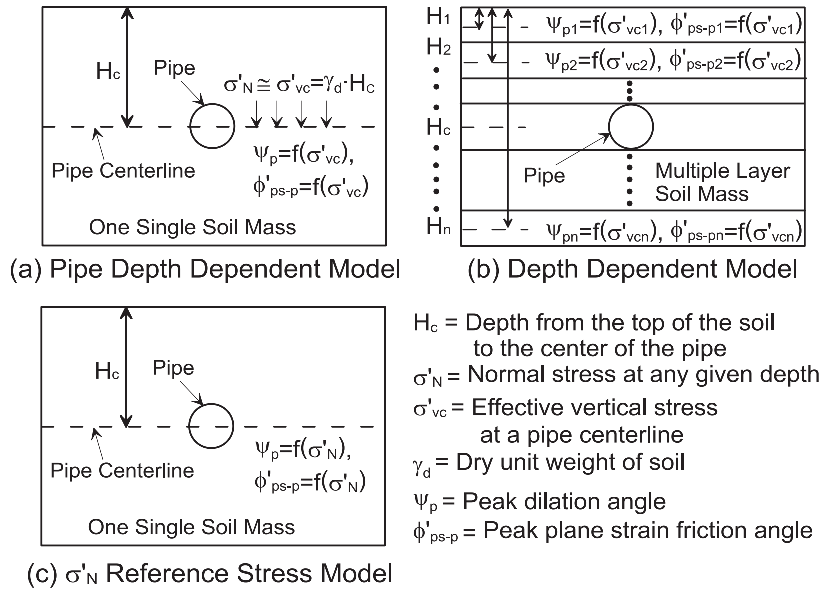

Fig. 1. Description of Pipe Depth Dependent Model, Depth Dependent Model, and σ'_N Reference Stress Model.

is used as a proxy for normal stress. Force vs. displacement curves for each model are compared to evaluate the difference in results associated with the modeling procedures.

The paper begins with summarizing the methodology for obtaining the MC soil strength parameters used in the finite element simulations followed by the comparison of force vs. displacement curves from each model. The paper concludes with recommendation for the numerical simulation practices.

2. Mohr–coulomb soil strength parameters

Modeling soil-pipe interaction under large ground deformation requires that the soil strength properties of the sand be determined by appropriate laboratory tests (Jung and Zhang, 2011). In this research, input parameters for RMS™ graded sand were obtained from direct shear (DS) test performed by Olson (2009). Olson (2009) provided the relationship between peak dilation angle (ψ_p) and dry unit weight (γ_d) at reference normal stress ($\sigma'_{N\text{Ref.}}$) of 2.1 kPa for RMS graded sand as

$$\psi_{p@\sigma'_{N\,\text{Ref.}}} = 6.99 \times \gamma_d - 109.48 \tag{1}$$

Olson (2009) also provided data for ψ_p vs. various normal stresses (σ'_N) and Jung (2011) digitized the data and provided the normalized $\psi_p/\psi_{p@\sigma'N\text{Ref.}}$ vs. σ'_N to estimate ψ_p for variable σ'_N, where σ'_N is taken as σ'_{vc}. The nonlinear regression equation for $\psi_p/\psi_{p@\sigma'N\text{Ref.}}$ is

$$\frac{\psi_p}{\psi_{p/\sigma'_{N\,\text{Ref.}}}} = \exp\left(-0.15 \ln \sigma'_N + 0.08\right) \tag{2}$$

To simulate soil-pipe interaction in plane strain condition, the DS test results must be converted to plane strain strength parameters. Lings and Dietz (2004) show the relationship between peak direct shear friction angle $\left(\phi'_{ps-p}\right)$, critical friction angle (ϕ'_{crit}), and ψ_p as

$$\tan \phi'_{ds-p} = \frac{\sin \phi'_{\text{crit}} + \sin \psi_p}{\cos \psi_p} \tag{3}$$

Olson (2009) reported ϕ'_{crit} for RMS graded sand as 40.8°. The calculated ϕ'_{ds-p} from Eq. (3) is then converted to the plane strain peak friction angle $\left(\phi'_{ps-p}\right)$, using the relationship first derived by Davis (1968) as

$$\sin \phi'_{ps-p} = \frac{\tan \phi'_{ds-p}}{\cos \psi_p + \sin \psi_p \times \tan \phi'_{ds-p}} \tag{4}$$

In order to achieve more reliable numerical prediction, Young's modulus should be varied according to depth (Gibson, 1967). However, the MC plasticity model used in this paper uses a constant Young's modulus to approximate the nonlinear stress–strain behavior of soil before yield, because the scope of this research is investigate soil strength characteristics. To select the Young's modulus, the procedure described by Jung and Zhang (2011) was applied to the model. Jung and Zhang (2011) proposed a relationship between Young's modulus for horizontal pipe movement (E_H), γ_d, and σ'_{vc} as

$$\frac{E_H}{P_a} = K\left[\frac{\gamma_d}{\gamma_w}\left(\frac{\sigma'_{vc}}{P_a}\right)^{\frac{\beta}{\alpha}}\right]^{\alpha} \tag{5}$$

where K, α, and β are constants, P_a is an atmospheric pressure, γ_w is unit weight of water, and $\left[(\gamma_d/\gamma_w)(\sigma'_{vc}/P_a)^{\beta/\alpha}\right]^{\alpha}$ is a scaled parameter combining γ_d and σ'_{vc}.

Using the data from the Trautmann and O'Rourke (1983) and Olson (2009), Jung and Zhang (2011) suggested the following parameters for K, α, and β as shown in Eq. (6). Young's modulus in this research was obtained from Eq. (6) as follows.

$$\frac{E_H}{P_a} = 10^{-0.264}\left[\frac{\gamma_d}{\gamma_w}\left(\frac{\sigma'_{vc}}{P_a}\right)^{0.075}\right]^{10.42} \tag{6}$$

The finite element simulations described in this research were performed with dry sand characterized as medium, dense, and very dense sand. The soil strength properties associated with each density description are summarized in Table 1. In the table, H_c is the depth from the top of the soil to the center of the pipe, and D is the external diameter of the pipe. The experiments performed by Trautmann and O'Rourke (1983), Turner (2004), and Olson (2009) showed that the friction and dilation angle were approximately ±1° and dry unit weight was ±0.15 kN/m^3 of the values in Table 1.The typical experimental results of lateral pipe movement in dry sand show that strain softening behavior occurs at locations of especially large displacement. To represent strain softening behavior of soil, the model proposed by Anastasopoulos et al. (2007), and