

Research Article

Safety Risk Analysis and Protective Control of Existing Pipelines Affected by Deep Pit Excavation in Metro Construction

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Urban underground pipelines undertake many tasks closely related to people's daily life and production, such as water supply, drainage, gas supply, and power supply. Metro projects are usually located in areas with dense underground pipelines; therefore, in the construction process of deep-foundation metro pit, some measures should be taken to protect the safety of underground pipelines. Under the engineering background of the Jiangbei foundation pit of the Wuhan Yangtze River Tunnel, the influence of soil disturbance caused by deep-foundation pit excavation is first simulated using the ABAQUS software on the displacement of underground pipelines and the dangerous area of underground pipelines is analyzed. Second, the most disadvantageous combination is analyzed for the risk factors of pipelines under the influences of multiple risk factors. Finally, a systematic additional partial reinforcement scheme (APRS) is proposed from the aspects of safety and economy to protect the safety of underground pipelines in the dangerous areas with greater risk. The results of measurement prove that the APRS is effective for pipeline protection and can provide reference for similar problems.

1. Introduction

In order to alleviate the increasing urban traffic volumes, underground space presents a viable solution for rapid development of China's metropolitan areas in the past 10 years. For metro engineering usually constructed in buildings and lifeline engineering (e.g., pipelines and conduit) intensive areas, and therefore, soil disturbances (e.g., lateral deformation and settlement of soil adjacent to the pit retaining its structure, bottom soil uplift) occur, leading to adverse impacts on underground pipelines around the pit. Excavation-induced ground movements cause pipeline deformation that may disrupt the conveyance of important services and resources (e.g., water, gas, electric power, and telecommunications) and threaten the safety and security of urban inhabitants (e.g., flooding and leakage of combustible gas from ruptured or leaking mains). Therefore, the study on the influence of deep pit excavation to the adjacent pipeline is a meaningful issue in geotechnical environment engineering.

Scholars at home and abroad have studied the influence of deep-foundation pit excavation on the adjacent underground pipelines mainly in two stages: in the first stage,

most scholars focused on the disturbing effect of deep-foundation pit excavation on the surrounding soil. For example, Peck [1] initiated a number of similar semi-empirical studies on deformation associated with deep excavations conducted by many researchers (Burland et al. [2]; Mana and Clough [3]; Clough and O'Rourke [4]; Ou et al. [5]; Wong and Patron [6]; Carder [7]; Fernie and Suckling [8]; Wong et al. [9]; Hsieh and Ou [10]; Long [11]; Yoo [12]; Moormann [13]; Leung and Ng [14]; and Wang et al. [15]) in the following more than 30 years. In recent years, Liu et al. [16] explored the different excavation approaches and their influences on the ground environment by means of numerical analysis. Tan and Wei [17] examined the performance of an over excavated metro station in soft clay within the Shanghai metropolitan area. Bryson and Zapata-Medina [18] presented a semiempirical design methodology that facilitates the selecting of the excavation support system stiffness in such a way that limits excavation-related ground movement. Wu et al. [19] quantified the effect of cross walls: 22 case histories, including 11 excavations with cross walls and 11 excavations without cross walls that are collected in the study and found

that cross walls can effectively reduce ground settlements by minimizing wall displacements.

In the second stage, based on the study of the disturbing effect of deep-foundation pit excavation on the surrounding soil, and the interactions were analyzed between underground pipelines and the disturbed surrounding soil (e.g., Rajani and Tesfamariam [20]; Guo and Stolle [21]; Hawlader et al. [22]; Roboski and Finno [23]; Cocchetti et al. [24, 25]; and Daiyan et al. [26]). A number of experimental (e.g., Hsu et al. [27]), theoretical (e.g., Cocchetti et al. [24, 25]), and numerical (e.g., Phillips et al. [28]) studies have been conducted to investigate the pipe-soil interaction during an oblique or three-dimensional pipe-soil relative movement. Several research studies (e.g., Iimura [29]; Marshall et al. [30]; Wang et al. [31]; Yu et al. [32]; Shi et al. [33]) have been developed for evaluating the safety in pipelines caused by ground movements. For example, Kim et al. [34] reported a study aimed at developing rapid, reliable, and cost-effective sensing systems for health monitoring and damage detection for buried concrete pipelines subjected to ground deformation. O'Rourke [35] explored key aspects of underground pipeline network response to the Canterbury earthquake sequence in Christchurch, New Zealand. Glisic and Yao [36] presented the development of a method for buried pipelines health assessment based on distributed fiber optic sensors. Chen et al. [37] investigated failure pressure of high strength pipeline with single and multiple corrosion using nonlinear finite-element analysis. Wang and Duan [38] investigated the influence of the excavation of foundation pit on the working behaviour of buried pipelines and to provide general references for safety assessment and protection of pipelines. The numerical analyses with a number of advanced features, such as pipe-backfill interface elements, large strain formulation, and mesh rezoning, has been investigated for the evaluation of soil pressures on laterally displaced pipelines by Chaloulos et al. [39]. The pipe was simulated using 3D shell elements while the saturated sand soil medium was simulated by employing discrete nonlinear springs along the pipeline [40]. Zhang et al. [41] presented a simplified displacement-controlled two-stage method and stress-controlled two-stage method to determine the deformation behaviour of pipeline structures caused by underground excavation in soil clays, aiming at explicitly pointing out the mechanism of construction interaction and rapidly predicting the mechanical behaviour of structures. Zhang et al. [42] constructed a three-dimensional model of pipeline and foundation pit to investigate the variation of pipeline deformation under the excavation of foundation pit and studied the effect of foundation pit excavation on the buried pipeline.

In fact, deep pit excavation has a great influence on the adjacent pipeline, and there are numbers of studies concerned about the interaction mechanism between the pipeline and soil (e.g., Dutta et al. [43], He et al. [44], Balkaya et al. [45], and Mahdavi et al. [46]), but there is a lack of study putting forward a systematic, economic, and effective reinforcement scheme to protect pipeline. Two aspects of the effect need to be evaluated for the pipeline reinforcement scheme: one, if there are no adequate measures to protect pipelines, accidents

may occur, which threaten the safety of project; two, if there are too many protective measures, it will result in the project cost escalations, which is adverse to the economy of project. The existing researches on this aspect are quite fragmentary and lack of systematic analysis on pipeline risk. In order to solve this problem, this paper systematically studies the most disadvantageous combination of factors affecting pipeline safety in the construction of deep-foundation pit. A systematic additional reinforcement scheme (APRS) is proposed to protect the safety of underground pipelines. The additional reinforcement scheme includes the following four characteristics: (1) systematicness: a systematic consideration on pipeline safety has been taken in this scheme under the impact of multiple factors combination; (2) pertinence: based on initial pit reinforcement, this scheme is an additional reinforcement that focused on the dangerous areas to pipeline safety; (3) comprehensive: this scheme is a comprehensive measure by synthesizing the usual reinforcement measures in construction; and (4) economy: by considering the reinforced effects and the economical of different reinforcement measures, this scheme chooses a reinforcement measure combination on the purpose of reducing the economic costs.

This paper is based on Jiangbei Pit of Wuhan Yangtze River Tunnel (JPWYRT) and analyses the existing pipeline risk induced by deep pit excavation of metro construction as follows: First, a finite-element model is constructed in this paper to analyze the dangerous areas where underground pipelines are exposed to hazards caused by the disturbed soil surrounding the foundation pit. Second, from the point of view of pipeline safety risk analysis, under the combined influence of multiple risk factors, the most disadvantageous combination of factors is obtained affecting the safety of underground pipelines. Finally, from the point of view of pipeline safety risk control, the reinforcement effect and economy of different reinforcement measures are comprehensively considered, and a set of systematic and practical additional reinforcement measures (APRS) are proposed to protect underground pipelines. The validity of the proposed scheme is verified through field measurement.

2. Modeling and Analysis of the Influence of the Soil Disturbed during Foundation Pit Construction on Underground Pipelines

2.1. Soil Disturbance and Pipe-Soil Interaction Theory.

Two phases are carried out to describe the excavation-induced mechanism of the pipeline as follows: one phase is soil movements process caused by excavation which are adjacent to the pit as shown in Figure 1; the other phase is similar to the Winkle-based methods as shown in Figure 2: the excavation-induced soil displacements are imposed on the pipe-soil interaction elements as distributed displacement boundary conditions. The additional pipeline stress and displacement caused by the soil movements are hazards to pipeline safety.

The movement regularity of soil adjacent to underground continuous wall (UCW) can be expressed as follows (Hsieh and Ou [10]):

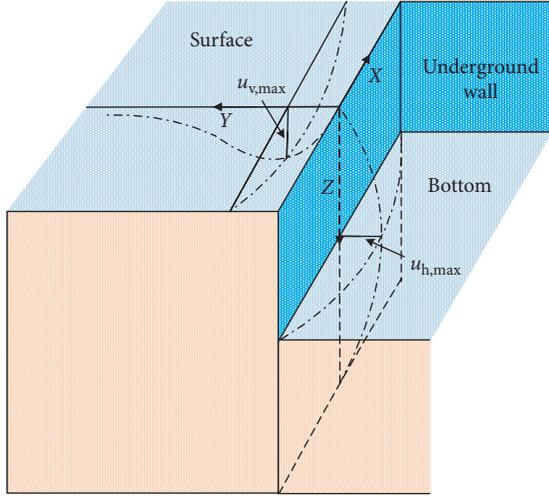


FIGURE 1: Soil movements adjacent to pit caused by excavation.

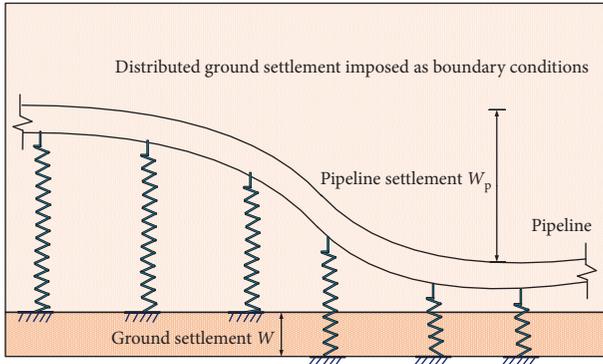


FIGURE 2: Finite-element analysis of pipeline responses to excavation-induced ground movement.

$$u_v(x, 0, 0) = \begin{cases} u_{v,\max}(x/H + 0.5), & 0 \leq x \leq 0.5H, \\ u_{v,\max}(-0.6x/H + 1.3), & 0.5H \leq x \leq 2H, \\ u_{v,\max}(-0.05x/H + 0.2), & 2H \leq x \leq 4H, \end{cases} \quad (1)$$

where $u_{v,\max}$ is the maximum settlement and H is the depth of pit. From this equation, the largest settlement appeared in $0.5H$ place, ground settlement out of $4H$ is approximate zero.

The behaviour of pipeline displacement subjected to the constraining force of the ground is generally represented by Winkler's beam on an elastic foundation, as follows:

$$\frac{d^4 W_p}{dx^4} + 4\lambda^4 W_p = \frac{q}{E_p I_p}, \quad (2)$$

$$\lambda = \sqrt[4]{\frac{K}{4E_p I_p}},$$

where W_p represents the vertical displacement at point X , $E_p I_p$ is the flexural stiffness of the pipeline, and q is the distributed load applied to the pipeline. $q = KW_p - KW$, W represents the

vertical displacement on pipeline, q is determined from the product of the ground spring coefficient λ .

2.2. Safety Risk Analysis of Pipeline. Due to soil unloading, the excavation leads to the movement of the bracing and underground continuous wall system (BUCWS), which led to the underground pipeline displacement adjacent to the UCW. Wang et al. [47] show that the pipeline failure is caused by differential ground movement associated with adjacent excavation, and the patterns of pipeline failure include transverse fractures caused by longitudinal bending moment and joint leakage of flexible pipes. In general, the pipeline damage is mainly in the following two modes: (1) Pipeline damage by overlarge stress. On the effect of additional stress and strain, the pipeline (usually the flexible pipeline) will be deformed, which may cause the pipeline yield, cracks, and damage. (2) Pipeline joint damage caused by overlarge deformation. Pipeline joint overlarge deformation and damage commonly appear in rigid pipelines under the excessive stress. Therefore, it is necessary to take measures to reduce the stress and displacement of pipelines.

The FE analysis is carried out in this work to investigate the excavation-induced ground movement effects on pipelines, using the software ABAQUS. In the FE analysis, the dangerous area which endangers pipeline safety in soil is simulated explicitly.

2.3. Finite-Element Model. Soil property around the Jiangbei pit is very complex, and the workplace of pit construction is very narrow. Under these conditions, UCW and struts were used as a BUCWS in this project. Figure 3 shows a schematic view of UCW trenching and concrete struts setting in the field.

The Jiangbei pit width is 29.3 m and the length is 43.6 m, and it has an excavated depth of 21.8 m. The UCW has a thickness of 0.8 m and depth of 37.5 m. Based on the previous experience, the width of zone impacted by excavation is about 3 to 4 times of the excavated depth, and the depth of the zone is about 3 to 4 times of excavated depth; therefore, the size of the model is $175.6 \times 162.9 \times 66$ m. The simplified model of pit and the origin of coordinates are shown in Figures 4 and 5, and the summary of soil parameters is shown in Table 1.

The Jiangbei pit is taken as the background of the FE model, and according to the symmetry, a 1/2 pit is used in the three-dimensional FE model. An 8-node linear brick is used in soil and UCW element, beam elements are used in struts element, and shell elements are used in pipeline element. Displacement boundary conditions for the model are as follows: YZ plane X-direction displacement is constrained, Y, Z direction displacement are free, XZ plane Y-direction displacement is constrained, X, Z direction displacement are free, and bottom plane of model X and Y direction are constrained.

2.4. Soil Movement Analysis and Its Validation. By the FE result, soil and UCW movements around the pit are shown in Figures 6 and 7. From the results shown in Figure 6, the



FIGURE 3: A schematic view of Jiangbei pit. (a) Diaphragm wall trenching. (b) Concrete struts setting.

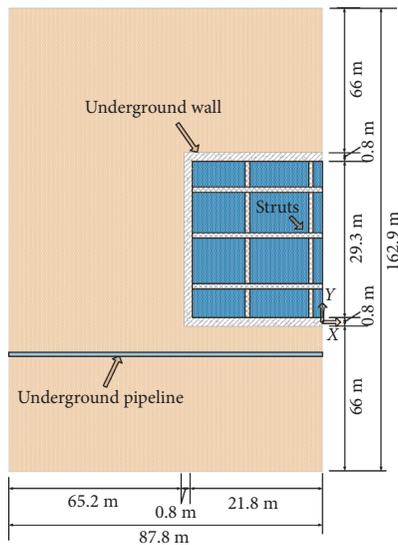


FIGURE 4: The cross-sectional X-Y simplified model view of the pit.

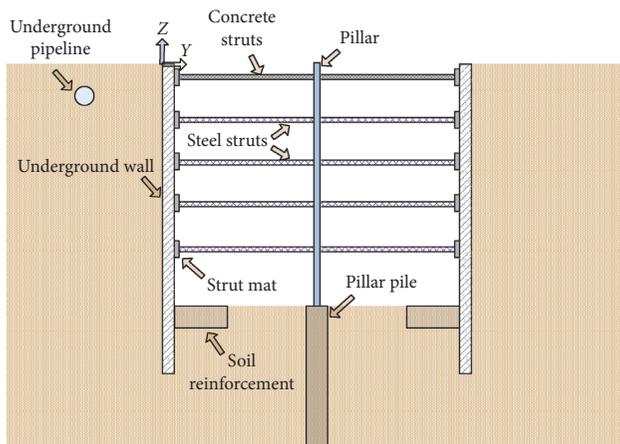


FIGURE 5: The cross-sectional Y-Z simplified model view of the pit.

stress in whole soil mass is quite tiny, while soil stress around the central section of the pit is larger; besides, due to the inhibiting effect by UCW, the stress around the corner of UCW is a bit larger. In Figure 7, we can find that the maximum displacements on UCW are areas around the central section of pit. Therefore, the pipelines on areas

around the central section of pit and at the corner of UCW are more dangerous than other areas.

The accuracy of FE model is verified by comparing the ground surface settlement in this paper with the statistical and theoretical results of Clough [4], Ou [5], Kung [48], and Wang [15]. The statistical and theoretical results were obtained by database of 300 case histories of wall displacements and ground settlements due to deep excavations in soft soils, which is similar to the condition in this project. Hence, these ground surface settlements are synthesized and normalized by the maximum settlement ($\delta_v/\delta_{v,max}$) replotted against d/H in Figure 8.

The FE result derived in this paper is quite close to the other results, suggesting that the FE model be accurate. In Figure 8, δ_v and $\delta_{v,max}$ are the subsidence levels at the measurement point and the maximum subsidence level, respectively; d is the distance from the pipeline to pit; and H is the pit excavation depth. In Figure 8, $\delta_v/\delta_{v,max} = 0.5$ when $d/H = 0$, and $\delta_v/\delta_{v,max} = 1$ is the maximum value when $d/H = 0.7$.

3. Analysis of the Most Disadvantageous Combination of Factors Affecting Underground Pipeline Safety

In the deep pit excavation, there are numbers of factors that affect the safety of the pipeline, such as the excavation process, the pipeline location, soil property, parameters of BUCWS, etc [49]. This paper particularly analyses eight major factors that affect pipeline safety and carries out the most adverse factors combination by the FE analysis.

3.1. Effect of Excavating Process. In order to simulate the pipeline displacement under impact of the pit excavation, the excavating process was divided into six steps, the excavating depths of step 1 to step 6 are 3.5 m, 3.5 m, 3.5 m, 4 m, 4 m, 3.3 m, respectively. Figure 9(a) shows the pipeline displacement regularity in the case of pipeline burial depth $h = 1.5$ m, distance out of the pit $L = 6.8$ m, the outer diameter of the pipeline is 0.4 m, pipeline thickness 1 cm. Because the pipeline is shallow buried, the pipeline displacement is significantly affected from the first two steps (excavated depth range from 0 to 7 m) of the excavating process, the trend of curve shows that the largest horizontal

TABLE 1: Summary of soil parameters.

Soil property	Saturated density r_{sat} (kN/m ³)	Compression modulus E_s (MPa)	Friction angle Φ (°)	Cohesion C (kPa)	Averages of soil thickness
Miscellaneous fill	18.94	4.08	11.5	31	1.75
Silty clay 1	18.88	5.36	7.44	37.92	3.99
Silty clay 2	19.11	5.71	18.86	21.0	2.15
Silty clay 3	19.32	9.26	26.48	14.6	1.51
Silty clay 4	18.74	6.27	20.34	21.0	3.54
Silt 1	18.04	4.60	4.5	6.0	2.10
Silt 2	18.85	8.23	27.45	15.33	3.06
Fine sand 1	19.21	11.7	20.2	10.0	3.06
Fine sand 2	18.9	11.98	32.73	7.57	8.01
Coarse sand	20.8	17.7	25	10	3.66
Silty clay 5	18.45	4.85	16.25	18.15	3.0

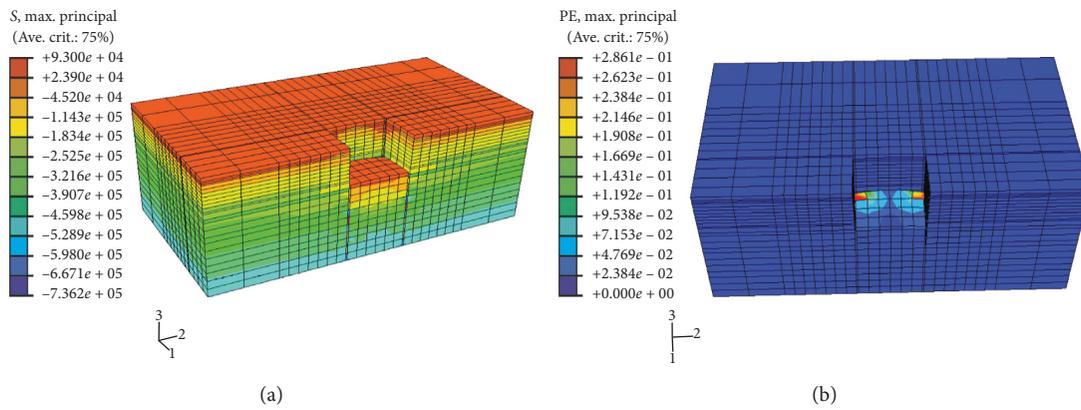


FIGURE 6: (a) The maximum principal stress of soil adjacent to the pit. (b) Soil plastic strain adjacent to the pit.

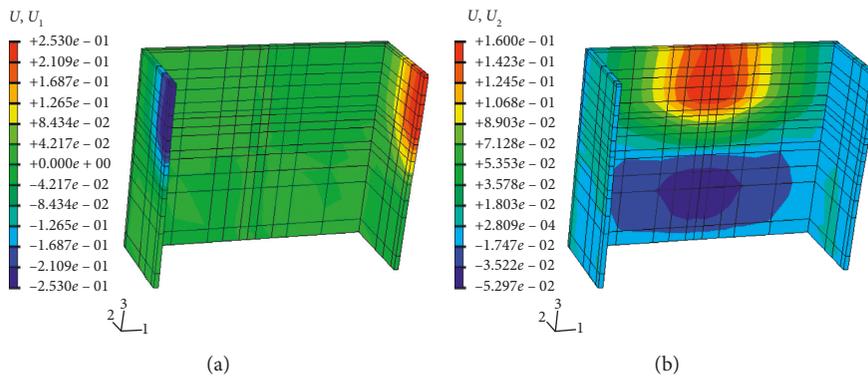


FIGURE 7: (a) The horizontal displacement cloud pictures of diaphragm wall. (b) The vertical displacement cloud pictures of diaphragm wall.

and vertical pipeline displacement values are located in the centre section of pit.

The excavating process has a great impact on the pipeline displacement, and pipeline displacement value increases by excavating depth increases. From step 1 to step 2, maximum pipeline horizontal displacement value on the centre section of the pit increased by 23.1%, while the maximum vertical displacement value increased by 15.2%, since the pipeline is shallow buried, the initial excavation

has a great impact on the pipeline; however, pipelines displacement value stay almost same after second excavation step.

In most projects, the pipeline is shallow, and the pipeline displacement regularity is closely related to the movement of the adjacent soil and UCW. With the increase of excavating depth, the excavation impact on shallow soil decreases, resulting that the initial excavation has a greater impact on the pipeline than subsequent excavation; hence, monitoring

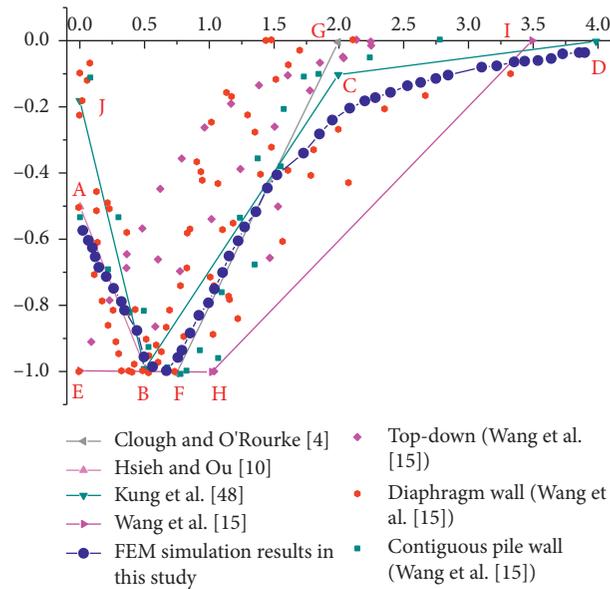


FIGURE 8: Relationship between ground settlement normalized by maximum settlement and normalized distance from wall.

and management need to be strengthened on initial excavation to reduce accidents.

Figure 9(a) shows the curve slopes of pipeline displacement in the corner effect areas that have significantly changed, where there will be great stress concentration, prone to pipeline damage by overlarge stress; maximum pipeline stress and displacement locate in the centre section of pit, prone to pipeline joint damage caused by overlarge deformation. Therefore, some appropriate security control measures need to be taken at these two dangerous areas to protect pipeline.

3.2. Effect of Different Soil Properties around the Pipeline. In this project, pipelines located in miscellaneous fill, and Young's modulus of miscellaneous fill E_s is 4 MPa. When Young's modulus of miscellaneous fill E_s changes, the changes of the pipeline displacement regularity are shown in Figure 9(b). Figure 9(b) shows that the horizontal and vertical pipelines displacement significantly decreased as soil Young's modulus E_s increased. It illustrates pipeline displacement can be reduced by improving soil property around the pipeline in project.

3.3. Effect of Different Distances away from Pit. With the changes of distances from pipeline to the pit, the changes of pipeline displacement are shown in Figure 9(c). From Figure 9(c), when the distance from pipeline to pit is about twice that of pit excavation depth, the horizontal and vertical displacement values of pipeline are only 47.1% and 21.8% of the displacement values at original position (i.e. $L = 6.8$ m), respectively, and it shows that pipeline nearer the pit take on more risk.

Figure 9(c) shows the pipeline under the influence of corner effect when the distance from pipeline to pit L is within the scope of 30 mm (about twice as much as the pit

depth). By the corner effect, the curve slopes of pipeline displacement values have significant changed at location $X = -22$ m. At this position, with the direction and magnitude of pipeline displacement significant changed, the pipeline (especially rigid pipeline) is easy to get great stress concentration, which is dangerous to pipeline safety and needs extra protection in the project.

3.4. Effect of Different Pipelines Burial Depths. Figure 9(d) shows pipeline displacement values with different burial depth, h is burial depth. Due to the burial depth of underground pipelines are generally less than 6 m, this paper discusses the burial depth range from 1 m to 6 m. From Figure 9(d), the underground pipeline displacement values increased with pipeline burial depth h increased (in the situation under discussion).

3.5. Effect of Different Pipelines Properties. Figure 9(e) shows pipeline displacement values with different pipelines property. Young's modulus of the polyvinyl chloride (PVC) pipe is smaller than other pipes; therefore, horizontal and vertical displacement values of PVC pipe are the maximum among these pipes, in the order of from big to small, it goes PVC pipe, concrete pipe, copper tube, cast iron pipe, and steel pipe. With Young's modulus of pipeline decreased, the pipeline is easily damaged by overlarge stress and strain, and with Young's modulus of pipeline increased, the pipeline joint is easily damaged by overlarge deformation.

3.6. Effect of Different Pipelines Outer Diameters. Figure 9(f) shows the displacement values of the pipeline with different pipelines outer diameters, i.e., $D = 0.4, 0.6, 0.8, 1.0$ m, respectively. The changes of the pipeline displacement values caused by outer diameter changes are quite small. However, due to the difference of pipelines' outer diameter,

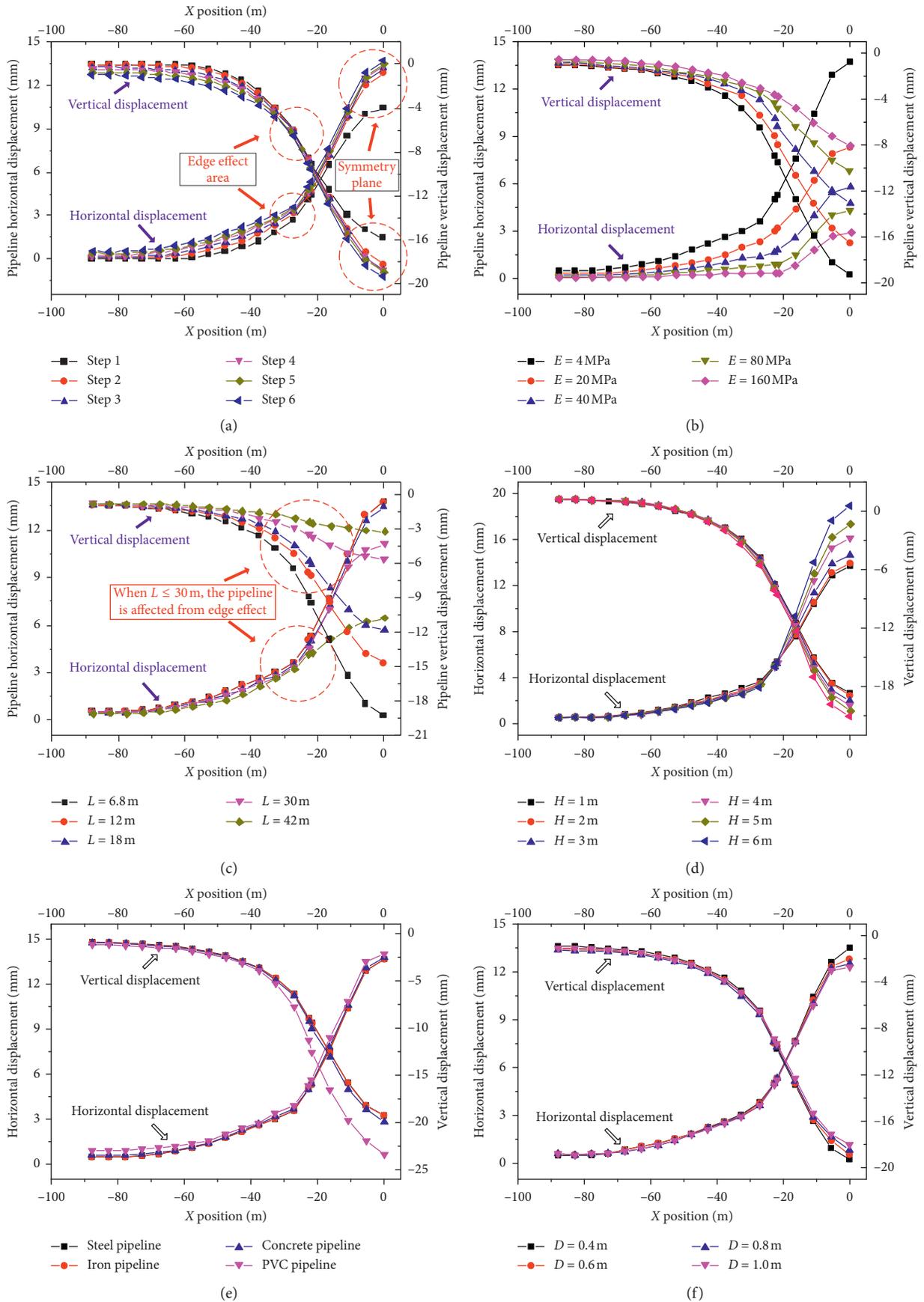


FIGURE 9: Continued.

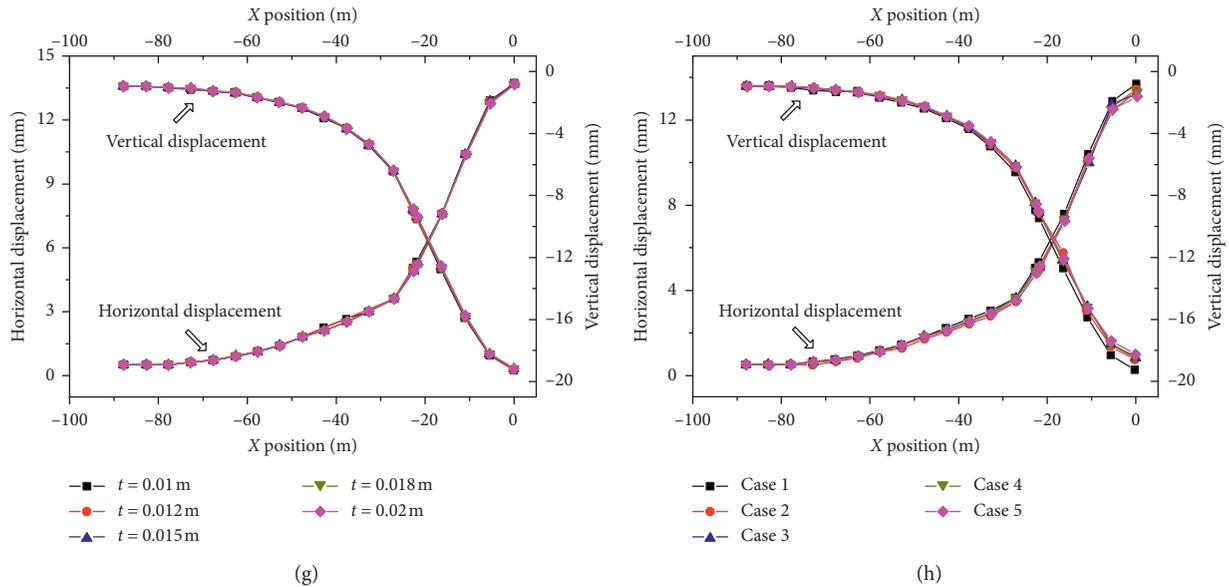


FIGURE 9: (a) Pipeline displacements on excavating process. (b) Pipeline displacements with different soil properties around the pipeline. (c) Pipeline displacements with different distances away from pit. (d) Pipeline displacements with different pipeline burial depths. (e) Pipeline displacements with different pipeline properties. (f) Pipeline displacements with different pipeline outer diameters. (g) Pipeline displacements with different pipeline thicknesses. (h) Pipeline displacements with the coexistence of multipipeline.

the pipeline stress, torque, and rotational angle at the joint become different; therefore, the outer diameter of pipeline also needs to be taken into consideration in the project.

3.7. Effect of Different Pipelines Thicknesses. Figure 9(g) shows pipeline displacement values with different thicknesses of the pipelines, i.e., $t = 1.0, 1.2, 1.5, 1.8, 2.0$ cm, respectively (where t is the thickness of pipeline). As seen in Figure 10, the changes of pipelines displacement values caused by changes of the pipelines thickness are quite small. Since the pipeline thickness have affected on the pipeline stress, this factor should also not be ignored in the project.

3.8. Effect of the Coexistence of Multipipeline. Since there are a variety of pipelines in JPWYRT (such as water supply, drainage, electricity, gas, and communications), clarifying the interaction between the pipelines is meaningful in the project.

In Figure 9(h), case 1 refers to pipeline displacement regularity in original model, i.e., it shows pipeline displacement values only taking the original pipeline (water supply) into consideration; case 2 refers to the original pipeline displacement regularity with a gas pipe (burial depth is 1.5 m, distance from the edge of pit is 6 m, the outer diameter of pipeline is 0.4 m) adjacent to the original pipeline; case 3 shows the original pipeline displacement regularity with a pipeline 7.2 m away from the original pipeline, which have the same outer diameter, pipe property, and burial depth; case 4 refers to the original pipeline displacement regularity when the original pipeline property is concrete, with a pipeline 7 m away from the original pipeline; and case 5 shows the original pipeline displacement regularity with a pipeline 14 m away from the original

pipeline, which have the same outer diameter, pipe property, and burial depth.

Figure 9(h) shows the coexistence of multipipeline has small effect on the original pipeline displacement. Therefore, the influence of coexistence of multipipeline can be ignored with certain realms in the project.

3.9. Comprehensive Factor Analysis. Based on JPWYRT, this paper particularly investigates the eight major factors that affect pipeline safety, as in Table 2. Under the impact of multiple factors combined, the most disadvantageous factor combination of pipeline safety have been carried out by the FE analysis as follows: the pipeline takes more risk around the centre section of pit in the initial excavating period, and when the distance from pipeline to pit edge is small, soil property around the pipeline is poor, pipeline burial depth is shallow, pipeline stiffness is small, pipeline outer diameter is small, and pipeline thickness is small. In addition, subject to the large stress in the pipeline is corner effect area, the pipelines (especially the flexible pipe) need to take appropriate security control measures to protect it. Therefore, based on original BUCWS, an APRS is carried out to protect pipeline in next section on the original excavating process, focused on dangerous areas to pipeline safety.

4. Analysis of the Safety Control of the Additional Partial Reinforcement Scheme (APRS) for Underground Pipelines

For the above most disadvantageous factors combination, an additional partial reinforcement scheme (APRS) combined with bracing structure and soil reinforcement is adopted to protect the existing pipeline. Soil reinforcement measures

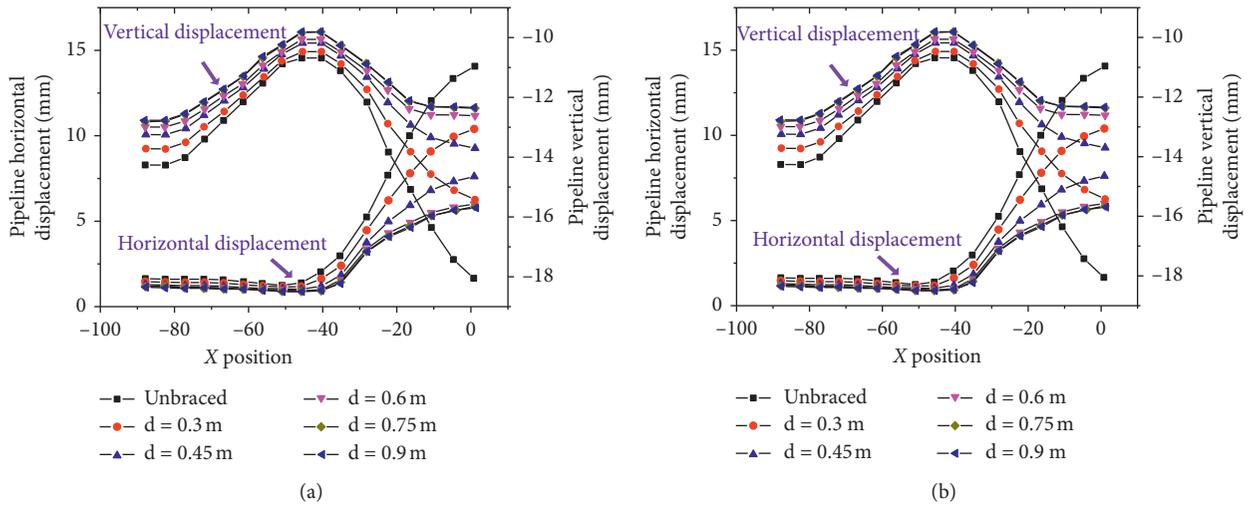


FIGURE 10: The effect on pipeline of different strut positions and diameters. (a) The pipeline displacement of different strut diameters in strut position 1. (b) The pipeline displacement of different strut diameters in strut position 2.

TABLE 2: Summary of pipeline safety factors in the FE study.

Pipeline safety factor	Effect degree		Effect on regularity
	Effect on horizontal displacement	Effect on vertical displacement	
1 Excavating process	General	General	As the pipelines are shallow buried, the initial excavation has a great impact on the pipeline. Therefore, monitoring and management on initial excavating period need to be strengthened to reduce accidents.
2 Soil property around the pipeline	Great	General	The horizontal and vertical pipeline displacement values significantly decreased with soil Young's modulus E_s increased. It illustrates pipeline displacement can be reduced by improving soil property around the pipeline in project.
3 The distance away from pit	Great	Great	The closer the pipeline away from the pit, the larger pipeline displacement values are. The pipeline under the influence of corner effect when the distance from pipeline to pit L is within the scope of 30 mm (about twice as much as the pit depth).
4 Pipeline burial depth	General	Weak	The underground pipeline displacement values increased with burial depth values h increased (in the situation under discussion). With Young's modulus of pipeline decreased, the pipeline is easily damaged by overlarge stress and strain. With Young's modulus of pipeline increased, pipeline joint is easily damaged by overlarge deformation.
5 Pipeline property	Weak	General	The changes of pipeline displacement values caused by outer diameter changes are quite small.
6 Pipeline outer diameter	Weak	Weak	The changes of pipeline displacement values caused by thickness of the pipeline changes are quite small.
7 Pipeline thickness	Weak	Weak	The coexistence of multipipeline has small effect on the original pipeline displacement.
8 The coexistence of multipipeline	Weak	Weak	

include the reinforcement at passive zone in the pit, the reinforcement underneath pipeline and the reinforcement beside pipeline [50], as shown in Figure 11. The influencing regularities of the four factors (i.e., thickness of the diaphragm wall, depth of the wall, stiffness of the strut, and position of the strut) on reinforcement are carried out. By comprehensive analysis of reinforcement effects and economic costs, an APRS is carried out to protect the existing pipeline.

4.1. Soil Reinforcement Measures. By the analyzing of above section, as the pipelines are shallow buried, pipeline displacement values significantly increased during the initial excavating period, the APRS needs to be taken on the initial excavating period. Therefore, a shallow pit model (i.e., pit depth is 7 m) is carried out, in order to simulate the impact of reinforcement measure on the initial excavating period.

In consideration of economic cost, usually a part of soil around the pipeline and pit is reinforced in the

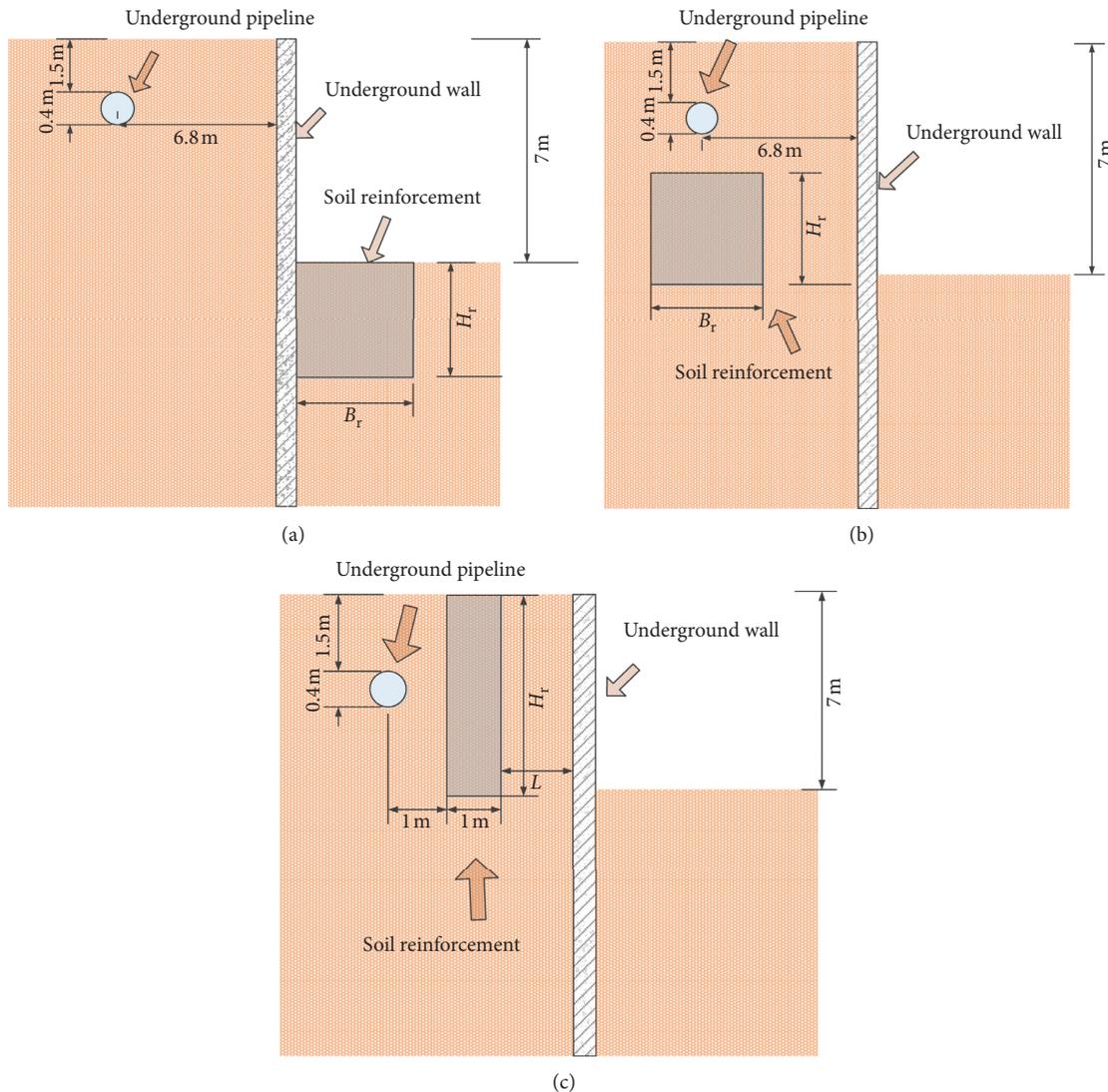


FIGURE 11: An illustration of the different reinforcement measure. (a) The RS at passive zone in the pit. (b) The RS underneath pipeline. (c) The RS between pipeline and pit.

soil reinforcement measures, such as the reinforced soil (RS) at passive zone in the pit, the RS underneath pipeline, and the RS between pipeline and pit, as shown in Figure 11.

4.2. RS at Passive Zone in the Pit Measure. An illustration of the RS at passive zone in the pit measure is shown in Figure 11(a), the pipeline displacement regularly by the reinforcement at the passive zone in the pit (soil reinforcement width $B_r = 3$ m) is shown in Figure 12(a). Figure 12(a) shows that the reinforcement at the passive zone in the pit can significantly reduce the existing pipeline vertical and horizontal displacement values. When RS Young's modulus $E_s = 30$ MPa, the pipelines' displacement have significantly decreased. The pipeline displacement values have decreased less, with RS Young's modulus increased beyond 30 MPa. By considering the economic cost, the reinforcement effect is enough with RS Young's modulus $E_s = 60$ MPa.

Figure 12(b) shows the maximum displacement values of underground pipelines ($B_r = 6$ m constantly) with ratio of the RS depth (i.e., H_r) to the RS width (i.e., B_r) changes, and the figure shows that the maximum displacement values of existing pipelines decreases with ratio of H_r/B_r increases. When the ratio increases to a certain value, almost $H_r/B_r = 2$, the change of the maximum displacement values caused by ratio of H_r/B_r change is quite small. This reaction in the horizontal displacement is more prominent than in vertical displacement.

Since the RS at passive zone in the pit is already adopted in the original reinforcement schemes, the RS at passive zone in the pit is not encompassed in the APRS.

4.3. RS underneath Pipeline Measure. An illustration of the RS underneath pipeline measure is shown in Figure 11(b), and the pipeline displacement regularly by the RS underneath pipeline (soil reinforcement width $B_r = 3$ m, Young's modulus $E_s = 60$ MPa) is shown in Figure 12(c).

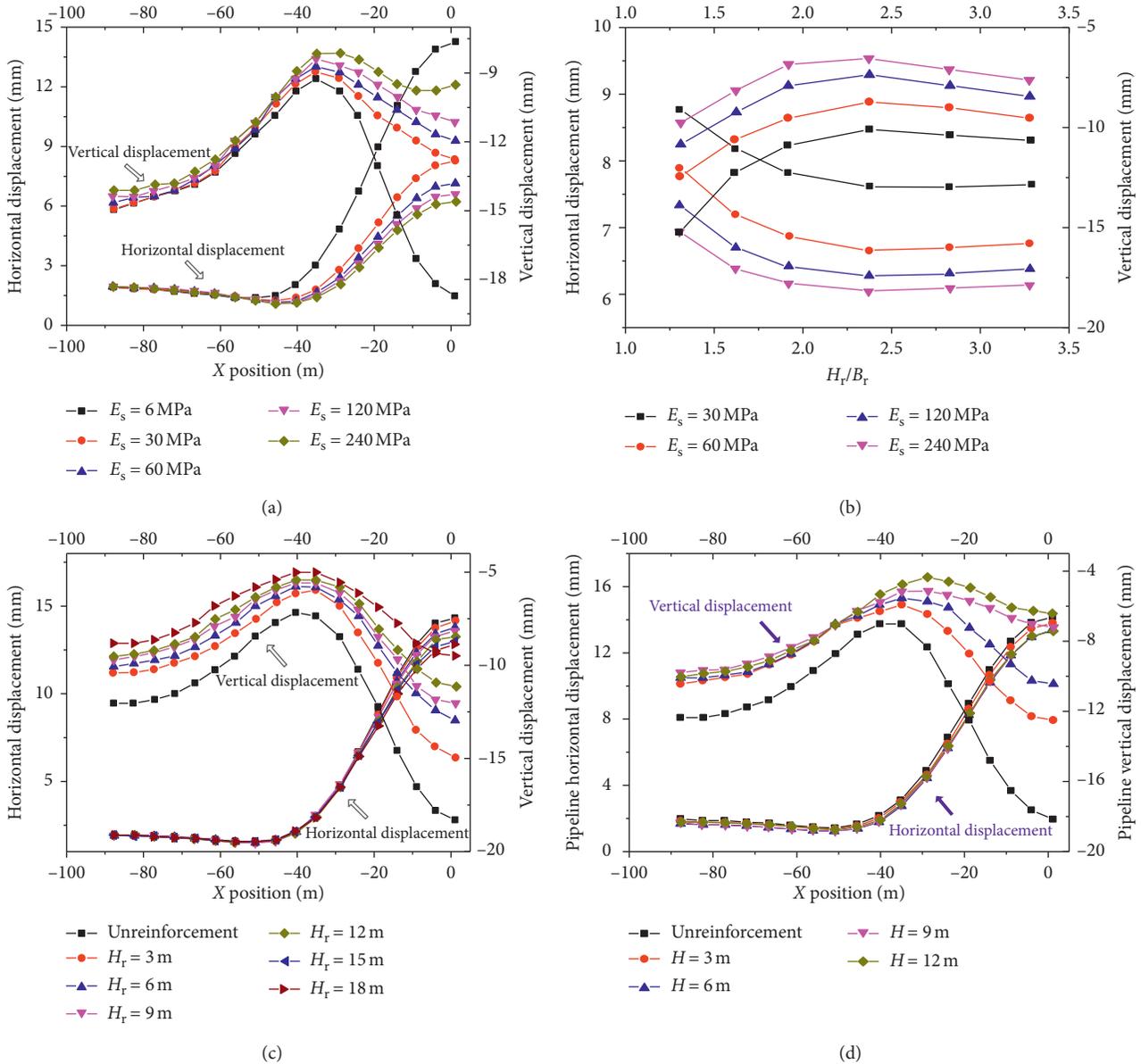


FIGURE 12: (a) The pipeline displacement regularity. (b) The maximum displacement of underground pipelines with ratio of the RS depth to the RS width changes. (c) The pipeline displacement regularity by the RS underneath pipeline. (d) The pipeline displacement regularity by the RS between pipeline and pit.

Figure 12(c) shows the reinforcement measure underneath pipeline has almost no effect to pipeline horizontal displacement, while it has a significant impact on the pipeline vertical displacement. When $H_r = 3$ m, vertical displacement is 31% of the maximum value; when $H_r = 12$ m, vertical displacement is 64% of the maximum value. As the RS depth increases, the vertical displacement of pipeline decreases; however, the pipeline vertical displacement values decreases slightly, with RS depth H_r increased beyond 9 m.

The RS underneath pipeline is a general measure adopted in the project, which has a significant impact on the vertical displacement of pipeline, while the economic cost of this measure is low. Therefore, the reinforcement underneath pipeline is encompassed in the APRS to reinforce the pipeline in dangerous areas.

4.4. RS between Pipeline and Pit. An illustration of the RS between pipeline and the pit measure is shown in Figure 11(c), the pipeline displacement regularity by the reinforcement measure underneath pipeline (the distance to pipeline and the pit is 1 m and 4.8 m, respectively, and soil reinforcement width $B_r = 1$ m, Young's modulus $E_s = 60$ Mpa) is shown in Figure 12(d). Figure 12(d) shows the reinforcement measure between pipeline and pit has almost no effect to pipeline horizontal displacement, while it has a significant impact on the pipeline vertical displacement.

The pipeline vertical displacement values have small decrease, with RS depth H_r increase beyond 12 m. Since the reinforcement between pipeline and the pit has significant impact on the vertical displacement of pipeline, while the economic cost of this measure is low, this measure is

encompassed in the APRS to reinforce the pipeline in dangerous areas.

4.5. Reinforcement with BUCWS. In order to build appropriate BUCWS, the influencing regularities of four factors (i.e., thickness of the diaphragm wall, depth of the wall, stiffness of the strut, and position of the strut) are carried out.

Soil horizontal displacement cloud diagram on the centre section is shown in Figure 13. Figure 13 shows that the soil horizontal displacement value on the upper part of pit is quite small with original BCUWS. While the soil horizontal displacement value of the top of the pit is less than the bottom, this regularity of soil horizontal displacement is beneficial to pipeline safety because the pipeline is generally shallow buried underground.

4.5.1. UCW Reinforcement. By the above analysis of Section 3 and Section 4, the pipeline around the centre section is in a greater danger; therefore, it is meaningful to investigate the soil movement around centre section with thickness and depth of UCW changes as shown in Figure 14.

Figures 14(a) and 14(b) show soil horizontal and vertical movement with thickness of UCW changes. The pit excavation effect on the soil range of 45 m (about twice the depth of the pit), and buildings and underground pipelines in this range should be paid attention to monitoring and taking protective measures. The soil horizontal displacement at lateral of to UCW significantly decreased by 36% with the thickness of UCW increased 40%; meanwhile, surface soil subsidence also significantly reduced with the increase of UCW thickness.

From the analysis above, in order to reduce the movement of soil in the adjacent pit, the measure of increasing UCW thickness to appropriate extent is feasible. However, due to the high economic costs of UCW installing, to attain a proper balance between pipeline safety and economic requirement, the thickness of UCW is selected as 800 mm.

Figures 14(c) and 14(d) show soil horizontal and vertical movements with depth of UCW changes. The soil movement adjacent to UCW decreased with the increase in depth of UCW; however, when the depth of UCW changes from 37.5 m to 40 mm, the changes of soil movement are quite small, and considering the economic cost, the appropriate depth of UCW is 37.5 m.

Pipeline displacement is related to soil movement, because of the high economic cost of diaphragm wall, and the measure of increasing the thickness and depth of UCW to reduce pipeline displacement is not taken in this scheme. However, in order to sustain the stability of the pit, an appropriate UCW thickness and depth are adopted as 800 mm and 37.5 m, respectively.

4.5.2. Bracing Reinforcement. Due to the low economic costs of bracing reinforcement, soil movement adjacent to UCW is generally reduced by bracing reinforcement in the project. Since pipeline displacement significantly increased during

the initial excavating period, the pipeline displacement regularity affected by setting bracing reinforcement during the initial excavating period (excavating depth is 3.5 m) is researched. The pit profile and planar graph by setting bracing reinforcement are shown in Figure 15.

As shown in Figure 10, this paper discusses the effect regularity of the different positions and sizes of additional strut on pipeline displacement. Position 1 is setting the strut at top of pit, and position 2 is setting strut at horizontal plane of existing pipeline. Figures 14(a) and 14(b) show pipeline displacement regularity with pipeline diameter $D=0.4$ m, depth $h=1.5$ m, distance from pit edge $L=6.8$ m, additional strut diameter d equal to 0.3 m, 0.45 m, 0.6 m, 0.75 m, 0.9 m, respectively, additional strut spacing equal to 3 m, and the thickness of strut equal to 16 mm.

Figure 10(a) shows that pipeline horizontal and vertical displacement are reduced by 52%, 35% with additional strut diameter d is 0.3 m in position 1; Figure 10(b) shows pipeline horizontal and vertical displacement are reduced by 64%, 50% with additional strut diameter d is 0.3 m in position 2. The reinforcement effect of position 2 is better than position 1, which illustrates that appropriate strut position is important for controlling the pipeline displacement. The effect of additional bracing reinforcement on pipeline horizontal displacement is larger than vertical displacement.

Figure 10 shows pipeline displacement reduced more than 50% by setting additional strut with diameter d equal to 0.3 m, and pipeline displacement decreased with strut diameter increased; however, bracing reinforcement has a small effect on pipeline displacement with additional strut diameter d beyond 0.6 m. Therefore, the size of additional strut adopted in this reinforcement scheme is 0.6 m. Besides, compared to the steel strut that can be recycled and has low economic cost, steel strut is adopted in this reinforcement scheme.

Therefore, this reinforcement scheme uses steel strut as additional strut, the strut diameter $d=0.6$ m, and the position of the strut is at the same horizontal plane of underground pipeline.

4.6. Comprehensive Analysis. Summarize the above reinforcement effect and economic cost of reinforcement measure in Table 3. To attain a proper balance between pipeline safety and economic requirement, an APRS is carried out to protect pipeline as follows: this scheme carried out the optimum parameter of initial BUCWS, and arrange a series of additional struts at the same horizontal plane of underground pipeline; then, in the dangerous areas to pipeline safety (i.e., corner effect area and centre section area), a targeted additional soil reinforcement is adopted underneath pipeline and adjacent to the pit.

4.7. Reinforced Effect. Based on the above analysis, in the Jiangbei pit, UCW thickness and depth are 800 mm and 37.5 m, there are five tier struts in the pit from top to bottom, strut spacing is 3 m, and first tier struts are concrete with a size of 800×900 mm, considering the economy, the others of

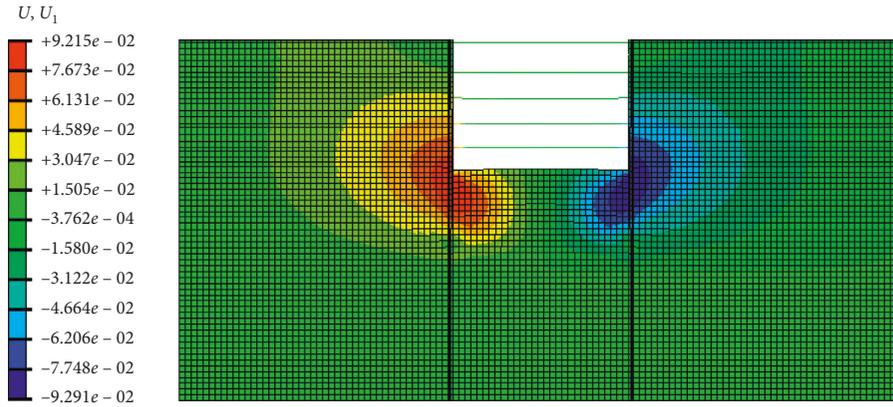


FIGURE 13: Soil horizontal displacement cloud diagram on the centre section.

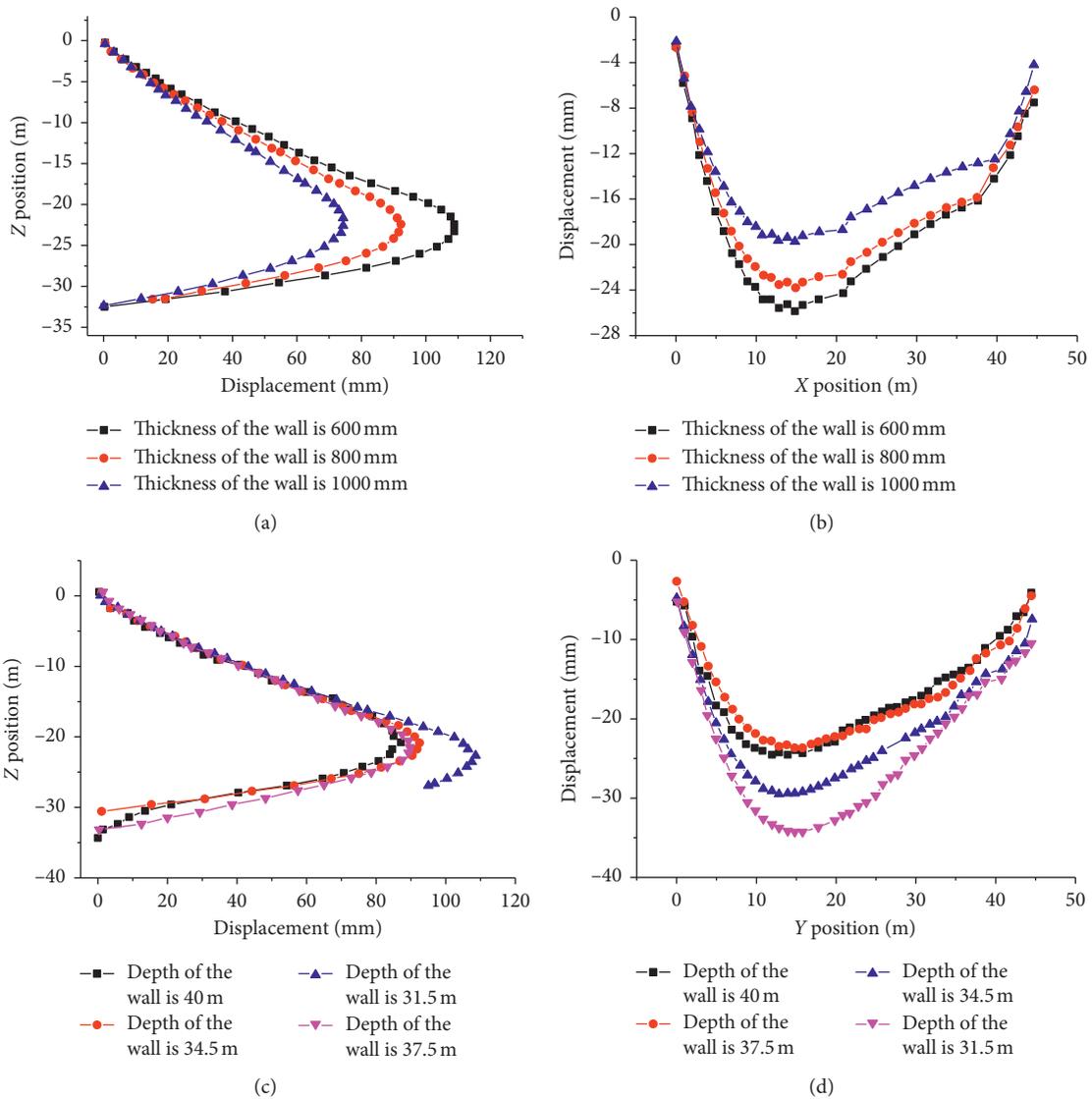


FIGURE 14: (a) The horizontal displacement of soil adjacent to the diaphragm wall. (b) The vertical displacement of soil adjacent to the diaphragm wall. (c) The horizontal displacement of soil adjacent to the diaphragm wall. (d) The vertical displacement of soil adjacent to the diaphragm wall.

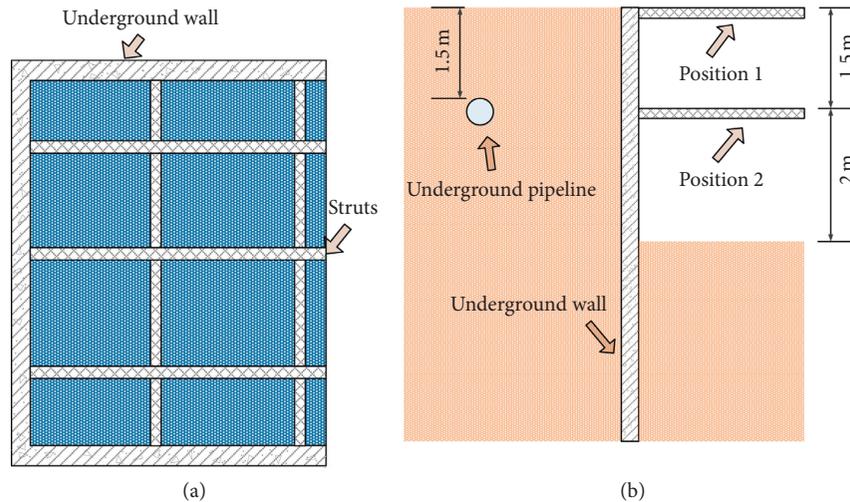


FIGURE 15: The diagrammatic sketch of pit with setting the strut. (a) The planar graph of set strut. (b) The profile of set strut.

TABLE 3: Summary of pipeline reinforcement measures.

Reinforcement measures		Effect on horizontal	Effect on horizontal	Economic cost	Reinforcement effect	Optimum parameters
The soil reinforcement at passive zone in the pit	Young's modulus E_s	Great	Great	High	General	$E_s = 60 \text{ MPa}$ When $B_r = 3 \text{ m}$, $H_r/B_r = 2$
	RS depth/RS width	Great	General		General	
The soil reinforcement underneath pipeline		Weak	Great	General	General	When $B_r = 3 \text{ m}$, $H_r = 9 \text{ m}$
The soil reinforcement between pipeline and pit		Weak	Great	General	General	When $B_r = 1 \text{ m}$, $H_r = 12 \text{ m}$
Bracing reinforcement	Position	Great	Great	Low	Great	At the same horizontal plane of underground pipeline $d = 0.6 \text{ m}$
	Strut diameter	General	General	Low	General	
Diaphragm wall reinforcement	Thickness	General	General	High	General	Wall thickness is 800 mm
	Depth	Weak	Weak	High	Weak	Wall depth is 37.5 m

struts are steel, which diameter and thickness are 609 mm and 16 mm. Besides, an APRS is carried out as follows: a series of struts are arranged with spacing is 3 m, depth is 1.5 m, diameter is 609 mm, and thickness is 16 mm; in the dangerous area to pipeline safety (i.e., corner effect area and centre section area), additional soil reinforcement is adopted underneath pipeline and adjacent pit.

According to GB5049-2009 Technical Code for Monitoring of Building Foundation Pit Engineering, the pit monitoring alarm value are as follows: (1) surface subsidence around pit is 25~30 mm; (2) rigid pipeline displacement is 10~30 mm when under pressure and 10~40 mm when not under pressure; and (3) flexible pipeline displacement is 10~40 mm. The soil movement and pipeline displacement adjacent to the pit are analyzed in this paper to validate the reinforced effect of reinforcement scheme.

Due to the fact that surface subsidence parameters are easy to measure in the project and there are a series of standards to control surface subsidence, surface subsidence parameters are selected to validate the reinforced effect of the reinforcement scheme. Figure 16 shows surface subsidence curve adjacent to the pit after using the reinforcement scheme. As can be seen from Figure 16, surface subsidence caused by excavation is not big, mostly

in the range of 30 mm, which meet the request in the GB5049-2009. It validates that stability of the soil can be guaranteed by using this reinforcement scheme.

Figure 17 shows that the maximum surface subsidence located at the area around the centre section of pit; when the distance from the pit gets large, the surface subsidence curve starts to somewhat flatten, and the surface subsidence value gets smaller. When the distance from UCW corner is 8~10 m, the surface subsidence suffers from corner effect, in which subsidence value has significantly changed. The areas around the centre section and corner of pit still are dangerous, which need to be taken more attention to monitoring.

There is a concrete pipeline adjacent to the edge of the pit, of which diameter is 0.4 m, pipeline length is 20 m, and the monitoring point was set as an interval of 5 m. Comparing the measure value with simulation value after used the reinforced scheme in Figure 18, the tendency of two curves are almost same, which validates that FE analyses results are consistent with the field situation. Due to the limitations of the simulation model, this model cannot consider the entire excavating process factors (e.g., the impact of groundwater), which causes that measure value is large than simulation value. The final measure displacement value of pipeline is 10 mm, which illustrates that the



FIGURE 16: Field scene of JPWYRT after setting the strut. (a) Field scene on the top of pit. (b) Field scene on the bottom of pit.

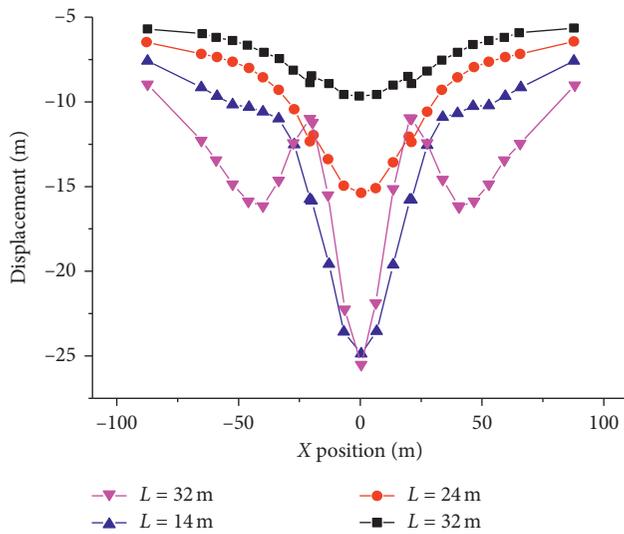


FIGURE 17: Soil settlement beside the pit.

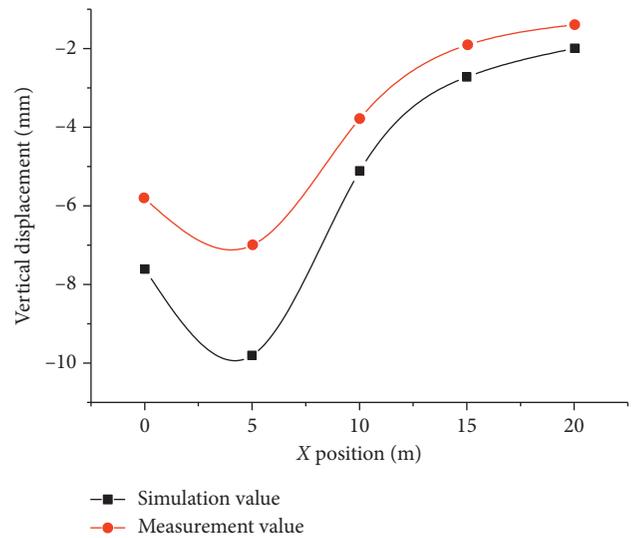


FIGURE 18: Comparison between the simulative value and measure value of pipeline vertical displacement.

use of this reinforcement scheme for pipeline protection is effective.

5. Conclusion

This paper takes the excavation of the Jiangnan and Jiangbei deep-foundation pit of the Yangtze River Tunnel in Wuhan as the engineering background. Firstly, from the point of view of pipeline safety risk analysis, the dangerous areas and the most disadvantageous combination of factors are obtained. Secondly, from the point of view of pipeline safety risk control, the reinforcement effects of different reinforcement methods are analyzed from the aspects of safety and economy. Finally, a set of additional partial reinforcement scheme (APRS) is synthesized to protect the safety of underground pipelines in dangerous areas where pipelines are at high risk. The validity of the APRS for pipeline protection is verified through field measurement. The main conclusions are as follows:

- (1) Through the analysis of a finite-element model constructed using ABAQUS, the dangerous areas are determined where pipelines are liable to be damaged, i.e., the symmetrical plane in the middle of the

foundation pit and the area with large stress under the influence of the end effect and the area with large displacement in the symmetrical plane in the middle of the foundation pit. In addition, the results of finite-element simulation show lateral surface settlement outside the foundation pit, which is consistent with the trend of variation of the curves predicted by Ou et al. [5]. The accuracy is verified of the finite-element model constructed in this paper.

- (2) By analyzing the factors affecting the safety of pipelines during the excavation and construction of deep-foundation metro pit, the most disadvantageous combination of factors is obtained affecting the safety of underground pipelines. Pipelines with the following characteristics have high risks: in the initial stage of foundation pit excavation, near the foundation pit, poor soil quality, larger buried depth, smaller stiffness, smaller diameter and thinner thickness, and pipeline location near the symmetrical plane in the middle of the foundation pit.
- (3) The safety and economy of various reinforcement measures are considered, and from the point of view

of reducing the economic costs while achieving adequate reinforcement effect, a set of additional partial reinforcement scheme (APRS) is proposed for protecting the safety of underground pipelines. The details include that on the basis of optimizing the parameters of foundation pit support and soil reinforcement in the passive zone of foundation pit, arrange a group of additional supports parallel to the axis of pipeline, and in the dangerous areas such as the symmetrical plane in the middle of the foundation pit, which are greatly affected by the end effect, reinforce the bottom of the pipeline and the local soil near the side of the foundation pit. In addition, analysis of the reinforced soil shows that the foundation pit does not cause excessive ground settlement after excavation, mostly within 30 mm, suggesting that the stability of soil is satisfied after the proposed reinforcement scheme is adopted.

Data Availability

The data used to support the findings of this study are included within the article. The calculation model used to support the findings of this study is available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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