Mechanism analysis of the retaining wall collapse of a foundation pit induced by water supply pipeline burst: A case study

Xiaoping Wei\textsuperscript{1,2*}, Xinpeng Li\textsuperscript{2,3}, Tingting Liu\textsuperscript{2,3}, Yi Luo\textsuperscript{2,3}, Wenzhao Chen\textsuperscript{4} and Zixu Wang\textsuperscript{1}

1 School of Civil Engineering and Architecture, Wuhan University of Technology, Wuhan, Hubei 430070, China
2 Sanya Science and Education Innovation Park of Wuhan University of Technology, Sanya, Hainan 572025, China
3 Hubei Key Laboratory of Road-Bridge and Structure Engineering, Wuhan University of Technology, Wuhan, Hubei 430070, China
4 School of Civil Engineering, University of South China, Hengyang, Hunan 421000, China

Abstract. Once a water supply pipeline bursts, the seepage field of the surrounding soil mass will change, and the safety of the adjacent foundation pit will be affected. In this study, a foundation pit accident was taken as an engineering case. On the basis of fluid-solid coupling theory and COMSOL Multiphysics, the mechanism of the retaining wall collapse induced by the bursting of a water supply pipeline was studied. Results indicated that in the early stage of this collapse, the shear strength of soil mass and the anchoring force weaken gradually. The retaining wall deformation develops slowly. In the late stage, with the failure of the top anchor cable, a continuous sliding surface connecting the retaining wall bottom and the ground surface appears in the soil mass. The retaining wall deformation increases rapidly, and the collapse may occur in a short time. In the construction process of a foundation pit, attention should be paid to the adverse effects caused by the bursting of a water supply pipeline. The monitoring of the anchor cable axial force and retaining wall deformation should be strengthened to ensure the long-term safety of the foundation pit.

1. Introduction
With the development of a city, the surrounding environment of foundation pit construction is becoming increasingly complex\cite{1-3}. The design of a foundation pit support structure should not only ensure its own safety but also reduce the influence on surrounding structures\cite{4}. Otherwise, accidents such as buildings cracking\cite{5}, ground settlement\cite{6}, and underground pipeline damage\cite{7} may occur. When a water supply pipeline is damaged by an excavation, the gushing water will reduce the shear strength of the soil\cite{8} and weaken the anchoring force of the anchor cable\cite{9}, endangering the safety of adjacent foundation pits. Existing studies mostly focused on the effects of construction on stress, deformation, and yield of municipal pipelines\cite{10,11}, including the impact of heavy rainfall on the safety of the foundation pit retaining wall\cite{12}. Few studies have been conducted on the impact of water supply pipeline bursting on the safety of the adjacent foundation pit retaining wall. In this study, a practical
engineering accident case in Nanning was taken as the research object to analyze and discuss the mechanism of the retaining wall collapse induced by the bursting of a water supply pipeline.

2. Characteristics of the foundation pit collapse
A real estate project in Nanning City is conducted at the intersection of Dongge Road and Xiangzhu Avenue, with a total building surface of approximately 1.03 million m². The project is developed by stages in which the construction site of Plot D (Phase II) is located at the south of Dongge Road. Figure 1 shows a satellite photo and the engineering site condition.

![Satellite image and project field photo](image)

**Figure 1.** Overview of the foundation pit
The supporting system of the foundation pit adopts the supporting pile and anchor cable. The supporting parameters are designed in different sections. The supporting structure of the foundation pit north side adjacent to Dongge Road (i.e., the yellow area in Figure 1(b)) adopts a Ф1000 mm cast-in pile with an interval of 1600 mm, and four rows of prestressed anchor cables are set between the piles, with an interval of 5 m for each row. The field soil layer contains artificial soil, strongly weathered mudstone, highly weathered argillaceous siltstone, and moderately weathered mudstone. Site groundwater is phreatic, whereas the stable water level is below ground 5 m. The design of the supporting structure of the north side of the foundation pit is displayed in Figure 2.

![Design of the north support structure](image)

**Figure 2.** Design of the north support structure of the foundation pit
Before May 25, 2019, a water supply pipeline with a diameter of 500 mm burst, and a gushing accident occurred on the north side of the foundation pit, which caused partial cracking of the concrete surface layer of the retaining wall of the foundation pit; the deformation of the supporting structure was still in the safe range. On the morning of June 8, 2019, the site monitoring personnel found that the deformation of the supporting structure on the north side of the foundation pit increased, which exceeded the warning value. The project was stopped, and emergency measures were taken. At around 17:30, the north side of the foundation pit collapsed. The collapse area was
approximately 60 m long, causing half of the road surface to collapse. No casualties were reported. The collapse process of the north side of the foundation pit is illustrated in Figure 3.

![Figure 3](image)

(a) Top view of the scene after the water gushing accident  
(b) Side view of the scene after the water gushing accident  
(c) Retaining wall collapse process I  
(d) Retaining wall collapse process II

**Figure 3.** Process of the foundation pit collapse[13]

As shown in Figures 3(a) and (b), the bursting of the water supply pipeline damaged the concrete surface layer between the crown beam and the first waist beam of the foundation pit. As seen in Figures 3(c) and (d), during the process of retaining wall collapse, the maximum horizontal displacement point was the top of the retaining wall, and the retaining structure rotated around a point on its lower part. It shows that the anchor cable on the retaining wall top failed first, resulting in the increase of the top horizontal displacement, which led to the overall failure of the supporting structure. The investigation team concluded that the main reason for the collapse was that the water supply pipeline on the north side of the foundation pit burst, which caused the complete failure of the anchor cable and the collapse of the retaining wall into the pit.

The process of the retaining wall collapse induced by the bursting of a water supply pipeline can be divided into two stages. In the early stage of long duration, the deformation value of the retaining wall changes slowly and in the safety range. In the later stage of short duration, the deformation value of the retaining wall develops rapidly and soon exceeds the safety value. Subsequently, the collapse occurs in a short time. However, the mechanism of each period is still unclear, and further exploration is needed to provide reference for future projects.

### 3. Numerical simulations and comparisons

#### 3.1 Introduction of the Poroelasticity Multiphysics coupling node

COMSOL Multiphysics has a powerful multi-field coupling solution capability, which has been widely used in the field of geotechnical engineering. The poroelasticity Multiphysics coupling node in the software refers to Biot’s consolidation theory[14] and introduces the water storage coefficient $S$. The equation is as follows:

$$
\rho_f S \frac{\partial p}{\partial t} + \nabla \cdot (\rho_f \mathbf{u}) = -\rho_f \alpha_B \frac{\partial}{\partial t} \varepsilon_{vol} \tag{1}
$$

$$
\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla \sigma + \mathbf{f}_V. \tag{2}
$$

Among them,

$$
S = \frac{\varepsilon_p}{K_f} + \frac{\alpha_B - \varepsilon_p}{K_S} \tag{3}
$$

$$
\sigma = C\varepsilon - \alpha_B \rho \mathbf{f}, \tag{4}
$$

where $\rho_f$ is the fluid density; $\rho$ is the density of porous media; $p$ is the pore pressure; $\mathbf{u}$ is the Darcy velocity; $\alpha_B$ is the Biot–Willis coefficient; $\varepsilon_{vol}$ is the strain change of the inhomogeneous body; $\sigma$ is the stress; $\mathbf{f}_V$ is the volume load; $S$ is the water storage coefficient; $\varepsilon_p$ is the porosity of porous media; $K_f$ is the compressibility of the fluid; $K_S$ is the elastic coefficient of solid; $\varepsilon$ is the strain.
3.2 Introduction of the numerical model
To highlight the influence of pipe bursting on the safety of the retaining wall of the foundation pit, this study does not consider the excavation process of the foundation pit and instead establishes a geometric model on the basis of the state of the completed foundation pit excavation. The overall width of the model is 80.0 m, and the depth is 40.0 m, among which the depth of the foundation pit is 22.2 m. The thickness of the pile in the numerical model is 0.72 m based on the equivalent stiffness method. The geometric dimensions of the model are shown in Figure 4.

Figure 4. Geometrical overview of the model
To simplify the analysis, the process of water gushing and stopping is ignored in the model analysis. The outlet section during water gushing is assumed to be the whole cross section of the pipeline. The difference between the roadbed and the ground layer is ignored, and the dynamic load of the vehicle is replaced by the static load. The applied range is the area corresponding to the actual road on the top of the model.
To study the mechanism of the retaining wall collapse of the foundation pit induced by the bursting of a water supply pipeline, the solid mechanics, Darcy’s law, truss module, and poroelasticity Multiphysics coupling interface in COMSOL Multiphysics are selected. The Mohr–Coulomb constitutive model is used for the soil mass, which is in saturated state. The porous elastic storage model is also employed, and the seepage flow satisfies Darcy’s law. The linear elastic material model is used for anchor cable and retaining wall. In the model, the material parameters of the soil mass, retaining wall, and anchor cable are calculated by referring to the engineering investigation data (i.e., Tables 1 and 2). The material parameters of water are obtained according to the software built-in material model. Pipeline water gushing is simulated by “well.” The sectional area and pressure are assigned according to the actual situation.

Table 1. Material parameters of soil layers

| Soil layer                        | Density (kg/m³) | Modulus of elasticity (MPa) | Cohesion (kPa) | Internal friction angle (°) | Permeability coefficient (cm/s) |
|-----------------------------------|-----------------|----------------------------|----------------|-----------------------------|---------------------------------|
| Artificial soil                   | 1800            | 3                          | 15 (10)        | 7 (5)                       | 2.5e-4                          |
| Strongly weathered mudstone       | 2100            | 15                         | 75             | 15                          | 1.6e-4                          |
| Highly weathered argillaceous siltstone | 2180          | 20                         | 40             | 30                          | 9.3e-3                          |
| Moderately weathered mudstone     | 2190            | 18                         | 150            | 20                          | 6.6e-4                          |

Table 2. Material parameter table of the supporting structure

| Part                | Modulus of elasticity (MPa) | Poisson’s ratio | Density (kg/m³) |
|---------------------|------------------------------|-----------------|-----------------|
| Retaining wall      | 3e4                          | 0.15            | 2385            |
| Anchor cable        | 1.95e5                       | 0.3             | 7864            |
3.3 Comparison of numerical model analysis results with field conditions

The appearance of the foundation pit after collapse is compared with the results of the numerical model analysis, as displayed in Figure 5.

![Figure 5. Comparison of collapse appearance and numerical simulation results](image)

From Figure 5, the displacement revealed by the numerical simulation is almost consistent with the middle part of the actual collapse section, indicating that the numerical model is in good agreement with the actual engineering.

The effective plastic strain distribution of soil mass before and after the top anchor cable failure is compared, as shown in Figure 6.

![Figure 6. Nephogram of the effective plastic strain](image)

From Figure 6, before the top anchor cable failure, the effective plastic strain area of the soil is mainly located in the bottom area of the retaining wall and the soil of the first layer, and no continuous plastic deformation area is formed. After the top anchor cable failure, the effective plastic strain area of the first layer soil mass is more developed than that in the normal operation of the supporting structure. The plastic deformation area appears in the second layer soil, and the continuous plastic deformation area appears in the soil mass outside the foundation pit from the surface to the bottom of the retaining wall. Combined with Figure 5 (b), the continuous plastic deformation area is the sliding surface, suggesting that the top anchor cable failure leads to the continuous sliding surface of soil outside the foundation pit, which is the reason for the foundation pit collapse accident.

4. Different durations of water gushing on the impact of the foundation pit analysis

4.1 Influence of water gushing time on the waterhead of the pile retained side

Figure 7 illustrates the waterhead curves of the pile retained side under different water gushing durations and compares them with the site situation of the foundation pit water gushing. In the figure, \( t \) is the duration of water gushing.
Figure 7. Comparison of the numerical simulation results with the water gushing situation
From Figure 7(a), the waterhead at each point of the pile retained side increases with time, whereas the growth rate decreases. The reason is that the seepage path between the water gushing point and the outside is gradually stable. The waterhead varies significantly within a depth of approximately 9 m from the pile top, and the highest value of the water head appears in the interval from the pile top to 5 m deep (i.e., the area between the crown beam and the first waist beam), indicating that water gushing is the most affected within this interval. This indication conforms to the characteristics of water gushing in the field shown in Figure 7(b).

4.2 Influence of water gushing time on the deformation of the foundation pit retaining wall
The bursting of the water supply pipeline increases the lateral force and deformation of the retaining wall of the foundation pit. The deformation data of the retaining wall under different water gushing durations are selected, whereas those before water gushing are subtracted. Then, the horizontal displacement change curves of the retaining wall under different water gushing durations are drawn, as illustrated in Figure 8. The negative value in the figure refers to the displacement into the foundation pit, and \( t \) is the duration of water gushing.

Figure 8. Horizontal displacement of the retaining wall under different water gushing durations
As displayed in Figure 8, the horizontal displacement of the retaining wall increases with time, but the change value per unit time tends to be stable with time. The reason is that the bursting of the pipeline increases the soil and water pressures in the surrounding soil mass, leading to the increase of the deformation of the retaining wall. However, with the gradual connection between the pipeline and the external seepage path, the soil and water pressures tend to be stable, including the retaining wall displacement.

At different times, the maximum horizontal displacement change point is the top of the retaining wall, and the change value increases with time. When duration comes to 100 minutes, the horizontal displacement of the retaining wall top changes by approximately 0.95 mm. It shows that the nearby water supply pipeline burst has little effect on the deformation of the foundation pit.
retaining structure, when the retaining wall and fixed condition (including pile bottom and anchor cable) are in normal operation.

4.3 Influence of water gushing time on ground surface deformation

The bursting of the water supply pipeline increases the stress on the overlying soil mass, which leads to the uplift and deformation of the ground surface. The surface subsidence data under different water gushing durations are selected, whereas those before water gushing are subtracted. Subsequently, the surface subsidence change curves under different water gushing durations are drawn, as shown in Figure 9. The positive values in the figure refer to the ground surface uplift, and \( t \) is the duration of water gushing.

![Figure 9. Surface subsidence change under different water gushing durations](image)

Figure 9. Surface subsidence change under different water gushing durations

Figure 9 displays that the ground surface is uplift at all times, and the uplift growth rate with time. The maximum surface uplift point is located directly above the pipeline, and the maximum vertical deformation in 100 minutes is approximately 22 mm. The reason is that the seepage path between this point and the pipeline is the shortest, and the seepage force is the largest. However, the vertical displacement of the surface is less than 2.5 mm outside the range of 5 m from the pipeline surface projection point and tends to be 0 mm outside the range of 20 m. Thus, the pipeline burst has a great influence on the surface deformation directly above, but the influence range is limited. The amplitude of the surface uplift decreases rapidly with the increase of horizontal distance from the pipeline.

5. Conclusions and recommendations

1. The bursting of a water supply pipeline can greatly increase the water pressure in the surrounding soil layer with good permeability, which can cause the local damage of the retaining wall surface layer of the foundation pit. The lateral pressure on the retaining wall increases, but the deformation is not large when the retaining wall strength and the embedded condition (including the pile bottom and anchor cable) are in normal operation.

2. The water supply pipeline burst has a great influence on the ground surface uplift deformation, but the influence range is limited. The amplitude of the surface uplift decreases rapidly with the increase of the horizontal distance from the pipeline.

3. In the early stage of the retaining wall collapse induced by the bursting of the water supply pipeline, the shear strength of soil around the water gushing point and the anchoring force of the anchor cable weaken. The deformation of the supporting structure of the foundation pit develops slowly. In the late stage, with the failure of the top anchor cable, a continuous sliding surface connecting the pile bottom and the ground surface appears in the soil outside the foundation pit. The deformation of the supporting structure increases rapidly, and the collapse may occur in a short time.

When a water supply pipeline bursts and water gushing occurs in foundation pit construction, attention should be paid to the adverse effects caused by water gushing, such as the increase of soil
weight, the decrease of soil shear strength, and the weakening of the anchor cable anchoring force. The monitoring of the anchor cable axial force and retaining wall deformation must be strengthened, and timely measures should be taken to ensure the long-term safety of foundation pits.

6. References
[1] Li M G, Zhang Z J, Chen J J, Wang J H and Xu A J 2017 Zoned and staged construction of an underground complex in Shanghai soft clay Tunn. Undergr. Space Technol. 67 187-200
[2] Bian X C, Hu H Q, Zhao C, Ye J N and Chen Y M 2021 Protective effect of partition excavations of a large-deep foundation pit on adjacent tunnels in soft soils: a case study Bull. Eng. Geol. Environ. 1-15
[3] Chen R P, Meng F Y, Li Z C, Ye Y H and Ye J N 2016 Investigation of response of metro tunnels due to adjacent large excavation and protective measures in soft soils Tunn. Undergr. Space Technol. 58 224-35
[4] Li Z, Han M, Liu L L, Li Y Y and Yan S H 2020 Corner and partition wall effects on the settlement of a historical building near a supported subway excavation in soft soil Comput. Geotech. 128 103805
[5] Bovolenta R and Bencich A 2021 Effect of deep excavations and deformable retaining structures on neighboring buildings: a case study Eng. Fail. Anal. 122 105269
[6] Zhang X M, Yang J S, Zhang Y X and Gao Y F 2018 Cause investigation of damages in existing building adjacent to foundation pit in construction Eng. Fail. Anal. 83 117-24
[7] Liu X B, Zhang H, Xia M Y, Wu K, Chen Y F, Zheng Q and Li J 2018 Mechanical response of buried polyethylene pipelines under excavation load during pavement construction Eng. Fail. Anal. 90 355-70.
[8] Al-Shayea N A 2001 The combined effect of clay and moisture content on the behavior of remolded unsaturated soils Eng. Geol. 62(4) 319-42
[9] Xie C, Li S C, Li S C, Liao Q K and Zhao S S 2017 Study of anchorage force loss of anchor cable under seepage flow and soil creep Rock and Soil Mechanics 38(08) 2313-21+34
[10] Luo X P, Lu S L, Shi J F, Li X and Zheng J Y 2015 Numerical simulation of strength failure of buried polyethylene pipe under foundation settlement Eng. Fail. Anal. 48 144-52
[11] Zhang J, Xie R and Zhang H 2018 Mechanical response analysis of the buried due to adjacent foundation pit excavation Tunn. Undergr. Space Technol. 78 135-45
[12] Wang Y, Zhang Y J, Li M F, Qi Y and Ma T H 2021 A Numerical Investigation of the Deformation Mechanism of a Large Metro Station Foundation Pit under the Influence of Hydromechanical Processes Geofluids 2021 5536137
[13] Li M 2019 Broken strings in June ・ Foundation pit collapse of Nanning Greenland Central Square https://zhuanlan.zhihu.com/p/83059467
[14] Biot M A 1941 General theory of three - dimensional consolidation J. Appl. Phys. 12(2) 155-64

Acknowledgments
This work was supported by the major science and technology projects of Sanya Yazhou Bay Science and Technology City Administration (SKJC-KJ-2019KY02) and the National Natural Science Foundation of China (51774222 and 51779197).