Study on Formation Deformation Caused by Leakage of Buried Pipeline

Zhongchang Wang, Jinrui Wu

Abstract— **In this paper, FLAC3D software is used to build a 3D fluid-solid coupling numerical model to study the formation deformation induced by buried pipeline leakage. Firstly, the frequent occurrence of underground pipeline accidents, especially the formation collapse caused by leakage, is analyzed. Secondly, the influence of leakage area, infiltration velocity, leakage position and buried depth on leakage diffusion range and surface settlement is discussed. The results show that leakage area and infiltration velocity are the key factors affecting leakage diffusion range and settlement, leakage location significantly affects spatial distribution characteristics of settlement, and pipeline buried depth has inhibition effect on local settlement, but it is necessary to pay attention to the cumulative effect of long-term low-magnitude deformation. The research results provide theoretical basis and technical support for the safe operation and maintenance of urban underground pipe network, and suggest that the dynamic assessment model of leakage risk should be constructed in combination with machine learning algorithm in the future to promote the intelligent development of urban geological disaster prevention and control.**

Index Terms—**pipeline leakage; stratum deformation; fluid-solid coupling; numerical modeling**

I. Introduction

Underground pipelines are regarded as the lifeline of a city and are important infrastructure for safe and stable operation of a city. According to statistics, the length of five main types of pipelines in China, including urban water supply, drainage, gas, heating and long-distance oil and natural gas pipelines, has exceeded 350km, and is increasing at an annual growth rate of about 13.17%. However, while speeding up the construction of new pipe network system, accidents of existing pipelines occur frequently. According to Statistical Analysis Report of Underground Pipeline Accidents in 2023 issued by Underground Pipeline Professional Committee of China Surveying and Mapping Society, 1406 accidents related to underground pipelines were collected from October 2022 to September 2023. See Figure 1 for details of monthly distribution of accidents. Among them, there were 1137 underground pipeline damage accidents, accounting for 80.87% of the total number of underground pipeline related accidents, 269 stratum collapse accidents, accounting for 19.13% of the total number of underground pipeline related accidents. Among the 138 stratum collapse accidents whose causes have been identified, 107 accidents were caused by underground pipeline problems and soil diseases, accounting for 77.5% of the total number of stratum collapse accidents.

Hydraulic pipeline is buried in shallow buried stratum of city. Loose soil in this area has characteristics of strong compressibility, low strength, large porosity and good permeability. Pipeline is easy to be affected by ground load disturbance, aging, improper construction and other factors to cause structural degradation, resulting in various defects and damaged openings [1]. The stratum collapse induced by pipeline leakage can be divided into two stages [2]. The first stage is water leakage caused by hydraulic pipeline damage, which increases the water content of soil in the leakage range and weakens the strength, resulting in uneven settlement of pipelines in a certain range. In the second stage, the weakened soil begins to lose along other channels and forms a large skeleton structure-hidden cavity in the soil, which reaches a critical stable state under the skeleton support and soil arch effect through stress balance. With the continuous loss of soil, the hidden cavity continuously expands to the surface and both sides of the soil, and finally the stratum collapse accident will occur when the soil itself cannot bear the gravity of the soil and the external load due to its cohesion. This paper focuses on the process of pipeline leakage state and leakage range, and focuses on different leakage state of hydraulic pipeline (For example: pipeline leak size, water pressure, soil properties, pipeline buried depth, etc.), to explore the mechanism of water seepage and erosion of loose soil and its influence on stratum collapse. In recent years, the frequent occurrence of urban road collapse accidents has aroused widespread concern in society. Water leakage from buried pipelines will affect the formation stability, and its influence degree and whether collapse will occur are closely related to the leakage range of pipelines. At present, the classical theories for the shape of pipeline leakage area include Newton fluid spherical diffusion model, spherical (cylindrical) diffusion theory formula, power law fluid permeation diffusion theory, Bingham slurry permeation diffusion theory formula [3-5]. Among them, Lan Xiongdong [6] deduced the formula of fluid diffusion range changing with time after water gushing in municipal pipeline on the basis of generalized Darcy law.Yang Zhiquan et al.[7] studied the cylindrical and hemispherical permeation diffusion forms of Newtonian fluid, Bingham fluid and power-law fluid respectively, and then derived the diffusion radius of hemisphere and the calculation formula of diffusion height of cylinder. Alsaydalani et al.[8] found that the fluidized failure range of soil was conical without considering the influence of side wall in the two-dimensional leakage hole erosion test. Song Guchang [9] revealed the spatio-temporal distribution characteristics of collapse accidents through systematic induction of cases in Beijing City from 2008 to 2017: the time dimension showed significant flood season

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concentration (accounting for 62% from July to August), and 80% of collapses occurred in shallow layer above 5m below the surface in spatial distribution. Chen Changyan [10] pointed out that underground pipeline leakage, engineering construction disturbance and traffic load overrun constituted the main disaster causes, providing important basis for accident prevention and control.Huang Leyi [11] revealed the evolution mechanism of seepage field after water supply pipeline damage through unsaturated soil seepage test, constructed water content gradient distribution model, and innovatively integrated time domain reflection method and geological radar detection technology to develop a nondestructive detection system with leakage location accuracy of 92%.

II. Establishment of Three-dimensional Numerical Model

A. *Modelling and meshing*

Aiming at the problem of pipeline leakage, FLAC3D is used to establish three-dimensional numerical model. As shown in the figure, the horizontal (Z axis) length of the calculation domain of the model is 20m, the vertical (Y axis) length is 20m, and the depth (Z axis) is 20m. After repeated trial calculations, the size of the calculation domain basically meets the influence requirements of boundary effect. The simulation area adopts a 20m×20m× 20m cube area, and the boundary conditions on the left and right sides are model boundaries. The upper part is the ground surface. A water supply pipeline with a radius of 0.4 m is buried 1m away from the ground surface. There is a crack in the pipeline. When the model is meshed by FLAC3D software, the continuity of the mesh must be ensured. In order to ensure the accuracy of the numerical simulation data, the mesh is refined near the model tunnel and in the middle. The model displacement boundary conditions are: the surface is free boundary; the lateral boundary and the bottom boundary of the model soil restrict the normal displacement respectively. The hydraulic boundary conditions of the model are: the left and right sides and the bottom are set as impermeable boundary, the bottom is set as zero pressure head, and the pipeline is impermeable boundary.

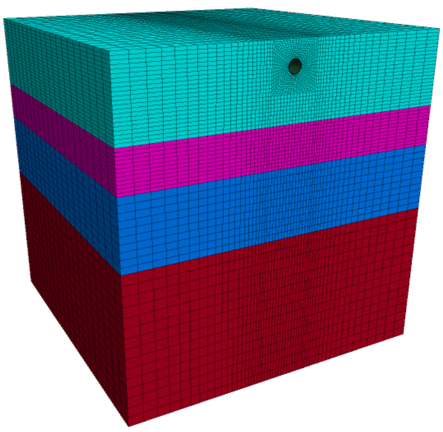

Figure 1 Three-dimensional numerical model

B. *soil parameters*

The soil mechanics and permeability parameters of the calculation model are listed in the table below.

Table 1 Geophysical parameters

Soil layers and materials	thickness/m	unit weight /(KN • m-3)	elasticity modulus /(MPa)	Poisson's ratio	cohesion	internal friction angle/(°)
plain fill	4.4	16.5	20	0.38	11	12.9
silty clay	2.4	18	23	0.3	20.8	25.3
pebble	4.1	19.5	25	0.3	43	24.6
moderately weathered slate	9.1	25.3	46	0.23	60	34.3

C. *calculation process*

This paper mainly studies the influence of water leakage during the tunnel operation period after completion. In the early stage, the excavation of pipeline is simulated first. The main analysis steps are as follows: 1. Initial geostress equilibrium. It is worth noting that the process of initial geostress equilibrium needs to adopt fluid-solid coupling mode. On the one hand, this is more in line with the actual situation, on the other hand, it can prevent secondary interference to deformation when fluid-solid coupling mode is opened. 2. Simulate pipeline excavation, clear the soil displacement before excavation, and then simulate the excavation process to calculate the results of pipeline excavation. 3. Set different leakage positions, leakage speeds, leakage areas, pipeline buried depths and other conditions to simulate leakage.

In order to study the influence of leakage area, leakage position, infiltration velocity and buried depth of pipeline on seepage flow of pipeline leakage water in unsaturated soil, and obtain the morphological characteristics and influence range rules of leakage zone formed in leakage process under different working conditions, 9 groups of working conditions are set in this simulation, as shown in the table below.

Table 1 working condition of calculation

	leak area/cm2	infiltration velocity/m/s	leak location	buried depth of pipeline/m
combination mode 1	50	1e-2	bottom	1
combination mode 2	100	1e-2	bottom	1
combination mode 3	200	1e-2	bottom	1
combination mode 4	50	1e-1	bottom	1

combination mode 5	50	1e-3	bottom	1
combination mode 6	50	1e-2	side	1
combination mode 7	50	1e-2	top	1
combination mode 8	50	1e-2	bottom	2
combination mode 9	50	1e-2	bottom	3

D. *Validation of computational models*

For any soil calculation model, if the initial stress generated is wrong, then all the subsequent analysis will also be wrong. In order to ensure the correctness of the model in each stage, it is also necessary to verify the results of multiple stages, from the initial results of pipe excavation to the final leakage results. Only by ensuring the correctness of each link model simulation can the correctness of the final simulation results be guaranteed.

Figure 3 is the vertical stress diagram of the tunnel after the completion of pipe excavation. It can be seen from the figure that the stress of the tunnel conforms to the stress form of the inner side of the upper and lower parts of the tunnel under tension and the inner side of the middle part under pressure.

Figure 3 shows the surface settlement curve after pipeline excavation, which presents a state of approximate normal distribution, consistent with the surface settlement curve shape predicted in peck formula. It is preliminarily proved that the simulation results are relatively consistent with the actual situation at the end of excavation of the model, which also lays a solid foundation for subsequent simulation.

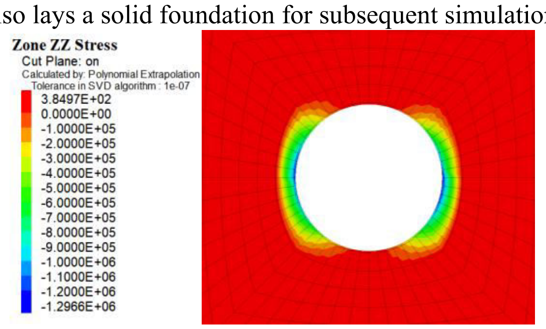

Figure 2 stress distribution nephogram around pipeline

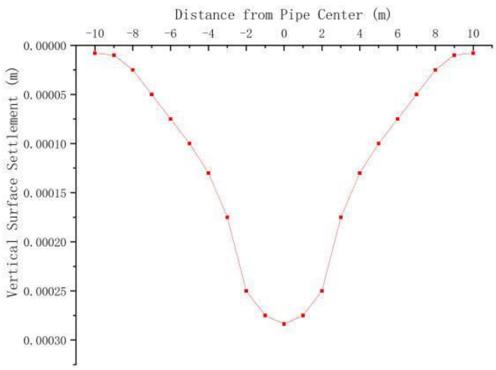

Figure 3 Surface Settlement Curve after Pipeline Excavation

III. ANALYSIS OF THE CALCULATION RESULTS

In the numerical simulation of pipeline leakage, the leakage area is closely related to the size of formation deformation. In order to ensure the accuracy of numerical simulation, the leakage area is selected for research and analysis. The leakage area is analyzed under three different working conditions of 50 cm2, 100 cm2 and 200 cm2 respectively, and the other construction parameters remain unchanged. Calculate the saturation degree of soil after 1 h, 6 h and 12 h of pipeline leakage under Condition 1, i.e. leakage area 50 cm2, infiltration velocity 1e-2m/s, leakage position at bottom and pipeline buried depth 1m, as initial comparison. Figure 4-Figure 6 show the calculation results under Condition 1:

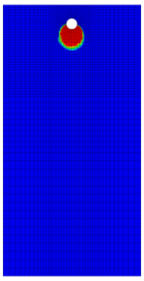

Figure 4 Soil saturation nephogram for 1h leakage under condition 1

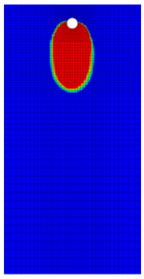

Figure 5 Soil saturation nephogram for 6h leakage under condition 1

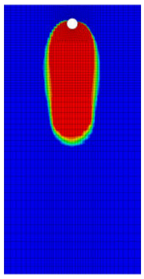

Figure 6 Soil saturation nephogram for 12h leakage under condition 1

After the initial hour, the seepage water diffused 1.08 m horizontally, 1.56 m vertically downward and 0.39 m vertically upward, and after 6 hours, the seepage water diffused 0.61 m horizontally, 4.76 m vertically downward and 0.61 m vertically upward. After 12 hours, the horizontal diffusion range reached 2.18 m, the vertical downward penetration depth reached 8.75 m, and the vertical upward diffusion reached 0.68 m. The horizontal diffusion rate was faster between 1 hour and 6 hours, and then slowed down. This is due to the gradual saturation of soil moisture, which hindered further horizontal diffusion; the vertical downward diffusion rate was faster between 1 hour and 6 hours, and then it slowed down, but still maintained a high penetration rate. This is because gravity promotes the downward penetration of water, especially at the initial stage; the vertical upward diffusion rate is relatively slow, and with the passage of time, the diffusion rate is further slowed down. This is due to the gradual saturation of water in the soil surface and the negative effect of gravity, which hinders the upward diffusion of water.

A. *Influence of Leakage Area on Pipeline Leakage*

Calculate the leakage conditions of the pipeline under working conditions 2 and 3, i.e. leakage area of 100 cm2 and 200 cm2 after leakage occurs for 1 hour, 6 hours and 12 hours. Soil saturation and ground settlement curves under working conditions 2 and 3 are shown in Figure 7-Figure 13:

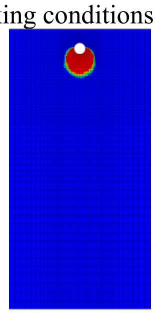

Figure 7 Soil

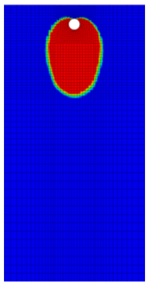

Figure 8 Soil

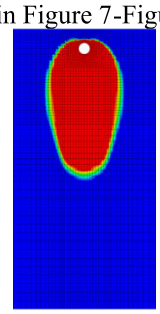

Figure 9 Soil

saturation nephogram for 1h leakage under condition 2

saturation nephogram for 6h leakage under condition 2

saturation nephogram for 12h leakage under condition 2

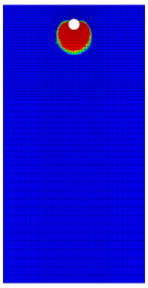

Figure 10 Soil saturation nephogram for 1h leakage under condition 3

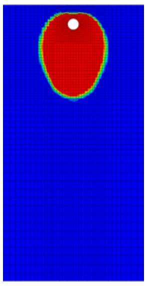

Figure 11 Soil saturation nephogram for 6h leakage under condition 3

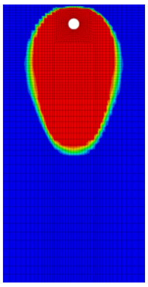

Figure 12 Soil saturation nephogram for 12h leakage under condition 3

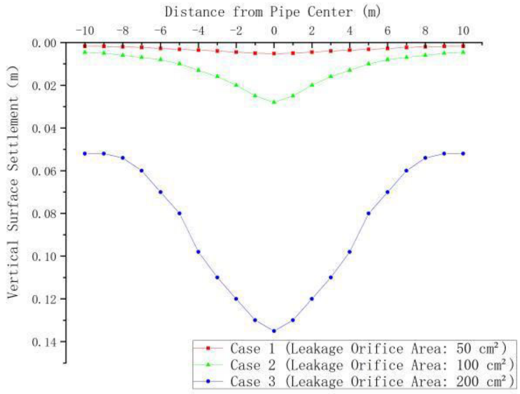

Figure 13 Surface subsidence curves for different leak areas

Figure 4-Figure 13 shows that: when the leakage area is $50cm^2$, the leakage water diffuses upward by 0.68 m, horizontally by 2.18 m, and penetrates downward by 8.75 m within 12 hours; when the leakage area is 100 cm^2, the leakage water diffuses upward by 1.19 m, horizontally by 2.8 m, and penetrates downward by 9 m; when the leakage area is $200cm^2$, the leakage water diffuses upward by 1.68 m, horizontally by 3.5 m, and penetrates downward by 9.1 m. This indicates that the larger the leak area, the larger the diffusion range of seepage water in all directions. As the leak area increases, the penetration depth of seepage water in the vertical downward direction also increases. This is because larger leaks provide more moisture, allowing seepage water to penetrate deeper into the soil. The increase in leak area leads to an increase in seepage velocity, especially in the vertical upward and horizontal directions. This is because larger leakage area allows more water to enter the soil at the same time, thus speeding up the leakage rate. It can be seen from the figure that the volume of high saturation area increases with the increase of leakage area. This indicates that leakage area directly affects the distribution pattern of leakage water in the soil. The larger leakage area, the larger leakage range, and the two are proportional.

When the leakage area is $50cm^2$, the maximum settlement is 0.00516 m; when the leakage area increases to 100 cm^2, the maximum settlement increases to 0.028 m; when the leakage area increases to $200cm^2$, the maximum settlement increases to 0.135 m, and the settlement range also extends to ±8m. The settlement distribution is symmetrical under all working conditions, but the settlement tank with large leakage condition is wider, indicating that the seepage flow diffuses to the periphery with the increase of area, which significantly intensifies the soil compression.

B. Influence of Infiltration Velocity on Pipeline Leakage

When the infiltration velocity is 1e-1m/s and 1e-3m/s, the soil saturation and ground settlement curves after leakage of pipeline are shown in Figure 14-Figure 20:

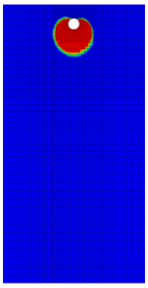

Figure 14 Soil saturation nephogram for 1h leakage under condition 4

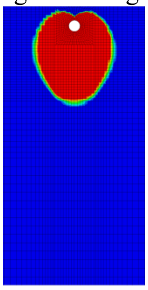

Figure 15 Soil saturation nephogram for 6h leakage under condition 4

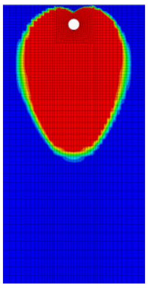

Figure 16 Soil saturation nephogram for 12h leakage under condition 4

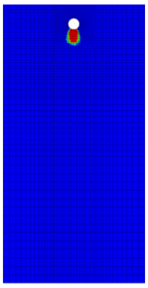

Figure 17 Soil saturation nephogram for 1h leakage under condition 5

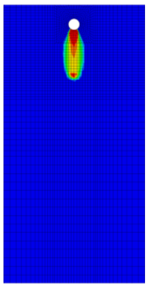

Figure 18 Soil saturation nephogram for 6h leakage under condition 5

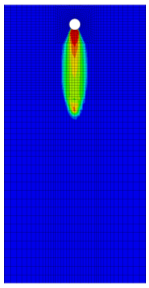

Figure 19 Soil saturation nephogram for 12h leakage under condition 5

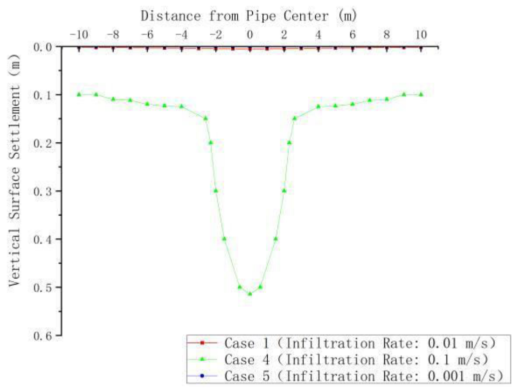

Figure 20 Surface subsidence curves at different infiltration rates

It can be seen from Figure 14-Figure 20 that when the infiltration velocity is 0.001m/s, the seepage water diffuses upward by 0.1m, horizontally by 0.97m, and penetrates downward by 6.45m within 12 hours, and the seepage depth is relatively large. This may be because the soil has enough time to absorb water at this velocity, so that water can penetrate deeper. When the infiltration velocity is 0.01m/s, the seepage water diffuses 0.68m upward, 2.18m horizontally and 8.75m downward. The seepage depth is also large, but the upward diffusion increases obviously. This is because the faster infiltration velocity leads to the accumulation of water in the soil surface layer, thus increasing the upward capillary action. When the infiltration velocity is 0.1m/s, the seepage water diffuses upward by 1.76m, horizontally by 4.17m and downward by 9.51m, which indicates that the infiltration velocity has a significant effect on the seepage range, higher infiltration velocity leads to faster seepage diffusion and slightly increased seepage depth, but the upward diffusion is more significant, because faster infiltration velocity leads to faster upward penetration of water. When the infiltration velocity is 0.001m/s, the seepage form is flat, and the horizontal and vertical diffusion are small. When the infiltration velocity is 0.01m/s, the seepage form is uniform, forming a large elliptical high saturation area. When the infiltration velocity is 0.1m/s, the seepage form is elongated in both vertical and horizontal directions, which is due to the faster infiltration velocity resulting in faster water infiltration.

The data show that the infiltration velocity is 0.1m/s, the maximum settlement is 0.51423m, and the secondary settlement peak appears at ± 3m, which reflects that the seepage is blocked and forms a local high pressure area; the infiltration velocity is 0.001m/s, and the settlement is only 0.00049m, which is evenly distributed and narrow.

C. Influence of Leakage Position on Pipeline Leakage

Figure 21-Figure 27 shows the soil saturation and ground settlement curves after leakage occurs when the leakage position is at the side or top of the pipeline:

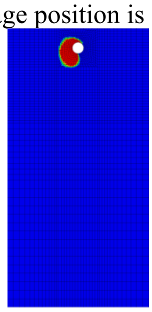
Figure 21 Soil saturation nephogram for 1h leakage under condition 6

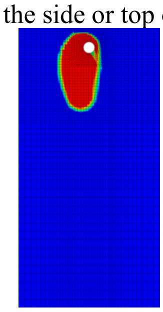
Figure 22 Soil saturation nephogram for 6h leakage under condition 6

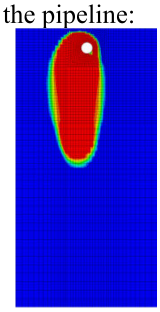
Figure 23 Soil saturation nephogram for 12h leakage under condition 6

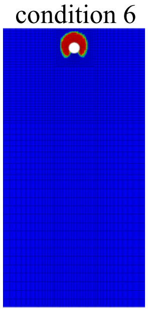
Figure 24 Soil saturation nephogram for 1h leakage under condition 7

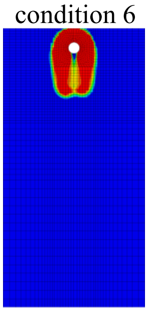
Figure 25 Soil saturation nephogram for 6h leakage under condition 7

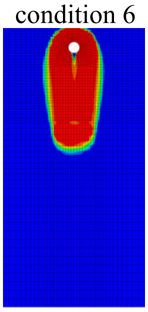
Figure 26 Soil saturation nephogram for 12h leakage under condition 7

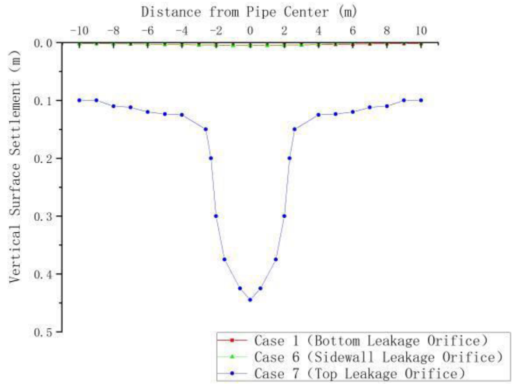

Figure 27 Surface subsidence curves at different leak locations

It can be seen from Figure 21-Figure 27 that: bottom leakage: upward diffusion 0.68m, horizontal diffusion 2.18m, downward penetration 8.75m; side leakage: upward diffusion 1.25m, horizontal diffusion 2.91m to the left, horizontal diffusion 1.34m to the right, downward penetration 8.62m; top leakage: upward diffusion 1m to the surface, horizontal diffusion 2.26m, downward penetration 8.12m. This indicates that the location of the leak has a significant effect on the extent of leakage, with lateral leaks causing uneven horizontal diffusion and top leaks causing moisture to reach the surface directly. The leakage depths at the bottom and lateral leaks are similar, but at the same leakage time, the bottom leakage depth is still greater than the lateral leaks. The leakage depth at the top leak is at a minimum of 8.12 m. This is because the leakage depth is the deepest at the bottom, the second at the side, and the highest at the top. The leakage from the bottom leakage port is symmetrical, forming an elliptical high saturation region. The leakage from the side leakage port is asymmetrical in the horizontal direction, and the diffusion range on one side is larger, because the position of the side leakage port determines that the leakage range to the horizontal side is larger. The leakage from the top leakage port is elongated in the vertical direction, and the leakage position is above the pipeline, and the fastest upward diffusion reaches the surface.

The maximum settlement of bottom leakage is 0.00516m; the maximum settlement of side leakage is 0.0052m; the maximum settlement of top leakage is 0.44481m, which indicates that when the leakage time is fixed, the closer the leakage position is to the ground, the greater the settlement after leakage occurs; the location of leakage directly regulates the spatial distribution characteristics of settlement by changing the seepage direction.

D. Influence of Pipeline Buried Depth on Pipeline Leakage

The soil saturation and ground settlement curves after leakage of pipeline with buried depth of 2m and 3m are shown in Figure 28-Figure 34:

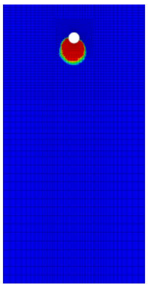

Figure 28 Soil saturation nephogram for 1h leakage under condition 8

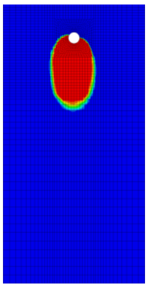

Figure 29 Soil saturation nephogram for 6h leakage under condition 8

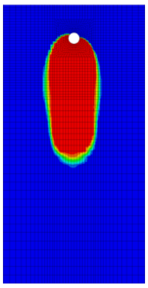

Figure 30 Soil saturation nephogram for 12h leakage under condition 8

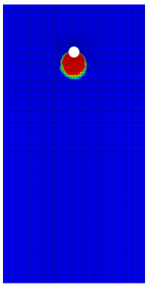

Figure 31 Soil saturation nephogram for 1h leakage under condition 9

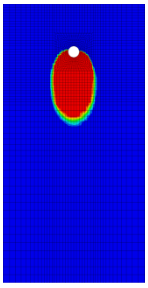

Figure 32 Soil saturation nephogram for 6h leakage under condition 9

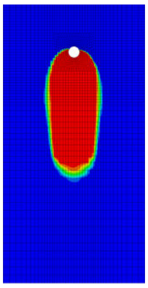

Figure 33 Soil saturation nephogram for 12h leakage under condition 9

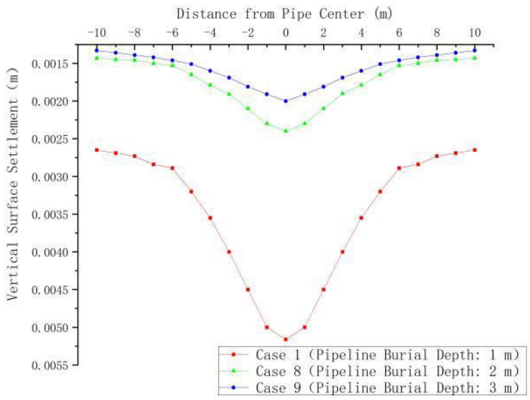

Figure 34 Surface Settlement Curves at Different Pipeline Buried Depth

It can be seen from Figure 28-Figure 34 that Condition 8 and Condition 9 have little difference from Condition 1 in leakage area form and leakage range, so it can be seen that pipeline buried depth has no great influence on leakage form and leakage range of pipeline.

The maximum settlement is 0.00516 m when the buried depth is 1m, 0.0024 m when the buried depth is 2m, and 0.002 m when the buried depth is 3m. The increase of buried depth inhibits soil compression by increasing overlying soil pressure, but leads to the expansion of energy dissipation range, which indicates that the long-term risk of large-scale low-magnitude deformation should be paid attention to.

CONCLUSION

Based on FLAC3D software, this paper constructs a 3D fluid-solid coupling numerical model, systematically analyzes the influence mechanism of underground pipeline leakage on formation collapse, and mainly discusses the quantitative relationship between leakage diffusion and surface settlement by parameters such as leakage area, infiltration velocity, leakage position and pipeline buried depth.

(1) There is a significant positive correlation between the leakage area and the leakage area. When the leakage area increases from 50cm² to 200cm², the horizontal diffusion area expands from 2.18 m to 3.5 m, the vertical downward penetration depth increases from 8.75 m to 9.1 m, and the volume of the high saturation region increases by 1.8 times. This indicates that the large leakage accelerates the process of soil weakening by accelerating the fluid transport capacity. The infiltration velocity has a nonlinear positive correlation with the seepage diffusion rate. When the velocity increases from 1e-3m/s to 1e-1m/s, the vertical upward diffusion distance increases from 0.1 m to 1.76 m, and the horizontal diffusion range expands to 4.17 m. The secondary settlement peak occurs due to high velocity seepage, and the maximum settlement reaches 0.514 m, reflecting the risk of local shear failure. The seepage path of the top leak is the shortest, which directly penetrates to the surface within 12 hours, and the maximum settlement (0.445m) is 86 times higher than that of the bottom leak (0.005m). The asymmetric diffusion caused by the side leak (the horizontal diffusion difference is 1.57m) indicates that the seepage direction has a significant regulation effect on the failure mode of soil mass.

(2) The diffusion rate is the highest at the initial stage of seepage (1-6h), with horizontal and vertical diffusion rates of 0.61 m/h and 0.76 m/h, respectively. After 12h, the saturated permeability coefficient of soil decreases and the diffusion rate attenuates to 30% of the initial value. The settlement amount accounts for 75% of the total deformation at this stage, indicating that the initial stage of seepage is the key window period for disaster prevention and control. The shape of settlement tank is controlled by seepage path, the bottom leakage forms symmetrical elliptical settlement area, while the top leakage causes surface collapse funnel, the maximum settlement gradient reaches 0.15m/m, which significantly increases the risk of ground structure instability.

(3) The leakage area and infiltration velocity are the key factors affecting the leakage diffusion range and settlement amount. The larger the leakage area and infiltration velocity, the larger the settlement amount and leakage range. The leakage position significantly affects the spatial distribution characteristics of settlement by changing the seepage direction. The top leakage leads to the maximum settlement, and the side leakage leads to asymmetric diffusion. The buried depth of the pipeline has a restraining effect on the local settlement amount, but the accumulated effect of long-term low-magnitude deformation should be paid attention to.

This study reveals the quantitative mechanism of stratum collapse induced by pipeline leakage through multi-parameter coupling analysis, which provides theoretical basis and technical support for the safe operation and maintenance of urban underground pipe network. In the future, it can be further combined with machine learning algorithm to construct dynamic assessment model of leakage risk, and promote the development of urban geological disaster prevention and control towards intelligent direction.

REFERENCES

[1] Davies J.P., Clarke B.A., Whiter J.T. Factors influencing the structural deterioration and collapse of rigid sewer pipes [J]. Urban Water, 2001, 3(1/2): 73-89.

[2] Guo Shuai. Study on groundwater infiltration and soil erosion in urban drainage system [D]. Zhejiang University, 2012.

[3] KUANG Jianzheng, ZAN Yuewen, WANG Jie. Theory and Engineering Example of Grouting in Geotechnical Field [M]. Science Press, 2001.

[4] Yang Xiuzhu, Wang Xinghua, Lei Jinshan. Study and application of Bingham slurry diffusion radius [J]. Acta Hydraulica Sinica, 2004,(06):75-79.

[5] Ye Fei, Chen Zhi, Sun Changhai, Han Xingbo, Yang Tao, Ji Ming, et al. Grouting seepage diffusion model for shield tunnel segments considering grout weight [J]. Chinese Journal of Geotechnical Engineering, 2016, 38 (12):2175-2183.

[6] LAN Xiongdong. Study on mechanism of unsaturated strata collapse induced by leakage of underground pipelines in city [D]. Shandong University, 2022.

[7] YANG Zhiquan. Grouting theory and simulation experiment of cement slurry in small-grain sandstone [D]. Kunming University of Science and Technology, 2008.

[8] Alsaydalani M., Clayton C. Internal fluidization in granular soils[J]. Journal of Geotechnical & Geoenvironmental Engineering. 2013, 140(3): 1-10.

[9] Song Guchang, Ye Yuanchun, Liu Qingren. Causes and Countermeasures of Urban Road Collapse in Beijing City [J]. Urban Roads, Bridges and Flood Control,2011,(08):250-252+9.

[10] CHEN Changyan, XIAO Min, JIA Hui, SU Zhaofeng, ZHANG Hui. Discussion on causes of underground diseases of urban roads and engineering classification based on comprehensive detection [J]. Bulletin of Surveying and Mapping, 2013,(S2):5-9.

[11] HUANG Leyi. Study on application of forward modeling and interpretation method of ground penetrating radar for leakage of urban underground water supply pipeline [D]. Beijing Jiaotong University, 2016.