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## 3D numerical modelling of the impact of tunnelling in soft soil on buried pipelines

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**ABSTRACT:** The underground space in urban areas is congested with structures, including pipelines, which are affected by underground construction such as tunneling. This paper investigates the problem of tunneling effects on buried pipelines, using finite difference code FLAC3D. A 3D numerical pipe-soil model is developed and tunneling effect is simulated with settlement troughs which are applied at the bottom of model. 2D and 3D settlement troughs are adopted respectively to study the pipeline behavior at the final state of tunneling and in the process of tunneling. A series of numerical parametric studies is performed to analyze various combinations of settlement profiles, joint stiffness, pipe material properties and soil properties. The results are summarized and presented in a normalized plot of relative joint-pipe stiffness, relative pipe-soil stiffness, joints spacing and relative position between joints and tunnel, which are validated with an analytical approach given by Klar et al. Effect of tunneling orientation relative to pipeline is also explored. The results indicate it might be un-conservative if the analysis only considers the final state of tunneling as the critical state but neglects the variation of stress in the process of tunneling.

### 1 INTRODUCTION

Tunnel excavation may cause damage to pipelines due to an increase of bending moments that depends on the distribution of soil settlement, the stiffness of pipe section, the characteristic of joints, the properties of soil and relative position of tunnel and pipeline. Several approaches have been proposed in the past, considering first continuous and jointed pipeline resting on a Winkler type elastic ground model to estimate the interaction between pipeline and soil (Klar et al. 2008). Wang et al. (2011) carried out finite element (FE) analysis to investigate the effects of tunneling-induced ground movement on pipelines. They found it might be un-conservative if design analysis only considers the case that the pipeline is perpendicular to the tunnel centerline. In reality, stresses induced in certain locations can exceed the plasticity criterion, joints have a complex geometry and a behavior that cannot be represented by a simple rotational spring and finally the interface between pipe and soil can experience both friction and loss of contact. This paper presents a 3D numerical soil-pipe model to estimate the behavior of pipeline due to tunneling that accounts for all of these complexities. Normalized solutions of vertical displacement and bending moment of pipelines are presented and validated against analytical solutions. Effect of tunneling orientation relative to pipeline is also explored.

### 2 THE 3D NUMERICAL MODEL

A 3D numerical model developed using finite difference code FLAC3D is proposed to represent the combination of pipeline and soil. The effects of tunneling are simplified, with applying a series of settlement troughs at the bottom of model. The pipeline is composed of 5 individual 3.7 m long central pipe sections (Figure 1).

The case of a pipeline transverse to the tunnel centreline is considered and the tunnel is beneath the center pipe section, which has been commonly believed to be the worst case for bending moment and rotation. The impact of tunneling mainly concentrates on certain pipe sections above the tunnel. Hence, the outlying pipe sections are considered as long continuous pipe sections (8.7 m) to reduce the quantity of

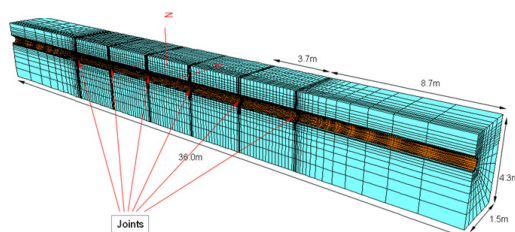


Figure 1. Mesh for half pipe-soil numerical model.

Table 1. Mechanical parameters of soil.

Parameter	Unit	Value
E	MPa	2.84
$\nu$	—	0.3
c	kPa	13
$\phi$	°	18
$\gamma$	kN/m <sup>3</sup>	17.5
$K_0$	—	0.5

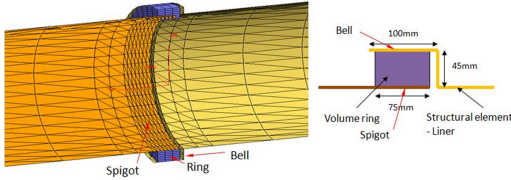


Figure 2. Finite difference mesh and sketch for joint.

elements and the time of calculation. Pipe sections are modeled as thin elastic shells. Soil is represented with 8-node volume element and Mohr-Coulomb model is applied as the soil constitutive model. Between pipe and soil, an interface with Coulomb frictional properties is introduced, which can provide a shear-directed frictional interaction and carry both compressive and tensile force in the normal direction. The soil is homogeneous and the backfill has the same mechanical property as the native soil. The mechanical parameters of soil are from a geological report of Shanghai, China (Table 1). The pipe-soil model is composed of 61704 volume elements and 10992 structural elements.

Pipe sections are connected to each other through joints. Both ends of each pipe section (spigot and bell) and joint are finely modeled (Figure 2). Both spigot and bell adopt the same structural elements and the same properties as pipe section. Joint is modeled as an elastic volume ring placed between spigot and bell. This approach has shown its ability to represent the behavior of real joints between concrete pipe sections measured in full scale laboratory experiments (Bucu et al. 2008).

A series of settlement troughs are applied at the bottom of 3D model as an external load, instead of simulating the tunnel excavation. The Gaussian curve describing the transverse settlement trough is characterized by  $S_{max}$  maximum vertical settlement and  $i$  the horizontal distance between the tunnel centerline and the inflexion point of settlement trough (Figure 3).

The transverse settlement trough is considered as the final state after tunneling. Nevertheless, the effect of tunneling is three-dimensional and the gradual changes of stress and strain on pipeline during tunnel passing by are analyzed with a series of 3D settlement troughs simulating the process of tunneling using a static approximate method. The LPS curve (Serratrice 2007) is adopted, which is a modified 3D

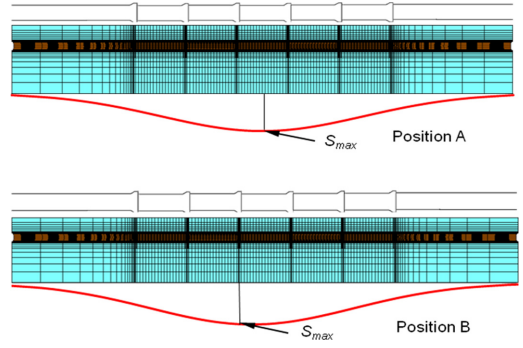


Figure 3. Relative pipe-tunnel position (Gaussian settlement trough).

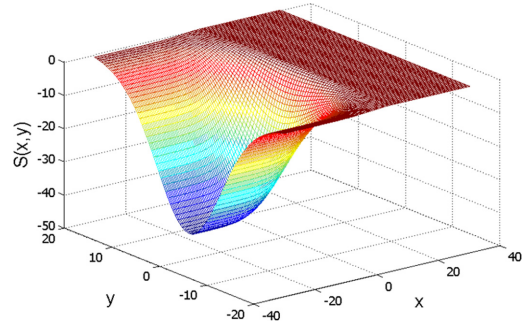


Figure 4. Profile of 3D settlement trough.

curve based on the curves of Loganathan and Poulos (1998) as illustrated in Figure 4:

$$S(x, y) = S_{max} f(x) g(y) \quad (1)$$

where  $S_{max}$  is the maximum settlement due to tunnel excavation,  $S(x, y)$  is settlement of a point with coordinates  $x$  and  $y$ ,  $x$  being the direction of the tunnel axis,  $f(x)$  and  $g(y)$  are elementary functions proposed by Serratrice (2007):

$$\text{if } x \leq x_0 \quad f(x) = 1 - \frac{e^{-AX^2}}{1 + X^2} \quad (2)$$

$$\text{if } x \geq x_0 \quad f(x) = 0 \quad (3)$$

$$g(y) = \frac{e^{-BY^2}}{1 + Y^2} \quad (4)$$

With:

$$X^2 = \frac{(x-x_0)^2}{H^2} \quad A = a \frac{H^2}{R + H^2} \quad (5)$$

$$Y^2 = \frac{y^2}{H^2} \quad B = b \frac{H^2}{R + H^2} \quad (6)$$

Where  $H$  is depth of pipe center,  $R$  is the radius of pipe,  $a, b$  are parameters,  $x_0$  is horizontal distance from  $S_{max}$  to excavation face.

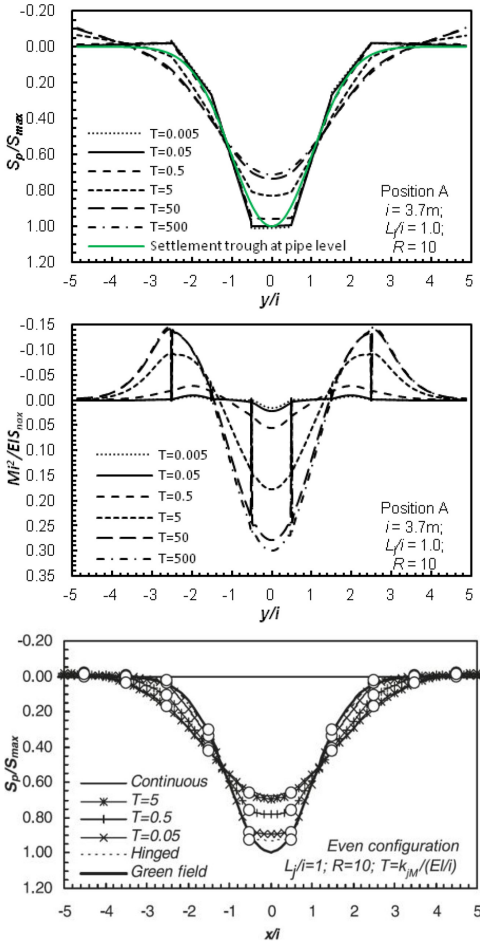


Figure 5. Normalized solutions for  $R = 10$  and  $L_j/i = 1.0$ , Position A: a) settlement trough b) bending moment and c) settlement trough with Klar et al. (2008) approach.

With the transversal and longitudinal settlement troughs measured in situ in Shanghai, the parameter  $S_{max}$ ,  $a$ ,  $b$ ,  $x_0$  can be calculated.  $S_{max} = 42.5$  mm,  $a = 4.2552$ ,  $b = 4.485$ ,  $x_0 = 5.1539$  m (Jan et al. 2008).

The process of tunneling is simplified to be the resultant of several static sub-steps. In each sub-step, once the position of TBM is determined, only the additional settlements are applied at the bottom of the model. Two possible cases are considered (Figure 3) in which the tunnel centerline is located respectively in-between the joints (Position A) and beneath one joint of the central pipe section (Position B).

### 3 PARAMETRIC STUDY

In this section, only the final settlement trough and its effect on pipe settlement and bending moments is considered.

The parametric study encompasses combinations of ground settlement profiles, pipe and soil properties.

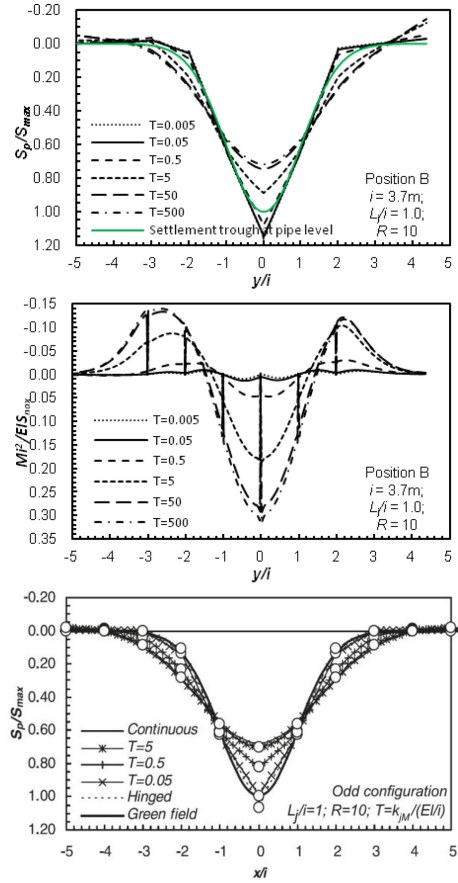


Figure 6. Normalized solutions for  $R = 10$  and  $L_j/i = 1.0$ , Position B: a) settlement trough b) bending moment and c) settlement trough with Klar et al. (2008) approach.

Several parameters are used in the normalization of the settlements and bending moments:

- (1) the joint stiffness ratio  $T$ :

$$T = \frac{k_{JM}}{EI} L_j \quad (7)$$

where  $k_{JM}$  is the joint stiffness for rotation ( $k_{JM} = \Delta M / \Delta \theta$ ),  $EI$  is the longitudinal bending stiffness of the pipe sections, and  $L_j$  is the spacing between the joints,

- (2) the relative pipe-soil rigidity factor  $R$ :

$$R = \frac{EI}{E_s i^3 r_0} \quad (8)$$

where  $E_s$  is the Young's modulus of the soil, and  $r_0$  is the radius of the pipe,

- (3) the joint spacing ratio  $L_j/i$ .

Figures 5–8 show the normalized settlements ( $S_p/S_{max}$ ) and longitudinal bending moment

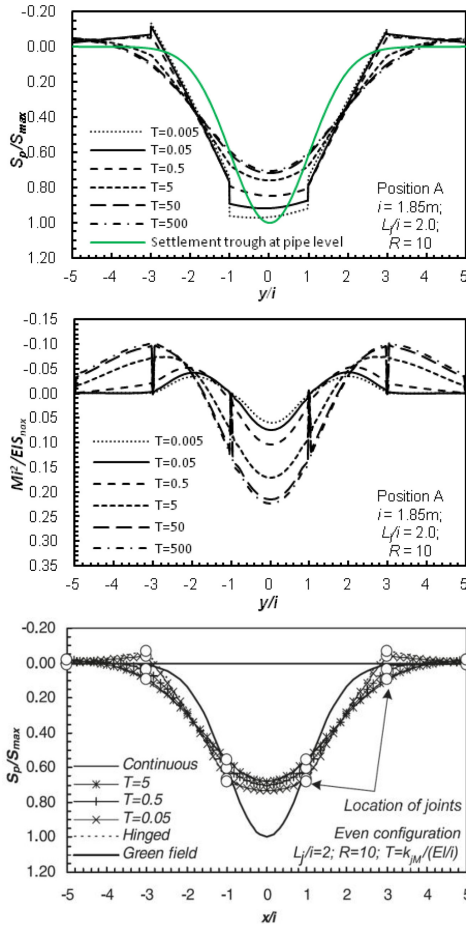


Figure 7. Normalized solutions for  $R = 10$  and  $L_j/i = 2.0$ , Position A: a) settlement trough b) bending moment and c) settlement trough with Klar et al. (2008) approach.

( $M_i^2/EIS_{max}$ ) of pipeline as a function of the joint rigidity for the cases of  $R = 10$  and:

- $L_j/i = 1.0$  for positions A (Figure 5) and B (Figure 6).
- $L_j/i = 2.0$  for positions A (Figure 7) and B (Figure 8).

For low joint stiffness ( $T < 0.5$ ), the pipe sections rarely bend (no mechanical damage or failure of the pipes) but there are obvious squeezing and rotation in the joints (leading to possible leakage or loss hydraulic performances).

As  $T$  increases, the pipeline acts from a hinged pipeline to a continuous one: the discontinuity of joints is reduced, there is an increase in the maximum bending moment and its position switches according to the position of tunnel centerline.

When  $T > 5$ , the pipeline acts like a continuous one. It coincides well with the settlement trough. The pipe sections bend visibly and it induces a high bending moment with a maximum right above the tunnel centerline.

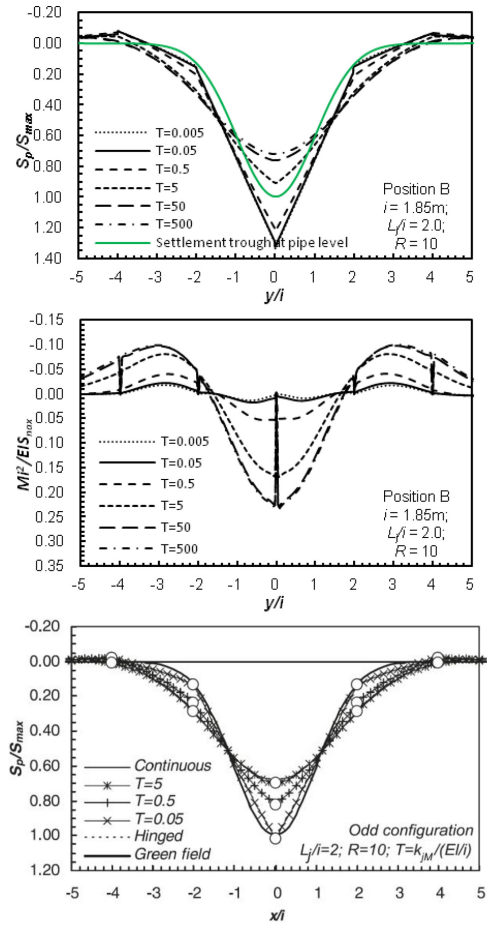


Figure 8. Normalized solutions for  $R = 10$  and  $L_j/i = 2.0$ , Position B: a) settlement trough b) bending moment and c) settlement trough with Klar et al. (2008) approach.

The results of numerical solution are close to those of Klar et al. (2008), especially for  $L_j/i = 1.0$ . However, it is found that the settlements of pipeline are always larger. When  $T < 0.5$ , the settlement at joints is even larger than the ground settlement trough. This phenomenon is mainly due to the plastic deformation of soil around joints (leading to more conservative solution with Klar's approach). More squeezing and rotation is induced but the pipe section presents smaller deflection and therefore smaller bending moment. This is particularly visible for  $L_j/i = 2.0$  (Figures 7 and 8).

#### 4 EFFECT OF TUNNEL-PIPELINE INTERSECTION ANGLE

It is commonly believed that the case of a pipeline perpendicular to the alignment of the tunnel ( $\theta = 90^\circ$ ) is the more conservative. Moreover, most analysis focus on the final state after tunneling but do not pay attention to the change of stress or strain during the process of tunneling. Therefore this section explores the effects

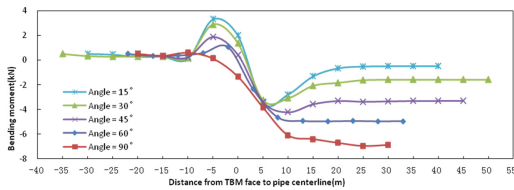


Figure 9. Bending moment of pipe at the cross section above tunnel.

of  $\theta$  during the 3D tunneling process (the series of 3D simulations considers the case of Position A,  $R = 0.5$  and  $T = 0.2$ ). The angle  $\theta$  does not impact the development of the settlement of pipe and its maximum value. Thus Figure 9 only presents the variation of bending moment in the cross section above tunnel centerline as the most critical situation.

It appears that the final bending moment decreases with the decrease of  $\theta$  from  $90^\circ$  to  $15^\circ$ . When  $\theta \geq 60^\circ$ , a small positive bending moment appears before the TBM arrives at the pipe centerline, then the bending moment descends rapidly to negative values and finally becomes constant.

For  $\theta < 60^\circ$ , the final value is unconservative because it is not the maximum negative value observed during the process of tunneling and the transient positive bending moment cannot be neglected. For  $\theta \leq 15^\circ$ , the maximum positive bending moment is larger than the maximum negative bending moment.

## 5 CONCLUSION

A 3D numerical pipe-soil model is introduced to simulate the behavior of pipeline due to tunneling. It considers elasto-plastic behavior for the soil, a refined

description of the joint behavior and the 3D effect of the tunneling process. When pipelines suffer the ground settlements induced by tunneling, the pipeline with more flexible joints produces larger vertical displacement and joint rotation, but it experiences smaller maximum bending moment than the pipeline with more rigid joints. It appears that Klar's elastic solution is more conservative in bending moment.

Effect of tunnel orientation with respect to the pipeline is also explored. For  $\theta < 60^\circ$ , the final bending moment is not the maximum value and the positive bending moment may be critical. The simplified 2D solution might thus be un-conservative.

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