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The Investigation of Subsidence Effect on Buried Pipes in 3D Space

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ABSTRACT

Buried pipes in the modern societies are considered as lifelines with a vital and essential role in the human life cycle. The performance of buried pipes is affected by many factors such as ground surface subsidence. In this paper, the effect of subsidence on pipelines is investigated using a three-dimensional numerical modeling developed in FLAC^{3D} software for four types of most commonly used pipes. The numerical results showed that ductile iron, steel, and polyethylene pipes with a diameter of 200 mm are stable in the presence of ground subsidence whereas the asbestos pipes at depths of 1 and 1.5 m are not stable; and thus should be buried deeper. In this regard, polyethylene pipes with equal diameter are recommended instead of asbestos pipes due to the high excavation and earth-filling costs and also environmental problems involved in the implementation of asbestos pipes.

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NOMENCLATURE

Δx	lateral deformation of pipe (mm)	I	inertia moment of pipe cross-sections (mm^4)
D_1	delay coefficient	K	subgrade coefficient
W_c	load per unit length of pipe (N/mm)	E'	soil reaction coefficient (N/mm^2)
r	average radius of pipe (mm)	α	Half of the central angle of the arc under the subgrade contact
E	elasticity modulus of pipe material (N/mm^2)	e	resistance coefficient of surrounding soil

1. INTRODUCTION

Water supply networks and water transmission lines are infrastructure component of urban communities. In this connection, paying attention to the problems of these networks is a top priority of managerial plans. Analysis of internal and external forces in the pipeline and finally subsidence and deformation of pipes is among the most important factors in the design of water pipelines. Subsidence or deformation of water pipes is an important factor in the pressures exerted to these pipes. The stress and subsidence created in these pipes are affected by the implantation conditions. Trench placement is the major pipe implantation method in most projects of urban water transmission lines in Iran. In this method, the pipe is placed in a relatively narrow trench drilled in undisturbed soil and then is earth-filled. So far, several studies have been conducted on underground pipelines and buried pipes. These studies are divided into three categories of analytical, numerical, and experimental studies. Mechanical analysis and design of pipelines are primarily analytical methods based on simplifying assumptions. Such an analysis solves the problem of the beam under distributed load, relying on rigid or elastic constraints. The simulations performed in mechanical analysis of underground structures have a significant role in engineering projects, considering the ability of computer software to perform calculations and structural analyses based on behavioral rules close to the natural behavior of the structures.

Numerical studies are carried out based on different approaches [1-11]. Takada et al. [1] investigated the relationship between the maximum strain generated in the pipe and bending angle. Jayadevan et al. [2] surveyed rupture and creep in steel pipelines of water

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transmission in the ground surface using FEM. They showed that the stress induced during failure of pipe and creating fractures in pipes is directly related to the impact of diameter to thickness ratio. They also indicated that with increasing the internal pressure of pipe, pipe deformation clearly decreases.

Kang et al. [3] showed that the surface pressure exerted on the pipes implemented in deep depth is always influenced by the subsidence of soil mass above and around the pipe. They also found that pressure on the pipe decreases if the top layer of the pipe is replaced by lighter materials with higher compressibility. Evidently, cast iron pipes are more appropriate options in this situation since their rigidity is higher than that of steel pipes. Ozkan and Mohareb [4] performed some experiments on the pipes and found that due to the plasticity condition of the pipe and loads in the given problem, among all investigated parameters only axial force is capable of moment distribution. They also concluded that the induced axial tension is effective in reaching a plastic condition resistance in the pipe.

Mahdavi et al. [5] developed a three dimensional continuum finite element model in Abaqus which included soil and pipeline. A parametric study was conducted afterward to understand the effect of critical parameters on the local buckling of pipes buried in firm clayey soil. An empirical equation for the critical buckling strain was proposed based on numerical results. Dadfar et al. discussed about cross-sectional ovalization of buried steel pipes subjected to bending moment induced by end displacements [6]. They found that the soil density and pipe flexural rigidity are important factors that control failure mechanism of the soil–pipe system.

The response of a buried reinforced concrete pipeline with gasketed belland-spigot joints subjected to traffic loading is investigated through three-dimensional numerical simulation by Becerril Garcia and Moore [7] and Xu et al. [8]. Zhang et al. [9] investigated the mechanical behaviour of a buried pipeline underground overload using the FEM. They indicated that the von Mises stress, plastic strain, plastic area size, settlement and ovality of the buried pipeline increase as the ground load and loading area increase.

Saberi et al. [10] performed a seismic analysis on the bent region in buried pipes and noted that in a full 3D soil-pipe interaction using Continuum Shell FE model, a substantial increase in the elbow strain is reached. Zhang et al. [11] analyzed the failure of buried pipes cross section in the operational phase and after the construction phase using numerical methods. Their results revealed that a high-stress distribution in the axial and peripheral direction under boulder load and the maximum equivalent plastic strain is created in the center. Their results also showed that deformation of protected crossover pipes is not less than that of unprotected pipes.

Figure 1 shows the deformation of buried pipe under subsidence. This figure clearly indicates the effect of subsidence conditions on buried pipes.

The present study models four types of pipe materials (polyethylene, steel, asbestos, and ductile cast iron) with different geometries in water distribution network. Because the impact of subsidence is more critical for pipes with a larger diameter, a simulation was performed for the maximum diameter of the pipe. The simulation was first performed for a depth of 1 m and if the resulting stresses exceeded the actually created stresses, it was repeated for a depth of 1.5 m. The finite difference method (FDM) based FLAC^{3D} software was used for the simulations performed in this work.

For this purpose, the efficiency of application and verification of the results was validated by analytical methods related to the buried pipes, followed by presenting the analysis and numerical results for different pipes.

2. EVALUATION OF LATERAL DEFORMATION IN FLEXIBLE BURIED PIPES BASED ON THE ANALYTICAL METHOD

Bearing capacity of all underground pipe was combined with two factors including the intact resistance due to geometric and mechanical properties of materials and lateral pressure in its flanks and surrounding. Lateral pressures create some stress that can deal with the stresses coming from external loads and, consequently, increase the bearing capacity.

Flexible pipes made of simple sheets, corrugated steel pipe, fiberglass, and polyethylene have a low inherent resistance. Resisting pressure of lateral side, which is caused by the significant deformation of pipes, has a major impact in increasing the bearing capacity. Lateral deformation of pipes and their considerable lateral resistance is a prominent structural feature of these pipes. This factor makes the pipe flexible with a small flexural strength, which able them to stand the pressures without being ruptured.

A circular or oval underground pipe exhibits the maximum load capacity, as long as its preparation and earthfill in lateral side pipe is performed precisely.

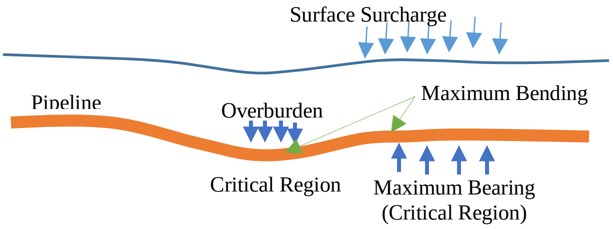

Figure 1. The effect of subsidence on buried pipes

The subgrade construction is also affected by the internal forces caused by the distribution of vertical pressure in the channel floor (Figure 2). If channel subgrade is shaped according to pipeline shape, more uniform pressure distribution in the floor is produced. Desired results in pressure distribution can be achieved if the pipe is placed on the flat subgrade and then lateral side wedge is filled and compressed. This problem is especially true for large diameters [12].

Unlike the rigid pipe which breaks caused by cracks or fractures in the shell, steel pipe failure is due to excessive lateral deformation. Due to lateral deformation, the horizontal diameter was significantly larger than the vertical diameter, and displacement to the outside wall of the pipe generate resistant pressure in the surrounding soil. Since this pressure is applied in the horizontal direction, the lateral deformation is reduced compared to the condition where there are only vertical pressures.

By increasing the height of earthfill, this behavior continues until the top of the pipe becomes almost flat. The increase in load causes the curvature of the crown to be reversed and deformed downside. As a result, the side faces deform inward and lateral resisting pressure is lost. Vertical deformation proceeds until subsidence occurs in the top soil, and finally pipe ruptures. At the end of the process, the mechanism of large deformation is converted to the large bending and exceeding stresses occurs in the pipe (Figure 3).

The following assumptions are used in the analytical relationships:

- Soil vertical loads can be calculated based on the Marston’s theory and are not uniformly distributed on the pipe.

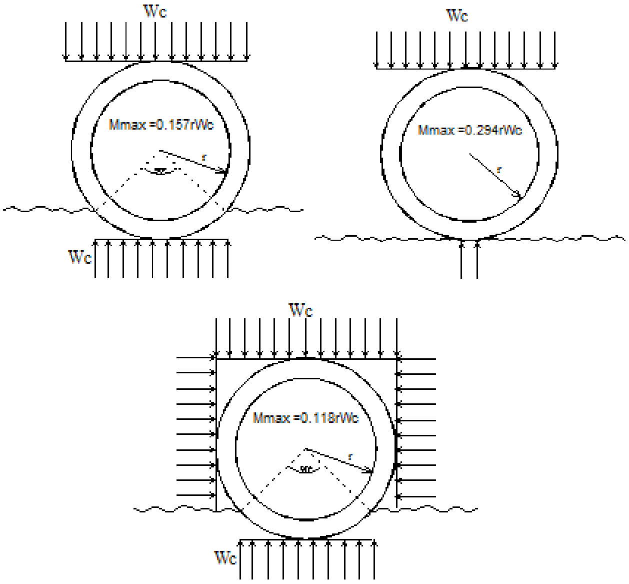

Figure 2. Effect of subgrade construction and method of earth-filling on the lateral side on the bending moment in the pipe [12]

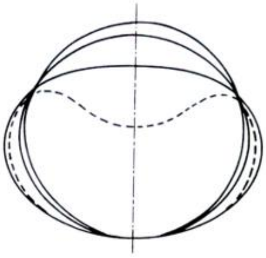

Figure 3. Stages of pressure and deformation increment [12]

- Subgrade vertical reaction is equal to vertical load and is distributed evenly in the subgrade.
- Lateral pressure in any side of the pipe is distributed in a parabolic pattern with a 100° angle from the middle of sections. Also, the maximum pressure is generated in the location of horizontal diameter and the lateral pressure is equal to lateral resistance coefficient of surrounding soil at half of the maximum lateral deformation. The pressure distribution is shown in Figure 4.

Due to the soil creep and increased lateral deformation of the pipe with time passage, delay coefficient must be incorporated in the relationship of maximum pipe deformation. The delay coefficient is always greater than one, and depends on the type of fill materials. If the soil is well graded and compacted, delay coefficient is approximately unity. In comparison, for a poorly-graded compressible soil, delay coefficient is about 2. However, in practice delay coefficient is considered 1.25. To reduce the delay coefficient, surrounding soil should be properly compacted to twice the diameter of pipe diameters on each side.

The Spangler’s relationship (Equation (1)) is used to calculate the lateral deformation of flexible buried pipe [13]:

$$\Delta x = D_l \cdot \frac{KW_c r^3}{EI + 0.061E' r^3} \tag{1}$$

where Δx, D_1, W_c, r, E, and I are respectively the lateral deformation of pipe (mm), delay coefficient, subgrade

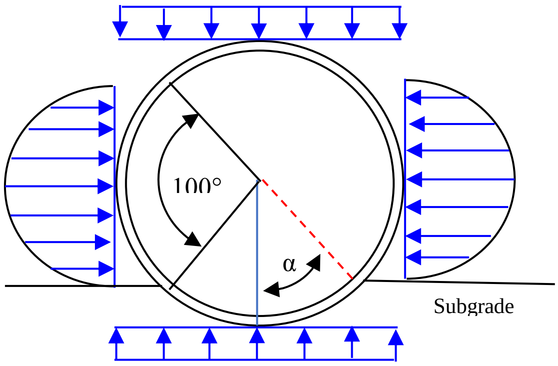

Figure 4. Distribution of hypothetical pressure around the flexible pipe [14]

coefficient which depends on the contact angle (Table 1), the load per unit length of pipe (N/mm), an average radius of pipe (mm), elasticity modulus of pipe material (N/mm^2), and inertia moment of pipe cross-sections (mm^4). Also, E' is modulus of soil reaction (N/mm^2) which is calculated using the following equation:

$$E' = er \tag{2}$$

where e is the resistance coefficient of surrounding soil. This parameter represents the pressure on the area per unit and is defined as one unit of pipe lateral deformation in the outside direction against the ground. A limited information is available about the actual value of this parameter. Although it greatly depends on the size of pipe, for a soil with the same density (homogeny soil), Equation (2) can be considered almost constant. Depending on the soil type (1.6-56 N/mm^2), the range of E′ is highly varying. The values of the soil stiffness (modulus of soil reaction, E') found to represent the types of soils and degrees of compaction for buried flexible pipe is illustrated in Table 2.

To validate the numerical model, the results were calculated using an analytical method in a simple case. In this section, geometrical conditions of the pipe, a trench (Figure 5), pipe material properties, and the properties of earth materials are calculated based on the procedure mentioned in the previous section. Finally, the deformations obtained by the analytical method were compared with FLAC^{3D} results.

The data used to validate numerical models are presented in Table 3. According to Table 2, E' was considered 7 N/mm^2 in this paper.

Based on Equation (1), the calculated horizontal deformation of the pipe is 0.112 mm.

3. 3D NUMERICAL MODEL

3. 1. Finite Difference Simulation Model

The finite difference method becomes a significant and general numerical tool to analyze of geotechnical works because of ability to considering of ground heterogeneity, non-linear soil behavior and soil-structure interaction.

TABLE 1. Subgrade coefficient (K)

Half of the central angle of the arc under the subgrade contact (α)	K
0	0.11
15	0.108
22.5	0.105
30	0.102
45	0.096
60	0.09
90	0.083

TABLE 2. Bureau of Reclamation values of E' for Iowa formula (for initial flexible pipe deflection)

Soil type-pipe bedding material (Unified Classification System)	*E' for* degree of compaction of bedding (N/mm^2)			
	I	II	III	IV
Fine grained soils (LL> 50) Soils with medium to high plasticity CH, MH, CH-MH	No data available; consult a competent soils engineer; otherwise use *E'* = 0			
Fine-grained soils (LL < 50) Soils with medium to no plasticity CL, ML, ML-CL, with less than 25 percent coarse-grained particles	0.35	0.7	2.8	7
Fine-grained soils (LL < 50) Soils with medium to no plasticity CL, ML, ML-CL, with more than 25 percent coarse-grained particles *Coarse-grained soils with fines* GM, GC, SM, SC3 contains more than 12 percent fines	0.7	2.8	7	14
Coarse-grained soils with little or no fines GW, GP, SW, SP contains less than 12 percent fines	1.4	7	14	21
Crushed rock	14		21	
Accuracy in terms of percent deflection (%)	±2	±2	±1	±0.5

I) Dumped
II) Slight, <85% Proctor, <40% relative density
III) Moderate , 85-95% Proctor, 40-70% relative density
IV) High , >95% Proctor, >70% relative density

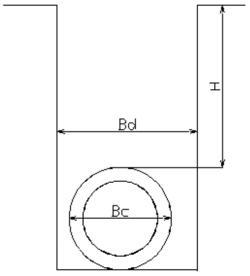

Figure 5. Pipe geometry and trench

TABLE 3. The data used in the validated numerical model

Parameter	Unit	Value
subgrade coefficient (K)	-	0.11
the load per unit length of pipe (W_c)	N/mm	1.32
the radius of pipe (r)	mm	45
elasticity modulus of pipe (E)	N/mm^2	950
soil reaction coefficient (E')	N/mm^2	7
inertia moment of pipe (I)	mm^4	83.3

At this model the open earthwork cutting width regarded 0.6 m with a cover height of 1 m. The model has dimensions of a 10 m length, 10 m width, and 5 m depth, consisting of 23296 3D brick elements, 320 shell element for simulating pipe, and 24024 nodes (Figure 6). The element sizes shown in Figure 6 were generated to meet the requirements for simulating the highest accuracy.

The model is regarded sufficiently large to allow any possible failure mechanism in order to develop and avoid any influence from the model boundaries. All translational and rotational degrees of freedom were restrained at the bottom of the model. Translations in transverse direction and rotations were restrained at the vertical faces of the model. The soil layers were regarded as an elastoplastic material in conformity with the Mohr-Coulomb failure criteria. The initial stresses were calculated through a first calculation of the soil deformation under specific gravity.

3. 2. Validation of the 3d Numerical Model

The buried pipe is simulated based on the following steps:

A) Simulate of the model geometry.

B) Define the properties of surrounding soil and pipe.

C) Apply different trenching and pipe installation stages.

- Excavate of the trench.
- Earthfill the subgrade.
- Earthfill the graded soil and install the casing.
- Earthfill the compacted soil above the graded soil.

Each of these steps is simulated and the displacement is obtained in the pipe wall. Then, the obtained numerical values are compared with the analytical results.

Because the pipe is located in the near of surface (1 m depth) and trench is narrow (0.6 m) and considering the effect of boundary conditions on numerical modeling, a 3D model with a width and length of 10 m and a height of 5 m was simulated (Figure 6). A pipe with a radius of 50 mm and a length equal to the length of model geometry at a depth of 1 m was modeled in this step.

In this paper, Mohr-Coulomb behavioral model was used to simulate the deformation behavior of a polyethylene pipe. Geotechnical properties of soil materials are shown in Table 4.

Figures 7 and 8 show the vertical displacement contours and lateral deformation of the pipe due to overburden pressure in the last step of the simulation, respectively.

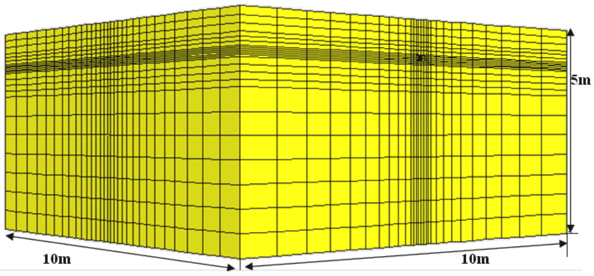

Figure 6. Geometry of the numerical model designed in FLAC^{3D}

TABLE 4. Geotechnical properties of soil materials

Soil Layer	Elasticity modulus (MPa)	Poisson's ratio (-)	Cohesion (kPa)	Friction angle (degree)
undisturbed soil	70	0.3	20	35
Subgrade soil	40	0.3	10	30
soil surround the pipe	35	0.3	15	30
Soil on top of the trenches	50	0.3	25	30

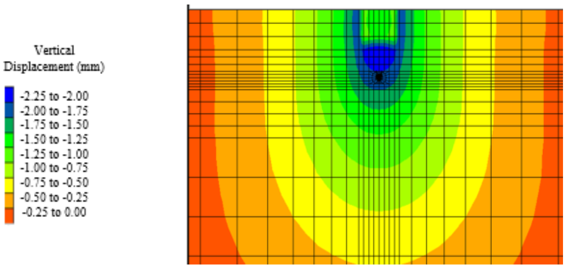

Figure 7. Vertical displacement contours

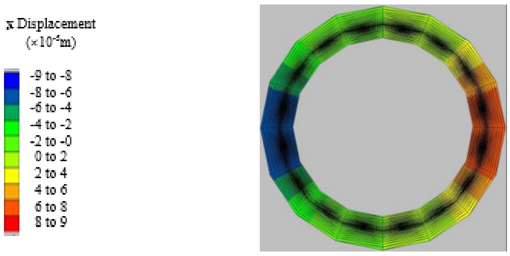

Figure 8. Lateral deformation of the pipe

As shown in Figure 8, the maximum lateral deformation in the pipe is 0.09 mm, which is acceptable considering the restrictive conditions of analytical relations (0.112 mm) in the determination of different parameters.

The dimensions of the designed trench are 0.6 m and 1 m respectively in width and height. Figure 9 illustrates the modeling geometry and the applied steps.

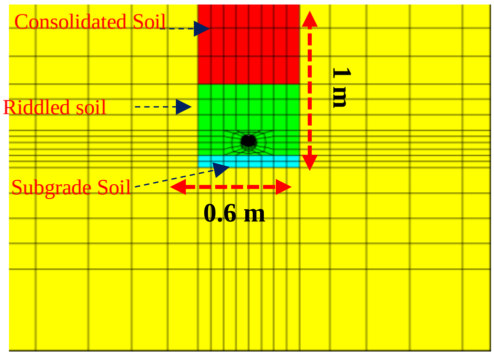

Figure 9. Geometry of trench

The valdiation is also done for different types of pipes. The comparistion between analytical and numerical results for different pipes are illustrated in Table 5. These results are also showed a gooed agreement between both methods. According to Table 5, it is cleare that with increasing the elastic modulus of pipe (more stiffness), the lateral displacement is desreased.

4. THE ESTIMATION OF DEFORMATION IN THE BURIED PIPE UNDER SUBSIDENCE LOAD

The geometry of the model, as shown in Figure 10, was simulated for studying the effect of subsidence on buried pipes. The depth was considered 1 m and a 10 cm subsidence was applied in the model. Modeling was done for four different types of pipes that are commonly used in Iran including polyethylene pipes with a diameter of 200 mm (PE200), steel pipes with a diameter of 400 mm (S400), asbestos pipe with a diameter of 300 mm, and ductile iron pipe with a diameter of 900 mm.

Figures 11-14 indicate the vertical displacement, axial force, bending moment and radial horizontal displacement caused by ground subsidence in different pipes. As shown in Figure 11, approximately 80% of the subsidence created in the ground surface reaches the PE200 pipe and the effect of subsidence on the S400 is the minimum. Figure 12 shows the profiles of axial forces along the pipe. According to this figure, the minimum and maximum axial forces are created in PE200 and cast iron pipes, respectively, because of their higher stiffness compared to other pipes.

TABLE 5. Comparison between analytical and numerical result for different pipes

Elastic Modulus (MPa)	$\Delta x_{Anlytical}$ (mm)	$\Delta x_{Numerical}$ (mm)
600	0.149	0.121
950	0.112	0.090
1300	0.090	0.080

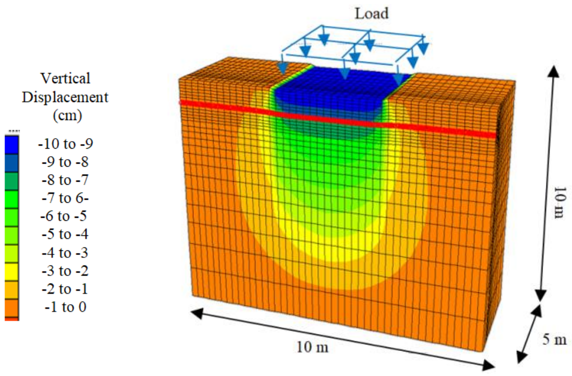

Figure 10. Cross section of simulated model with buried pipe

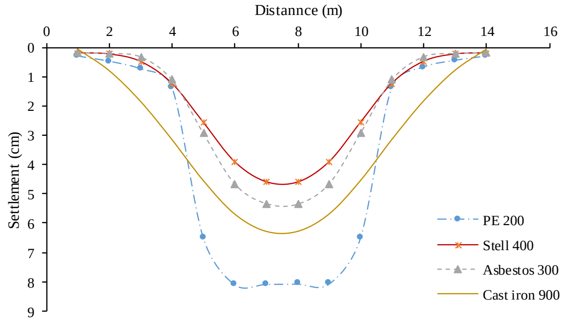

Figure 11. Vertical displacement in the pipes caused by the ground subsidence

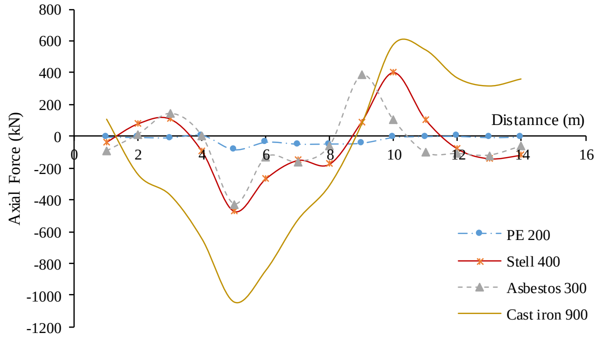

Figure 12. Axial force profile in the pipes caused by the ground subsidence

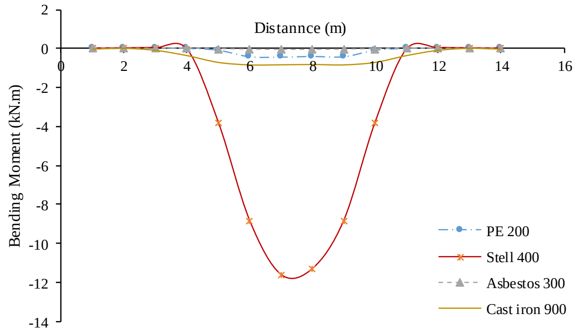

Figure 13. Bending moment profile in the pipes caused by the ground subsidence

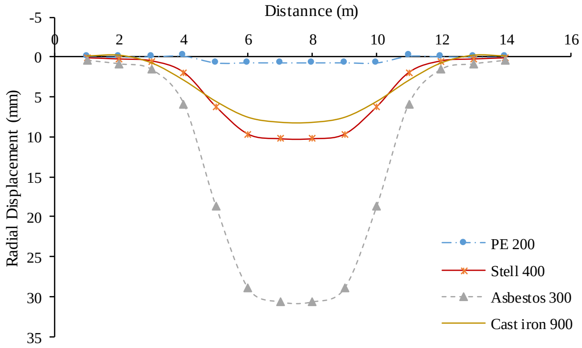

Figure 14. Radial displacement in the pipes caused by the ground subsidence

Indeed, the more the pipe stiffness, the higher the axial force.It has to be noted that the stiffness of a pipe is originated by a combination of size (diameter) and elasticity modulus. Figure 13 represents the profiles of bending moment along the pipe. As shown in this figure, the bending moment in the three polyethylene, steel, and asbestos pipes are very low (due to their low stiffness) and the amount of bending moment in steel pipe is 12 kN. According to the maximum compressive stress generated in the steel pipe (200 MPa) and compared to the maximum allowed stress (250 MPa), the steel pipe will not fail. Figure 14 presents the radial displacement in different pipes. It is observed that the maximum radial displacement occurs in the asbestos pipes with a diameter of 300 mm which, due to the positive axial forces in asbestos pipes, are under tension force. As a result, according to the inability of asbestos pipe under tension, the pipe will not resist the applied load.

5. CONCLUSION

In this paper, the effect of subsidence on widely used buried pipes in the water supply industry was investigated using a 3D numerical modeling. In the first step, the numerical modeling results were validated through the analytical method. Next, numerical models were simulated for different pipes and the resultant force and displacement induced by a ground surface subsidence of 10 cm were calculated. The results of the prepared 3D model are:

- For pipe PE, burying the pipe at a depth of 1 m will not pose a problem.
- Analysis of ductile iron, S400, and PE200 also showed that these pipes withstand the effect of subsidence. Thus, a burial depth of 1.5 m is recommended for ductile iron and steel pipes. However, a burial depth of 1 m is suitable for smaller diameters.
- Asbestos pipes do not have the ability to withstand the effects of subsidence at depths 1 and 1.5 m. Thus, because the created stresses exceed the allowable stress in the asbestos pipe, it should be buried deeper. However, due to the increasing cost of excavation and earth-filling, and also environmental problems of asbestos pipes, it is recommended to use polyethylene pipes for water transfer purposes.

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FLAC^{3D} Software

چکیده

لوله‌های مدفون در جوامع مدرن از شریان‌های حیاتی به شمار می‌آید که نقشی حیاتی و اساسی را در چرخه زندگی بشری ایفا می‌نماید. در این میان، عوامل مختلفی بر عملکرد لوله‌های مدفون تاثیر می‌گذارند. یکی از عوامل تاثیرگذار بر لوله‌های مدفون، نشست سطح زمین می‌باشد. در این مقاله با استفاده از مدل‌سازی سه بعدی عددی توسط نرم افزار FLAC^{3D} اثر نشست بر چهار نوع لوله پرکاربرد در خطوط انتقال، بررسی شده است. نتایج عددی نشان دادند که برای لوله‌های چدن داکتیل و فولادی و پلی‌اتیلن با قطر ۲۰۰ میلی‌متر توانایی تحمل تاثیرات نشست را دارند، اما لوله آزبست توانایی تحمل تاثیرات نشست در اعماق ۱ و ۱/۵ متر را ندارد و بایستی این لوله‌ها در اعماق بیشتری مدفون شود. اما، با توجه به افزایش هزینه خاک‌برداری و خاک‌ریزی، و همچنین مشکلات زیست محیطی لوله‌های آزبست، پیشنهاد می‌شود از لوله پلی‌اتیلن با قطر معادل استفاده گردد.

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