Journal of Mining and Environment (JME) Vol. 16, No. 3, 2025, 1027-1041

Shahrood University of Technology

Journal of Mining and Environment (JME)

Journal homepage: www.jme.shahroodut.ac.ir

Iranian Society of Mining Engineering (IRSME)

# The Influence of Pipe Jacking on Earth Deformation

Ehsan Taheri*, Reza Mohammadpour, and Mohammad Hossein Mokhtarzadeh

*Faculty of Engineering, Tarbiat Modares University, Tehran, Iran*

**Article Info**

*Received 6 May 2024*

*Received in Revised form 21 June 2024*

*Accepted 28 July 2024*

*Published online 28 July 2024*

DOI: 10.22044/jme.2024.14508.2727

**Keywords**

*Trenchless methods*

*Pipe-jacking*

*Numerical modeling*

*Ground deformation*

*Sensitivity analysis*

**Abstract**

In recent years, the demand for new trenchless methods has dramatically risen. Pipe jacking is a trenchless method widely used in recent years. Ground deformation is one of the significant parameters that may lead to unrepairable harm to facilities and even people. So, ground deformation analysis is necessary for safety and design reasons. The present study analyzes the factors affecting ground deformation during pipe jacking. This is a descriptive-interventional study. Pipe jacking causes soil displacement in three dimensions (3-D). Therefore, 3-D numerical methods were applied for analysis. In this study, numerical simulation was performed using PLAXIS finite element numerical software, taking the case study into account. The effect of each parameter on the ground deformation pattern was studied in three directions; the uplift and their exact position were then analyzed. It should be noted that displacement analyses were performed in two areas: pipe crown and ground surface. Also, the relation of each parameter was estimated with the ground subsidence. Finally, the effect of each different factor and their sensitivity index were determined using sensitivity analysis. The highest subsidence occurs at the end of the shield due to stress relaxation. Considering the results, it was found that the relationship between the internal friction angle and subsidence is linear and direct. The relationship between the elastic modulus and subsidence is also linear but indirect. The results indicate that the most sensitive factor of ground deformation is the diameter, but the least sensitive factor is the face pressure.

## 1. Introduction

With the acceleration of urbanization in recent years, there has been a rapid increase in trenchless methods. The trenchless methods provide the best underground facility methods from the economic, environmental, and safety points of view [1]. With nearly 200 years of experience developing advanced underground excavation techniques, construction is faster, safer, and more cost-effective than ever [2]. In pipe jacking, excavation and jacking into the ground through hydraulic jacks are performed simultaneously [3]. Various factors may affect the ground deformation pattern during pipe jacking, the most important among which are excavation face pressure, grout pressure, the diameter of the borehole, overburden, and the geotechnical parameters, including the elastic modulus, cohesion, and friction angle. Each parameter will influence ground displacement, considering the sensitivity rate. Therefore, estimating the ground deformation and the sensitivity analysis of each effective parameter is very important in pipe jacking. Numerical methods have been developed due to their high cost, time, and measurement errors in experimental and field studies. Numerical methods have been proposed as one of the most well-established, suitable methods for solving computer problems in various engineering fields [4]. A critical issue to consider in pipe jacking is to predict the ground deformation pattern for safety and design purposes. The effect of different parameters on the ground deformation and their sensitivity should be determined so that the ground is deformed optimally with proper design.

Pipe jacking has significant environmental benefits compared to traditional open-cut methods.

Corresponding author: e_taheri@modares.ac.ir (E. Taheri)

In general, trenchless methods minimize the outputs and excavation materials. This, in turn, leads to reduced vibrations and disturbance at the ground level [5-7].

Pipe jacking was first used in early 1896 to install a concrete catchment under the North Pacific Railroad in the United States, although this method was not popular in the United States until 1950 [8]. The use of pipe jacking was also considered in Vienna in the late nineteenth century [9]. The developments leading to modern pipe-jacking devices have occurred mainly in Japan, Germany, and the United Kingdom. The slurry pressure balance shield concept was introduced in England and Germany in the late $19^{th}$ century. The patents of the slurry devices in the United Kingdom were granted to John Bartlett in 1964, although there were problems with the first experimental use of the device in the New Cross test tunnel in southern London in 1971 [9,10]. The first case of using pipe jacking in Japan was in 1948 when a 600 mm diameter cast iron pipe was installed to carry a gas pipeline under the railway, and this method became very common there [11]. Japan also began experimenting with the "slurry shield" in 1964 on very soft coastal alluviums. In Germany, the experiments were carried out in 1976 using the "Hydroshield" in Hamburg. Various excavation machines with continuous tunnel face support were introduced in Japan from the late 1960s until the 1970s and 1980s [12].

Using numerical analysis and Plaxis 3D finite element software, Liu & Lu (2012) analyzed a project in Kaohsiung Park in Taiwan. Significant parameters in the study included advancement size, soil improvement ratio, and void contraction ratio. The study showed that ground deformation under 38mm would be safe under artificial excavation, and any displacement from 100 to 150 mm from manufactured projects would cause severe hazards. They also found that jacking distance (a), gap shrinkage (Gp), and contraction ratio (CR) all affect the stability at the tunnel level when the jacking distance is less than 0.3m and the contraction ratio less than 2.5% ($Gp \leq 3.8$ cm), the safety level will be higher [13].

Mojallal and Orumchi (2017) proposed a new method for designing the grout mix based on its shear rather than compressive strength, enabling a reduction in the amount of cement consumed. Moreover, the settlement caused by the Tunnel Boring Machine (TBM) is measured using a point network system [14].

Salim Al-Maamori et al. (2018) investigated the Time-Dependent Deformations (TDD) in a tunnel made by pipe jacking in Queenston shale (QS) using the finite element methodology. The study showed that "time" is vital in controlling the deformation and stresses produced in the tunnel cover [15].

Considering ground settlement in soft soil as the engineering background, Han et al. (2019) investigated the effects of pipe jacking on ground subsidence using numerical simulation. The study focused on the factors that mainly influenced ground surface settlement, including in-situ stress release rate (or ground loss ratio), chamber pressure, elastic modulus of soil, buried depth, and pipe diameter. Their main conclusions were as follows: the in-situ stress release rate and pipe diameter were proportional to the surface subsidence; Chamber pressure, elastic modulus, and buried depth were inversely proportional to the surface subsidence, and finally, from the point of view of the influence on surface settlement, the sensitivity of pipe diameter and elastic modulus of soil was the greatest, followed by burial depth and chamber pressure. The stress release rate was the most minor [16].

Zhang et al. (2019) provided a 3-D finite element model using ABAQUS software. The study used the Pipe-Soil Interaction(PSI) element to simulate the interaction of the pipeline and the soil and the effects of parameters like soil elastic modulus, stress release rate, lateral pressure coefficients, pipeline elastic modulus, and buried depth on the ground deformation rate was investigated. The results indicated that the correlation order of parameters is $E_s > P > H > K_0 > E_p$. So, the soil elastic modulus has the highest sensitivity in the pipeline subsidence, and the subsequent stress release rate has the most considerable effect. The elastic modulus of the pipe has the slightest impact on the pipeline subsidence [17].

Ma et al. (2021) analyzed soil areas affected by pipe jacking construction. The study delves into the mechanisms of soil disturbance and examines patterns of soil deformation using random medium theory. The research utilizes data from an electrical transmission pipeline project in China to explore lateral deformations in deep soil, pore water pressures, stratified settlement, and earth pressures. The areas affected by pipe jacking are classified into distinct zones, including the extrusion disturbance zone, shear disturbance zone, unloading disturbance zone, and consolidated zone. Soil disturbance arises from the excavation process and the use of grouting to stabilize the surrounding soil. Excess pore water pressure resulting from pipe jacking excavation can induce stratum movement and ground subsidence. The horizontal stress of the soil increases during tunneling machine excavation. The inclination angle of the tunneling machine's front is approximately 45° − θ/2, and the inclination angle of the boundary between the unloading disturbance zones on both sides and the consolidation zone is approximately 45° + θ/2, where θ represents the internal friction angle of the soil [18].

There is a wide range of excavation methods in pipe jacking, such as micro tunnel boring machine (MTBM), face excavation shield, mechanical shield, pressure slurry excavation system, and earth pressure balance shield machine (EPBM). In most cases, selecting an excavation method depends on the ground maintenance method. It should be noted that the ground conditions will play a significant role in choosing the excavation method, determining the type of shaft built, and the ground maintenance system. Some of the advantages of this method include high speed, minimum workforce required, reduced ground disturbances, the flexibility of excavation method, working with unexpected ground conditions, no need for two-stage coverage, reduced leakage in the jacked pipes, increased worker safety, long pipe jacking possibility, no ground surface disturbance, and no traffic jam, the possibility of using the pipe jacking technique where other methods could not be used, as well as pipe possibility of jacking in different soils [4,16].

Disadvantages of this method include high fixed costs, requiring relatively straight alignment, difficulty replacing damaged pipes, the need for more shafts for long pipelines (approximately every 1000 feet), and the need to increase thrust force after every stop [16]. Rahjoo et al. (2012)(2012) conducted a comparative analysis of various techniques for determining jacking loads in trenchless pipe jacking. Accurately predicting jacking forces is crucial as they directly impact the design of the pipe jacking system. The study delves into multiple factors influencing jacking loads, such as soil conditions, lubrication, and overcut size. Additionally, it evaluates three distinct methods for calculating jacking loads: the ASCE 27 method, the Staheli model, and the Bennett model [19].

Zhen et al. (2014) examined instances of steel pipe-jacking incidents during underground construction. The study delved into a specific occurrence where a steel pipe buckled under the influence of high water and earth pressure. The analysis used a finite element model to simulate the pipe's deflection under actual water and earth pressure. The findings indicated that the deflection fell within the elastic range, resulting in no permanent damage to the pipe. Additionally, the research investigated the pipe's stability under jacking forces, ultimately attributing the pipe's buckling to a combination of high confining pressure and jacking force. The study suggested two potential solutions to address this issue: increasing the wall thickness of the pipe and incorporating stiffening ribs [20]. In 2023, Tang et al. The surface deformation resulting from excavation gradually reduces and stabilizes once the overlying soil layer on the pipe jacking exceeds 1.5 times the diameter of the pipe. The settling tank constructed becomes wider as the jacking pipe goes deeper. The additional weight above the jacking pipe further intensifies the ground surface settlement. Furthermore, the maximum ground surface deformation value decreases as the overlying load increases, especially when the load is high (0.018 MPa). The studyvarious factors, such as the thickness of the overlying soil layer, the depth of the jacking pipe, and the weight of the overlying load, all affect the ground deformation caused by pipe jacking construction in soft soil areas [21].

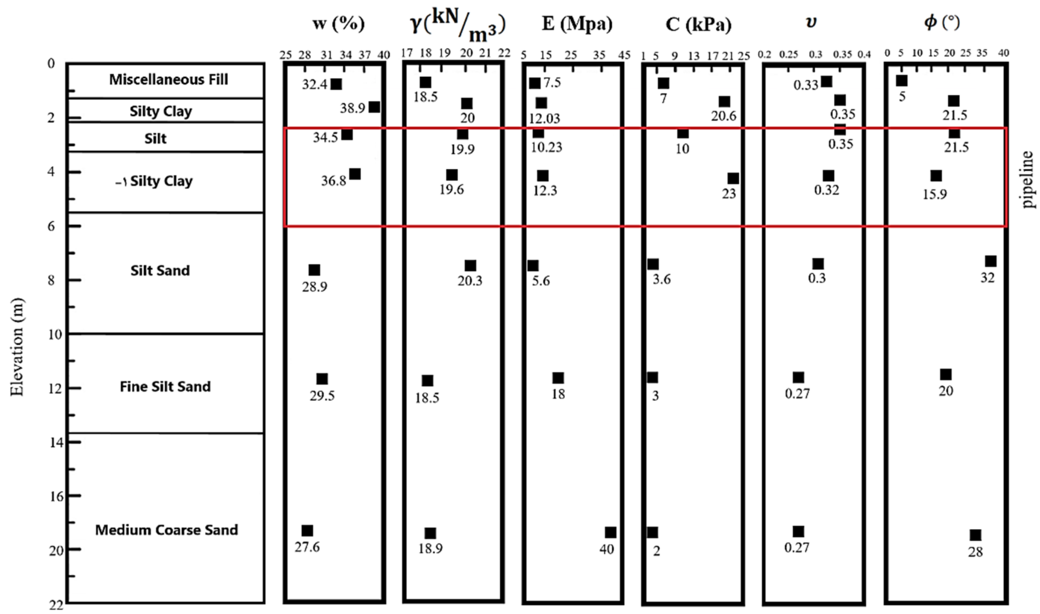
Liet al. (2007) noted that the impact of pipe-jacking construction on the stress change of the surrounding soil is limited. The study also recommends consolidating the road surface and improving soil conditions before construction to minimize ground deformation. It was found that soil pressure reaches its maximum point when the soil is directly above the machine head, and soil stress decreases as the machine head moves forward [22]. , Cui et al.(2023) developed a method to quantitatively assess the impact of different factors on soil deformation after constructing a pipe-jacking tunnel. They collected data from constructing 24 rectangular pipe-jacking tunnels in soft soil layers in China to create a system for evaluating post-construction surface settlement and soil loss rate. Their findings indicate that the relative burial depth of the pipe-jacking tunnel in the soft clay layer has the most significant effect on post-maximum ground settlement, followed by the section area of the pipe-jacking tunnel. The relative height coefficient of the groundwater level has the most minor influence[23]. The present study utilizes 3-D numerical finite element methods to analyze effective parameters such as excavation face pressure, injection grout pressure, diameter, overburden, and various state geotechnical parameters. The study aims to examine the relationship of each parameter with ground displacement and evaluate the sensitivity of each parameter. Therefore, the numerical analysis results will aid in determining the optimal conditions for a successful project design.

## 2. Basic assumption for pipe jacking simulation

In this descriptive-interventional study, the ground deformation pattern was studied and analyzed based on the finite element numerical simulation and using the PLAXIS 3D software. After that, the results obtained from field and experimental studies were compared with numerical modeling results to confirm their accuracy. Finally, the effect of each factor was examined using sensitivity analysis, and the sensitivity index of each parameter from the most sensitive to the least important factor influencing the ground deformation is provided. In addition, the hybrid effect of several parameters on the ground displacement and the sensitivity percentage of the ground surface and pipeline crown toward changes in the parameters were investigated.

### 2.1. Project Introduction

This study summarises the seven layers of soil and the main soil parameters and values adopted for the model in Figure 1. The inner and outer diameters of the pipeline are 2720 and 3300 mm, respectively. A single pipe link is 2 meters long, with 100 links. The pipe jack is a disc-type unipolar jacking device balanced with ground pressure. In addition, there are sewer, water, and gas pipes around the pipeline. The soil around the pipeline consists of silt and clay particles, and the depth of the pipeline center measured from the ground surface is 4400 mm [24-25].




Note: w = Water content, $\gamma$ = Soil Unit Weight, E = Elastic modulus, C = Cohesion, $\upsilon$ = Poisson ratio, $\phi$ = friction angle

**Figure 1. Physical and mechanics parameters of typical soil layers in the site**

### 2.2. Model geometry

In the pipe jacking method, excavation operation, pipe jacking, and grout injection are performed simultaneously. Therefore, these factors are also considered simultaneously in the simulated numerical model. Eight 2 m excavation steps (length of each pipe link) were created in the finite element model. First, the power transmission pipeline in China, investigated in a field monitoring study, was selected as a database. Due to axial symmetry, only half of the model was chosen for simulation. Considering that in the elastoplastic environment, radial and tangential stresses reach natural stress at a distance of 6 times the diameter of the excavation space, the dimensions of the original model, according to Figure 2, are 20 m along the X-axis, 40 m along the Y-axis, and 20 m along the Z-axis.

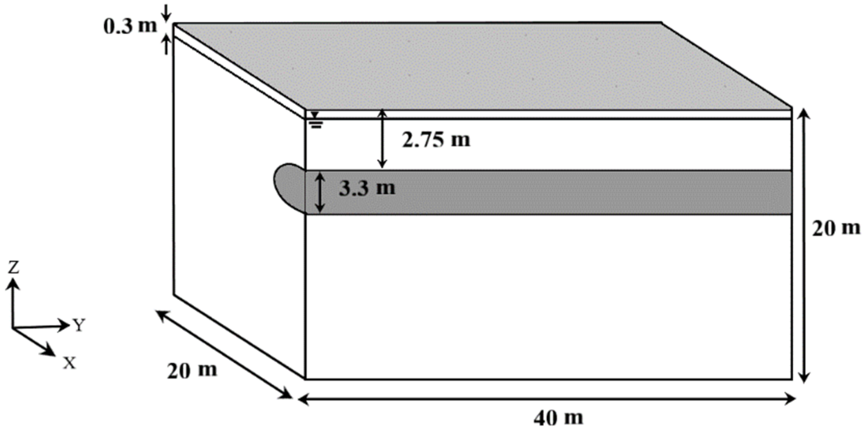



**Figure 2. Geometric model of numerical simulation**

### 2.3. Numerical calculation model and simulated work steps

The study employed a numerical model, as illustrated in Figure 3, and utilized Plaxis 3D version 2020 finite element numerical software for simulation. The model featured a borehole with defined soil layers and groundwater levels, and its dimensions were determined in the Structures module. Based on the database, the excavation shield was described as a cone, with the thrust pipes and slurry layer behind them.

Using the Mesh module, the model was meshed into small (quadrilateral) elements, with the Medium meshing type applied, resulting in a total of 70602 elements and 123586 nodes. The Staged Construction module analyzed the model in plastic and static type modes, simultaneously simulating excavation, pipe jacking, and grout injection to mirror real-world project implementation processes.

The software automatically applied in-situ stresses and pore water pressure in the initial calculation phase. The second phase considered the first 10 meters of the pipeline before excavation, installing the shield and thrust pipes while applying excavation face pressure, grout pressure, thrust force, and interaction between the shield, pipes, and surrounding soil. Eight 2 m excavation steps were then defined, and the model was solved using finite element numerical methods.

Ultimately, vertical and lateral displacements of the ground surface and pipe crown and their uplift level were examined in the numerical model, and the results were compared to the theoretical values and field measurements. In the next step, the parameters that are effective in the ground deformation pattern, such as the depth of the pipeline (overburden), excavation diameter, face pressure, grout injection pressure, elastic modulus, cohesion, and the internal friction angle, were analyzed. The sensitivity of each variable in the ground deformation was analyzed using the relevant equations.

## 3. Results and discussion

In the pipe jacking operation, in case the construction process is not controlled correctly, the strength and deformability modulus of the soil is vastly reduced, which can lead to uplift and subsidence problems and the creation of cracks in the buildings, the collapse of surface facilities, and fracturing of proximate pipelines. So, it is necessary to analyze the effect of various parameters in ground deformation and their sensitivity, which are explored below.

### 3.1. Effect of overburden on displacement

With the increase in the overburden, the subsidence in the ground surface and pipe crown will be reduced significantly. Based on observations, if the depth increases from 2.75 m to 6.75 m, the maximum subsidence in the ground surface decreases from 7.3 mm to 4.8 mm. That is, if the depth increases 2.5 times, the subsidence is reduced by 34.2%. So, the deeper the pipe is driven, the lower the range of effects of pipe jacking on surface displacement. As expected, the displacement is higher in the pipe crown than the ground surface, the maximum of which is 8.3 m in the overburden (6.75 m) and has increased 1 mm compared to the ground surface.

Increased overburden would lower the lateral displacement. In other words, the displacement would be more prominent when the pipeline is near the ground surface. The maximum displacement range for various overburden conditions varies between 0 mm and 4 mm. The reason for maximum displacement at the beginning of the pipeline is the leading thrust force and maximum friction and grout injection pressure compared to other parts. When the jacked pipe passes through the hole, the pipe and the head of the excavation machine create friction with the surrounding soil. Under the influence of the frictional cut, the soil is drawn along the pipeline, which majorly moves the soil along the direction of excavation. It can be found from Figure 4 that the closer the pipeline is to the ground surface, the larger the soil layer will make a more extensive move along the pipeline, and the deeper the pipeline, the smaller this movement will be. The maximum displacement will occur around the tunnel face (4.15 mm), which is related to the height of the overburden (2.75 m).

Our research shows that the excavation machine can cause a maximum uplift of approximately 8 m (2.4D), gradually decreasing. Our numerical model supports this finding. As shown in Figure 4, the closer the pipelines are to the ground surface, the more significant the uplift. However, it is essential to note that the surface uplift is minimal and can be disregarded. This was only demonstrated to assess the impact of overburden on surface uplift. Our analysis indicates that an overburden of approximately 6.75 m would result in zero uplift. Therefore, it can be concluded that this is the optimal pipeline depth when only surface uplift is considered.

### 3.2. Effect of diameter on displacement

The results of Figures 5 and 6 indicate that the increase in the diameter causes higher vertical displacement on the ground surface and at the top of the pipeline. Also, the range of longitudinal and transverse subsidence will rise. According to the numerical model, if the pipe diameter increases 2.5 times, the highest vertical displacement ($u_z$) will be increased from 5.01 mm to 8.57 mm (i.e., 71.06%). At the top of the pipeline, it will increase from 6.78 mm to 9.98 mm (i.e.47.2%). Considering the longitudinal curve, it can be stated that the maximum vertical displacement ($u_z$) will occur at the ending part of the shield, whether at the ground surface or at the pipe crown, which is due to the conical shape of the shield and the release of the in-situ stresses. When the diameter of the pipe is more extensive, a wider area around the pipe will be in contact with the soil, increasing the friction and interaction and leading to elevated displacement.

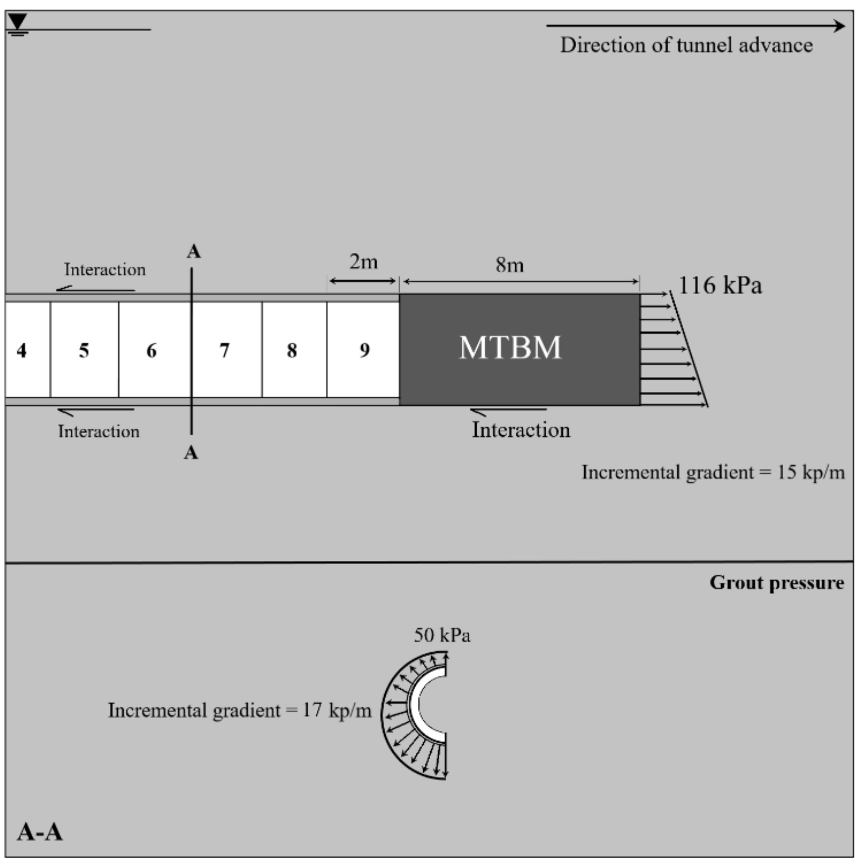
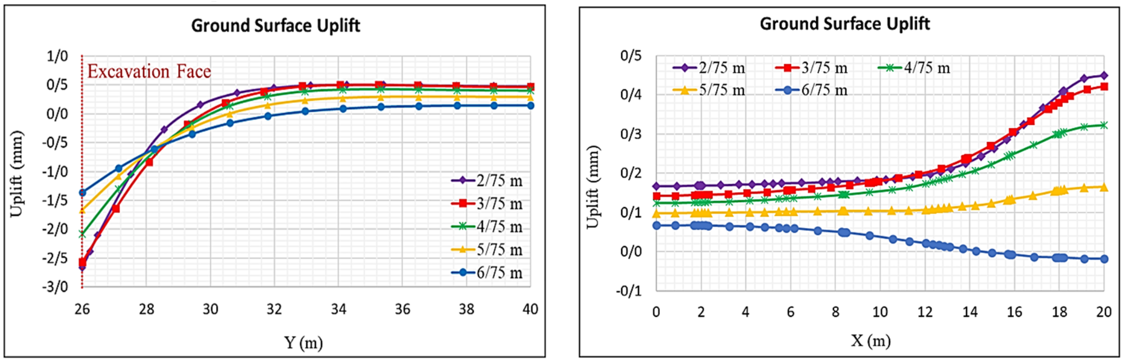
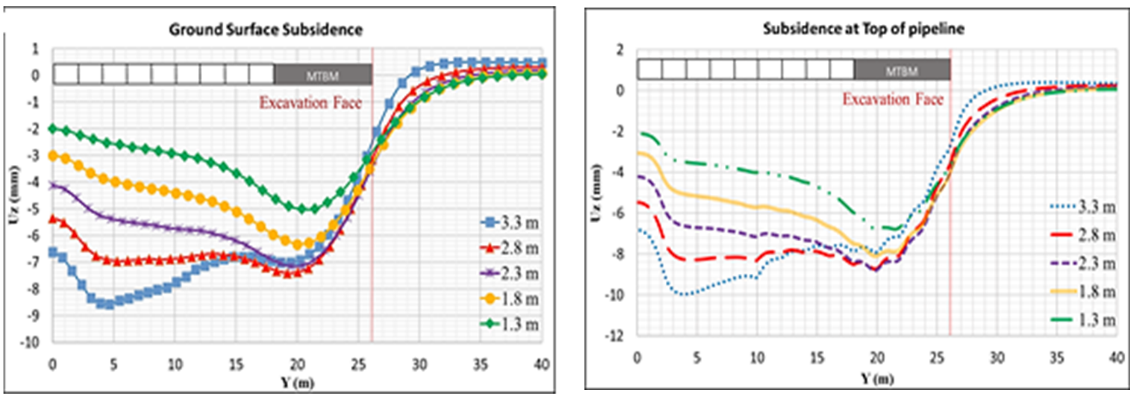



**Figure 3. The details of the numerical model (Face pressure, Grout pressure)**



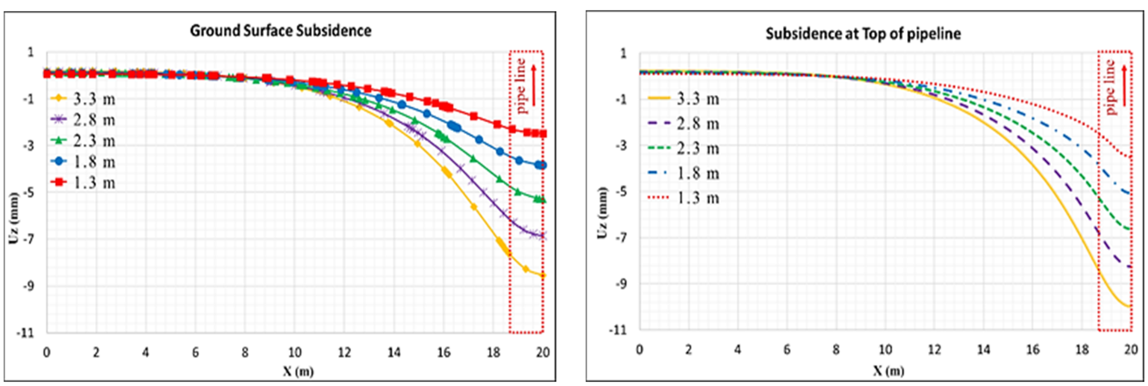

**A. Longitudinal** **B. Traverse (6 m against the Excavation Face)**

**Figure 4. Longitudinal and traverse diagram of ground surface uplift**




**A. Ground Surface** **B. Top of pipeline**

**Figure 5. Vertical deformation (uz) in the longitudinal direction after advancement of the shield by 26 m**




**A. Ground Surface** **B. Top of pipeline**

**Figure 6. Traverse diagram of vertical deformation ($u_z$) at a 4m distance from the pipeline**

According to the observations, as the diameter of the pipe increases, the lateral displacement along the ground surface also increases. This is due to the rise in grout injection pressure and the enhanced friction and interaction between the jacked pipe and the soil, resulting in a higher displacement rate. The most significant displacement of 4.1 mm occurs at the lateral part of the pipeline, specifically in the largest diameter of 3.3 m.

In Figure 7, it is observed that the maximum displacement occurs at the tunnel face. This is due to the combination of the pressure of the excavation face with the thrust force, which is at its maximum on the tunnel face. Additionally, the friction and interaction between the pipes and the surrounding soil assist the soil movement along the jacking direction.

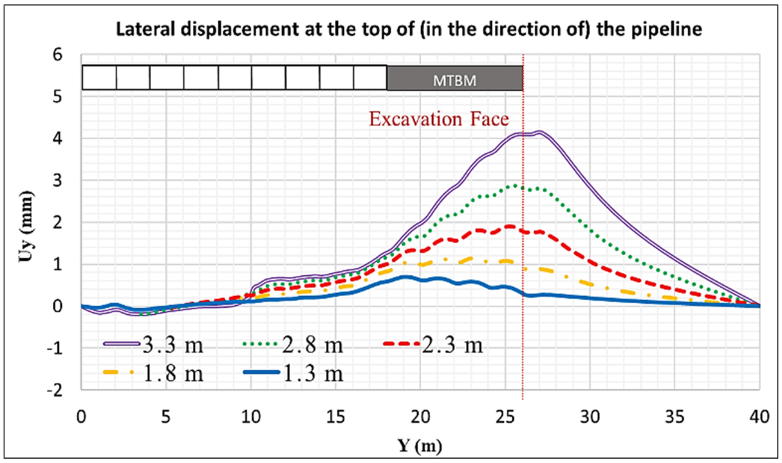
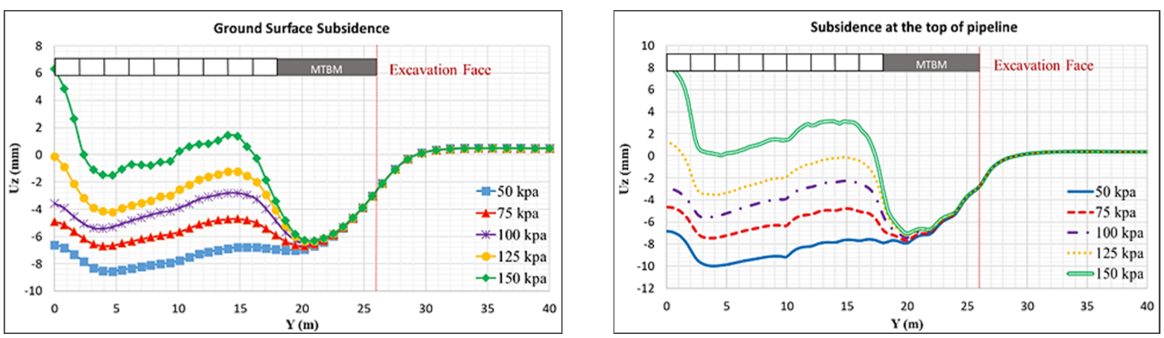



**Figure 7. Longitudinal diagram of lateral deformation ($u_y$) in the 26 m advance of the shield**

The results indicate that with the increase in the pipe diameter, the ground uplift is increased against the excavation face. The parameter with the highest effect on the surface uplift is the excavation face pressure. With the increase in diameter, the excavation face pressure will rise accordingly. Finally, it will lead to an increase in the surface uplift.

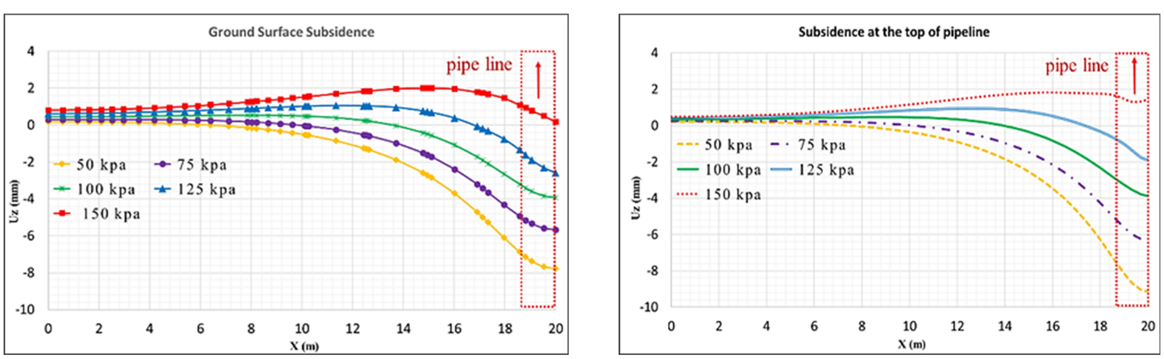
### 3.3. Effect of grout pressure on displacement

The results of Figures 8 and 9 indicate that the subsidence decreases with the increase in the grout injection pressure. In other words, if the injection pressure behind the pipes is very high, it may lead to a surface uplift. In the simulated numerical model, the slurry is injected continuously in the pipe-jacking process, and the changes are pronounced.




**A. Ground Surface** **B. At the top of pipeline**

**Figure 8. Longitudinal diagram of vertical ($u_z$) deformation with the 26 m advance of the shield**




**A. Ground Surface** **B. At the top of pipeline**

**Figure 9. Traverse diagram of vertical ($u_z$) deformation at a 10 m distance from the pipeline**

It can be concluded that the higher the grout injection pressure, the more the surrounding soil will be displaced in the vertical pipeline direction (X-direction). Its effect is also maintained in the horizontal direction, i.e., the displacement will increase along the pipeline. According to Figure 10, it can be concluded that at an injection pressure of 50 kPa, the maximum displacement was 0.86 mm, and with an increase in injection pressure to 150 kPa, the maximum displacement will also increase to 12.68 mm. So, it can be found that if the grout injection pressure rises three times, the lateral displacement (ux) will grow around 15 times.

### 3.4. Effect of excavation face pressure on displacement

The results indicate that increasing the surface uplift against the excavation shield will increase the excavation face pressure. In addition, Figure 11 suggests that the variations in the excavation face pressure will only have minor effects on the vertical deformation of the ground. However, considering the end of the excavation shield, it can be stated that the increase in the excavation face pressure will reduce the subsidence in the ground surface and upper part of the pipeline.

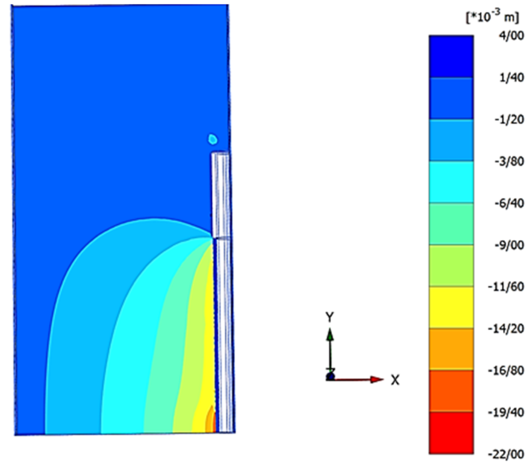
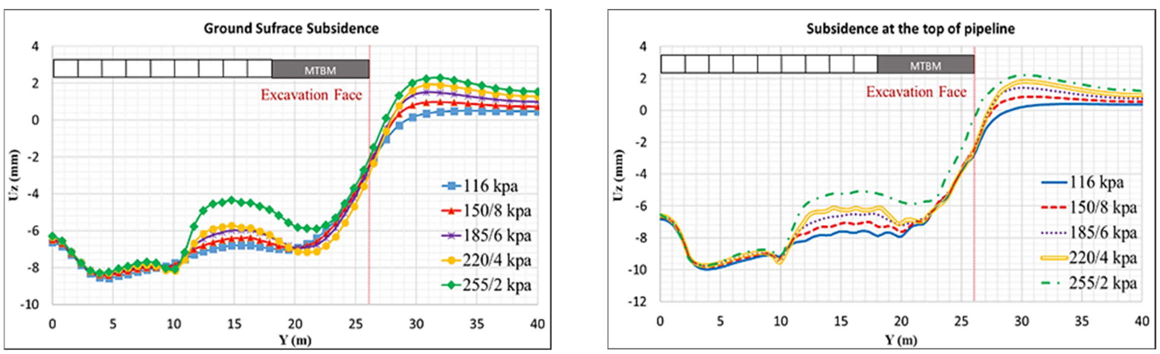



**Figure 10. Longitudinal section of displacement ($u_x$) at a depth of 4.4 m and injection pressure of 150 kPa**




**A. Ground Surface** **B. At the top of pipeline**

**Figure 11. Longitudinal diagram of vertical ($u_z$) deformation with the 26 m advance of the shield**

As shown in Figure 12, in front of the excavation shield, a pressure increase in the tunnel face leads to an increase in lateral displacement. The results show that a 120% increase in the pressure of the excavation face causes a 517% increase in lateral deformation. In other words, the lateral deformation will be 4.3 times higher. An elevation in the excavation face pressure causes soil separation in front of the tunnel face, and the soil will move toward the lateral parts of the pipeline, so the higher the pressure, the greater the displacement.

According to Figure 13, in the front of the shield, where excavation has not been done yet, there will be a surface uplift under the pressure of the excavation face. This will also cause a lateral displacement of soil ($U_x$) escaping from the pipeline. At the back of the shield, where the excavation has been performed and subsidence has occurred, the lateral displacement of the soil ($U_x$)) will appear in the pipeline.

In general, the excavation face pressure causes the soil to move toward the pipeline. Increased pressure on the tunnel face will raise the lateral displacement in front of the tunnel face, eventually increasing ground surface displacement. According to the results, an increase in the excavation face pressure (139.2 kPa) will lead to an increase (351.3%) in the displacement at a distance of 1 m from the tunnel face.

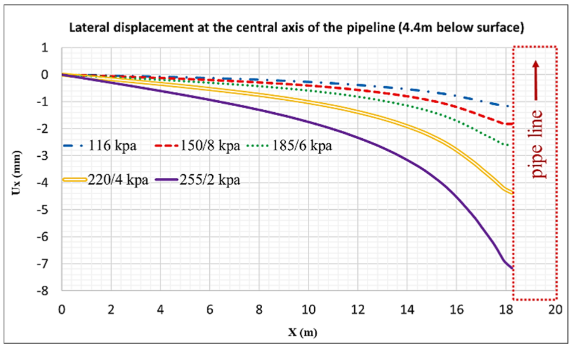



**Figure 12. Traverse diagram of lateral deformation ($U_x$) in the 26 m advance of the shield**

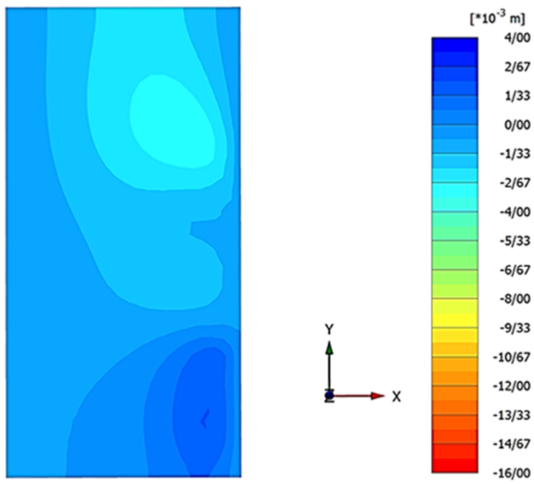



**Figure 13. Lateral displacement contour ($U_x$) in the 26 m advance of the shield and ground surface**

### 3.5. Effect of Elastic modulus on displacement

Investigation of the effect of elastic modulus on the ground deformation pattern showed that an increase in the strength and hardness of the soil would reduce turbulence and vertical deformation. A 20% increase in the elastic modulus reduces the ground subsidence from 8.57 mm to 7.05 mm (17.7%), and at the top of the pipeline, the subsidence rate drops from 9.98 mm to 8.23 mm (17.5%). In other words, the percentage of subsidence reduction at the top of the pipeline and the ground surface is the same due to the 20% change in elastic modulus. With the increase in the elastic modulus of the soil layers, the lateral displacement ($u_x$) decreases. According to the observations, the maximum displacement is around the pipeline, and moving away from it reduces the displacement rate.

An increase in the elastic modulus will increase the hardness of the soil and ultimately reduce the surrounding soil's lateral displacement in the pipeline's advancement direction. As shown in Figure 14, the highest horizontal displacement occurs around the excavation face. This is due to the pressure of the fluid injected into the excavation face, the friction between the shield and the surrounding soil, and the interaction between them. The maximum displacement is due to the 20% elastic modulus reduction (5.15 mm). The lowest displacement is due to the 20% increase in elastic modulus (3.48 mm). In other words, increase in the elastic modulus by 40% reduces the lateral displacement (uy) by 48%.

As expected, like displacement, the ground uplift also works in other directions, i.e., with the increase in the elastic modulus, we will observe a decrease in the uplift. The maximum surface uplift (0.62 mm) occurs in the minimum elastic modulus and at 34.27 m from the pipeline (8.27 m in front of the tunnel face).

### 3.6. Effect of cohesion on displacement

The shear strength in the soil surface depends on the cementation (cohesion) strength of the two layers. Thus, with the increased cohesion, the shear strength and displacement decrease. Considering the longitudinal diagram of the vertical deformation ($u_z$), the maximum displacement is 12.3 mm at the ground surface and 15.43 mm at the top of the pipeline, which is related to the minimum cohesion, 0.01C. So, it can be concluded that a 25% increase in displacement occurs from the top of the pipeline to the ground surface.

As expected, according to Figure 15, cohesion is a strength parameter of the soil, which leads to a decrease in the soil movement along the pipeline. Therefore, it leads to a reduction of lateral displacement.

According to the observations, the maximum lateral displacement at the maximum cohesion value (C) is 4.14 mm, and at the minimum cohesion value (0.01C), it reaches 5.37 mm. It can be concluded that with a 99% increase in cohesion, the lateral displacement decreases by 29.4% (these displacements occur at the tunnel face).

### 3.7. Effect of friction angle on displacement

The internal friction angle (φ) is crucial in analyzing mechanical and strength-related issues. According to the Mohr-Coulomb failure criterion, the soil's shear strength relies on its cohesion and factors such as its friction angle and slipperiness between particles.

The importance of the friction angle (φ) comes into play when the shear strength overcomes soil cohesion (C). According to the Mohr-Coulomb relation, a higher internal friction angle leads to a higher ratio of shear stress (τ) to vertical stress (σ) on the discontinuity surface, resulting in increased displacements and eventual failure along the surface. An increased friction angle leads to smoother slippage between soil particles, resulting in a higher displacement rate. A higher friction angle (above 30°) increases the soil dilation angle (ψ) and volume, leading to increased ground deformation. As shown in Figure 16, an increase in the friction angle results in a rise in the vertical displacement at the ground surface and the top of the pipeline.

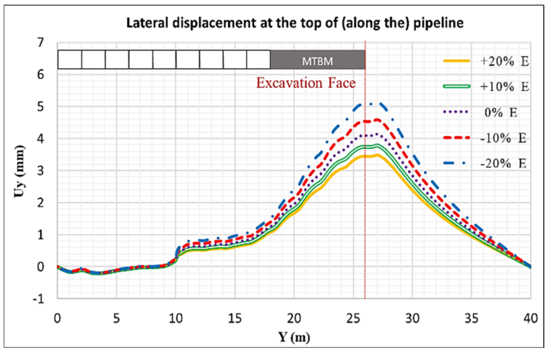


Figure 14. Lateral displacement ($u_y$) in the 26m advancement of the shield

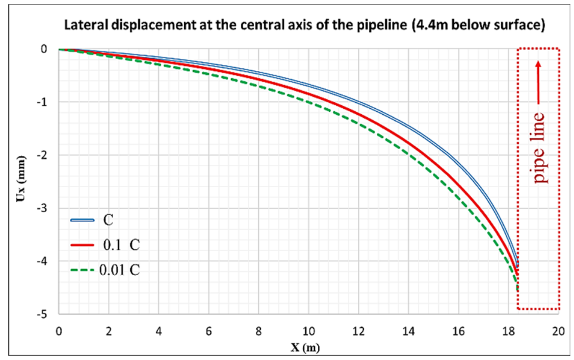
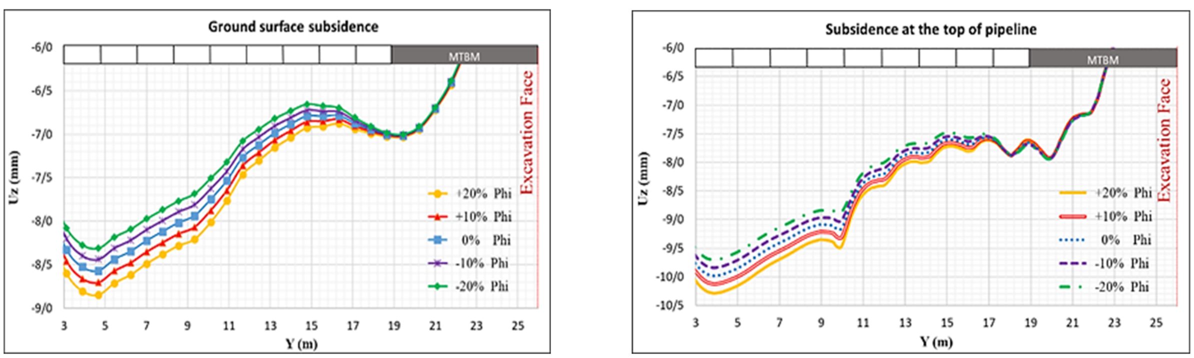


Figure 15. Traverse diagram of lateral deformation ($U_x$) in the 26 m advancement of the shield



A. Ground Surface

B. At the top of pipeline

Figure 16. Longitudinal diagram of vertical ($u_z$) deformation with the 26 m advance of the shield

As anticipated, the rise in the friction angle has resulted in more significant lateral displacement along the pipeline. The findings suggest that displacements increase in three dimensions (X, Y, Z) as the friction angle increases, but the magnitude of change is minimal and less responsive. Notably, it should be acknowledged that the displacements are insignificant, with the maximum displacement (4.23 mm) attributed to a 20% increase in the friction angle. With the increased friction angle of the soil layers, the dilation angle increases, and slipperiness between soil particles increases, eventually leading to higher displacements. The uplift before the excavation shield will increase at the top of the pipeline and the ground surface. Finally, the general conclusion is that increasing the friction angle will increase the displacements in three dimensions.

### 3.8. Relationship of parameters

The relationship of each studied parameter with the ground subsidence is summarized in Table 1.

**Table 1. Relationship of each parameter with ground subsidence**

| | |
|---|---|
| **Over Burden(m)** | **U=0.0483 $O^3$-0.803 $O^2$+4.5689 O-14.807** |
| **Diameter (mm)** | U=-0.9147$d^3$+6.5632 $d^2$-16.54 d+7.4327 |
| **Grout Pressure (kPa)** | U=8× $10^{-6}$ $G^3$-0.0029 $G^2$+0.3367 G-19.114 |
| **Face Pressure (kPa)** | U=-2× $10^{-5}$ × $P^2$+0.0088 P-9.3396 |
| **Elastic Modulus(MPa)** | U=0.0724 E-8.582 |
| **Cohesion (kPa)** | U=0.2367 Ln(C)-7.6371 |
| **Friction Angle(°)** | U=-0.0843 ϕ-7.234 |

Based on the findings, there is a clear linear relationship between the friction angle and ground settlement subsidence and a linear yet indirect relationship between the elastic modulus and subsidence. Additionally, other parameters were determined to have non-linear relationships. In a study of the combined impact of diameter and elastic modulus on subsidence, the results indicate that increasing the elastic modulus decreases subsidence, while increasing the diameter increases subsidence. As demonstrated in Figure 17, the maximum subsidence at the ground surface (10.05 mm) is linked to the maximum diameter (3.3 m) and changes in the elastic modulus (-20%). Conversely, the minimum subsidence (4.19 mm) is associated with the minimum diameter (1.3 m) and changes in the elastic modulus (+ 20%). Therefore, it can be concluded that reducing the diameter by 154% and increasing the elastic modulus by 40% results in a 140% decrease (i.e., 2.4 times) in ground subsidence.

As expected, due to the proximity to the pipeline, the subsidence at the pipe crown is more significant than the ground surface. The maximum subsidence in the pipe crown (11.66 mm) is related to the maximum diameter (3.3 m) and changes in the elastic modulus (-20%). The minimum subsidence (5.69 mm) is associated with the minimum diameter (1.3 m) and changes in the elastic modulus (+ 20%). Therefore, it can be said that with a 154% decrease in diameter and a 40% increase in elastic modulus, the ground subsidence decreases by 105% (i.e., two times).

As shown in Figure 18, the change in ground surface subsidence is more significant than the pipe crown under the influence of equal changes in two parameters (diameter and elastic modulus). As a result, it can be stated that the ground surface is more sensitive than the pipe crown to changes in these two parameters.

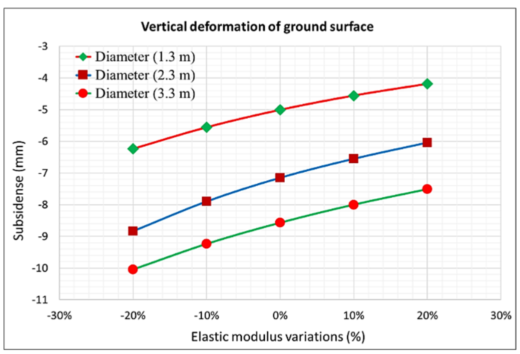



**Figure 17. Simultaneous effect of diameter and Elastic modulus on ground subsidence**

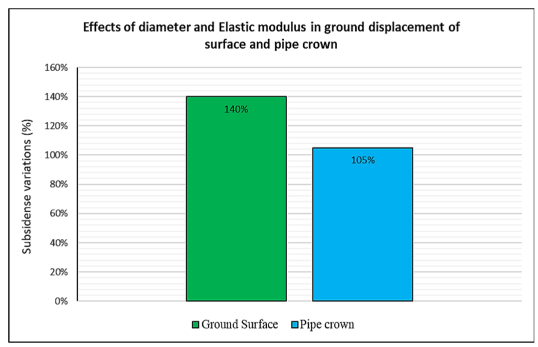



**Figure 18. Effect of diameter - elastic modulus on the percentage of displacement changes in the ground surface and the pipe crown**

The sensitivity index of each parameter indicates its importance and impact on the deformation of the ground surface. Parameters whose sensitivity index is more extensive than other variables (regardless of positive or negative sign) are more sensitive and essential and should be used more accurately in preliminary studies. The sensitivity index of the parameters examined is given in Figure 19.

According to the observations, the order of sensitivity and importance of the studied parameters will be as follows:

$$D > G > E > O > \varphi > C > P$$

The results indicate that, compared to other variables, the diameter is most sensitive, and the excavation face pressure is less sensitive to ground surface subsidence. So, more caution should be taken in the initial studies.

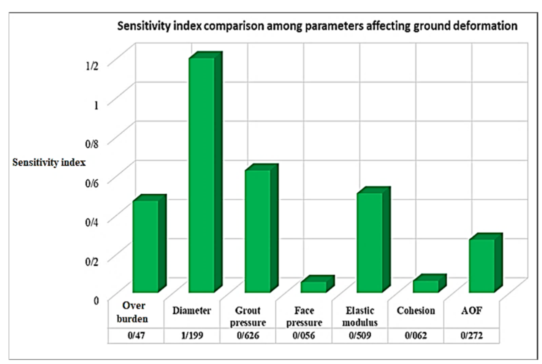



**Figure 19. Sensitivity of the parameters affecting the ground deformation**

## 4. Conclusions

Considering ground deformation during pipe jacking in soft soil as an engineering field, this study investigated the effect of pipe jacking on ground displacement using numerical simulation. It focused on factors influencing ground deformation in three dimensions: excavation face pressure, grout pressure, diameter, overburden, cohesion, friction angle, and elastic modulus.

This study investigated the ground deformation pattern using the finite element numerical simulation and the PLAXIS 3D software. Finally, the effect of each factor was measured using the sensitivity analysis, and the sensitivity index of each parameter was determined – from the most sensitive to the least sensitive factor to the ground deformation. In this study, the values of the modeling, precisely the conical shape of the excavation shield, grout injection pressure efficiency, and excavation face pressure, were considered to be close to real-world values. Also, the displacement was analyzed in three dimensions: at the ground surface,and pipe crown.

The results of this study are as follows:

The results indicate that, compared to other variables, the diameter is the most sensitive, and the excavation face pressure is the most minorly sensitive to ground surface subsidence. So, more caution should be accounted for in initial studies. Of course, it should be noted that the pressure of the excavation face also has the most excellent effect on the ground surface uplift in front of the tunnel face.

An increase in the excavation face pressure leads to increased lateral displacement (along the pipeline) in front of the tunnel face, ultimately leading to increased displacement in the ground surface. According to the results, the increase (139.2 kPa) of the pressure of the excavation face is followed by an increase (351.3%) in the displacement at a distance of 1 meter from the tunnel face.

The soil before the excavation face is mainly subjected to a positive thrust force. Therefore, a specific uplift will occur. The maximum uplift occurs at about 8 m in front of the excavation face and then gradually decreases.

Theoretical calculations, measurements, and numerical simulations all estimate the onset of subsidence in an area of approximately 1D in front of the excavation face, after which the subsidence rate increases rapidly. The subsidence rate directly below the excavation face includes the ultimate subsidence values of 39%, 49%, and 56%, respectively. In general, with the passage of the excavation machine, the excavated face tends to be stable.

There is a linear relationship between the friction angle and the subsidence. That is, with the increase in the angle of friction, the subsidence increases linearly ($U=-0.0843\ \phi-7.234$). The relationship between the elastic modulus and subsidence is linear; with an increase in the elastic modulus, the subsidence rate decreases linearly ($U=0.0724\ E-8.582$).

A decrease in the cohesion of soil layers leads to an increase in subsidence, and if this decrease is in the range of 90% of the initial value, subsidence will increase significantly. It should be noted that the sensitivity of the soil layer through which the pipeline passes (1-Silty Clay) is -0.062 and has the highest value compared to other layers. Therefore, this layer is more critical than cohesion changes.

Under the influence of equal changes in two parameters (diameter and elastic modulus), the change in ground surface subsidence is more significant than that in the pipe crown. As a result, the ground surface is more sensitive than the pipe crown to changes in these two parameters.

The results indicate that most subsidence occurs at the end of the excavation shield. This is because of the shield's conical shape and the stress release.

## Funding

No funding was received to carry out the present research work.

## References

[1]. Niu, Z., Cheng, Y., Zhang, Y., Song, Z., Yang, G., & Li, H. (2020). A new method for predicting ground settlement induced by pipe jacking construction. *Mathematical Problems in Engineering*, *2020*(1), 1681347.

[2]. Dziuban, B., Ling, H. I., & Li, L. (2018). Failure mechanisms of shallow tunnel in sandy ground. *Transportation Infrastructure Geotechnology*, *5*, 318-331.3. Tsitsas, G., Kolev, C., Radoi, L., & Petrila, V. (2017, April). Technical and Contractual Trends for Micro Tunneling Projects in Romania and Bulgaria. In *Advanced Engineering Forum* (Vol. 21, pp. 609-618). Trans Tech Publications Ltd.

[3]. Royal, A. C. D., Hunt, D. V. L., Rogers, C. D. F., & Chapman, D. N. (2010). Numerical simulation of the creation and performance of extruded concrete linings in microtunnelling. *Tunnelling and underground space technology*, *25*(6), 745-753.

[4]. Boonsiri, I., & Takemura, J. (2015). Observation of ground movement with existing pile groups due to tunneling in sand using centrifuge modelling. *Geotechnical and Geological Engineering*, *33*, 621-640.

[5]. Jia, P., Zhao, W., Khoshghalb, A., Ni, P., Jiang, B., Chen, Y., & Li, S. (2020). A new model to predict ground surface settlement induced by jacked pipes with

flanges. *Tunnelling and Underground Space Technology*, *98*, 103330.7. Zhou, S., Wang, Y., & Huang, X. (2009). Experimental study on the effect of injecting slurry inside a jacking pipe tunnel in silt stratum. *Tunnelling and Underground Space Technology*, *24*(4), 466-471.8. Yu, F., Sun, D., Sun, G., Ling, S., Hu, M., & Ma, J. (2021). A modified mix design method for pervious concrete based on Mohr-Coulomb failure criterion. *Construction and Building Materials*, *269*, 121801.

[6]. Shimada, H., Khazaei, S., & Matsui, K. (2004). Small diameter tunnel excavation method using slurry pipe-jacking. *Geotechnical & Geological Engineering*, *22*, 161-186.10. Barbera, L., Iseley, D. T., & Tanwani, R. (1993). Historical Development of Trenchless Construction Methods and Equipment in the United States. In *Proceedings of Trenchless Technology Advanced Technical Seminar, Trenchless Technology Center, Vicksburg, MS*.

[7]. Thomson, J. (1993). *Pipejacking & Microtunnelling*. CRC Press.12. Tyrer, J., Paraskevopoulou, C., Shah, R., Miller, R., & Kavvadas, M. (2023). Tunnelling with Full-Face Shielded Machines: A 3D Numerical Analysis of an Earth Pressure Balance (EPB) Excavation Sequence Using the Finite Element Method (FEM). *Geosciences*, *13*(8), 244.

[8]. Liu, W. T., & Lu, X. Y. (2012). 3D Numerical Analysis of Soil Structure Interaction Behaviors of Pipe Jacking Construction. *Applied mechanics and materials*, 204, 534-538.

[9]. Orumchi, H., & Mojallal, M. (2017). Shear strength design of a mechanized tunneling grout mix: case study of the Tehran Subway Line 6 Project. *Transportation Infrastructure Geotechnology*, *4*, 18-36.

[10]. Al-Maamori, H. M. S., El Naggar, M. H., & Micic, S. (2018). Numerical modeling of time-dependent deformation and induced stresses in concrete pipes constructed in Queenston shale using micro-tunneling technique. *Journal of Rock Mechanics and Geotechnical Engineering*, *10*(2), 290-309.

[11]. Han, X., Li, W., Chen, T., & Liu, W. (2019). Sensitivity analysis of ground settlement induced by pipe-jacking construction in soft soil stratum. In *E3S Web of Conferences* (Vol. 136, p. 04028). EDP Sciences.

[12]. Zhang, K., Chavez Torres, J. L., & Zang, Z. (2019). Numerical analysis of pipelines settlement induced by tunneling. *Advances in Civil Engineering*, *2019*(1), 4761904.18. Ma, W., Wang, B., Wang, X., Zhou, S., & Wang, B. (2021). Soil layer disturbance caused by pipe jacking: measurement and simulation of a case study. *KSCE Journal of Civil Engineering*, 25, 1467-1478.

[13]. Rahjoo, S., Najafi, M., Williammee, R., & Khankarli, G. (2012). Comparison of jacking load models for trenchless pipe jacking. In *Pipelines 2012: Innovations in Design, Construction, Operations, and Maintenance, Doing More with Less* (pp. 1507-1520).

[14]. Zhen, L., Chen, J. J., Qiao, P., & Wang, J. H. (2014). Analysis and remedial treatment of a steel pipe-jacking accident in complex underground environment. *Engineering structures*, *59*, 210-219.

[15]. Tang, J., Xu, J., Zhou, D., Huang, D., Zeng, K., Li, Y., & Chen, Z. (2023). Ground surface deformation caused by pipe jacking construction in a soft soil area: An experiment-based study. *Buildings*, *13*(7), 1628.

[16]. Li, F., Fang, K., & Li, H. (2007). Application of ANSYS 3D FEM in studies of surface deformation caused by pipe jacking. *Wuhan University Journal of Natural Sciences*, *12*(4), 633-637.23. Cui, G. J., Xie, J. S., Sun, Y. H., & Gao, Y. J. (2023). Analysis and Prediction of the Factors Influencing Postconstruction Surface Deformation of Pipe-Jacking Tunnel in Soft Clay Strata in China. *Advances in Civil Engineering*, *2023*(1), 6474415..

[17]. Sterling, R. L. (2020). Developments and research directions in pipe jacking and microtunneling. *Underground Space*, *5*(1), 1-19.

[18]. Kramera, S., Liub, J., & Provencioc, G. (2018). Advantages and Disadvantages of Trenchless Construction Approach as Compared to the Traditional Open Cut Installation of Underground Utility Systems. In *Creative Construction Conference 2018* (pp. 129-138).

# تاثیر لوله رانی بر تغییر شکل زمین

**احسان طاهری*، رضا محمدپور و محمدحسین مختارزاده**

**دانشکده فنی، دانشگاه تربیت مدرس، تهران، ایران**

ارسال ۲۰۲۴/۰۵/۰۹، پذیرش ۲۰۲۴/۰۷/۲۸

* نویسنده مسئول مکاتبات: e_taheri@modares.ac.ir

**چکیده:**

در سال‌های اخیر، تقاضا برای روش‌های جدید بدون ترانشه به شدت افزایش یافته است. لوله رانی یک روش بدون ترانشه است که در سال‌های اخیر بسیار مورد استفاده قرار گرفته است. تغییر شکل زمین از اساسی ترین پارامترهایی است که ممکن است منجربه آسیب‌های غیر قابل جبران به تأسیسات و حتی افراد شود. بنابراین پیش‌بینی تغییر شکل زمین ناشی از عملیات لوله‌رانی برای اهداف ایمنی و برنامه‌ریزی امری لازم و ضروری است. هدف مطالعه حاضر تحلیل عوامل مؤثر بر تغییر شکل زمین در طول عملیات لوله رانی است. این مطالعه بصورت توصیفی - مداخله‌ای می باشد. تکنیک لوله‌رانی منجربه جابجایی خاک در سه بعد می‌شود لذا از روش عددی سه بعدی جهت تجزیه و تحلیل استفاده شد. در این مطالعه شبیه سازی عددی با استفاده از نرم‌افزار عددی المان محدود پلکسیس و با در نظر گرفتن مطالعه موردی انجام گرفت. تأثیر هر یک از پارامترها در الگوی تغییر شکل زمین در سه راستا و نیز تخمین میزان برآمدگی‌ها و محل دقیق آن‌ها مورد بررسی قرار گرفت. لازم به ذکر است تجزیه و تحلیل جابجایی‌ها در دو قسمت تاج خط لوله و سطح زمین انجام شد. در گام بعد رابطه هر یک از پارامترها با نشست سطح زمین برآورد شد و درنهایت تأثیر هر یک از عوامل مختلف با استفاده از آنالیز حساسیت سنجیده شد و شاخص حساسیت هرکدام مشخص گردید. نتایج نشان می‌دهد که بیشترین نشست در قسمت انتهایی سپر حفاری به دلیل اجازه ترخیص تنش اتفاق می‌افتد. رابطه بین زاویه اصطکاک داخلی و نشست سطح زمین به‌صورت خطی و مستقیم بوده و رابطه بین مدول کشسان و نشست نیز به‌صورت خطی اما غیرمستقیم می‌باشد. حساس‌ترین عامل نسبت به نشست سطح زمین قطر فضای حفاری و کم‌اهمیت‌ترین عامل فشار صفحه حفاری است.

**کلمات کلیدی:** روش‌های بدون ترانشه، لوله رانی، مدلسازی عددی، تغییر شکل زمین، تحلیل حساسیت.