Experiment and numerical simulation on seepage failure of sand caused by leakage of underground water pipe

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Abstract. Underground water pipe leakage accident is a serious threat to the city road and people's life safety, the internal mechanism is necessary to carry out related study. In this paper, numerical simulation technology and model test device was used for researching on the effect of different factors on the seepage failure of sand. The research shows that the evolutionary process of sand seepage failure induced by underground water pipe leakage can be divided into three stages: unfluidized stage, stable cavity stage and fluidized stage. At the initial stage, the pressure distribution at different height reaches a peak with the increment of water pressure and flow rate. When the water pressure and flow rate is beyond the peak, cavity would occur at leakage hole. Under the action of seepage force, the cavity would dissipate at the surface of soil, and the distribution of fluidized bed pressure would maintain a stable state. Moreover, the smaller the leakage diameter, the greater the critical water pressure is. In a numerical test of a wedge angle of 62 degrees, F (upward drag force) is equal to the W (weight of wedge), which indicates the cavity reaches a force balance. The wedge with an angle of 62 degrees is significant to the sample model used in numerical simulation.

1 Introduction
With the process of urbanization development, it brings huge conveniences to people by underground pipeline transportation. However, the city underground pipeline burst leakage caused by accident in an endless stream due to historical reasons, the soil pollution and poor corrosion resistance of pipeline. The rise of underground water level caused by pipeline leakage makes bearing capacity of local pavement with extremely decline under the action of water-soil fluid coupling, which causes sudden collapse of the road.

At the present stage, it is still in the exploratory stage for the research on underground water pipe leakage. The soil flowing phenomenon appear in sand under the influence of hydraulic penetration. The small particles gradually break away from the soil skeleton and cause erosion of the internal structure of the soil, which is the piping phenomenon under the action of seepage [1]. The loss of fine particles will change the inner pore structure of soil, thus affecting the physical properties of soil [2-4]. The flow of sand and water is essentially a complex mixing flow when sand soil occurs the seepage failure cause by leakage of underground pipe. Away from the place of leakage, water exists in the form of porous media flow; While near the place of leakage, water exists in the form of pore flow. The hydraulic effect of mixed flow is related to the size of leaking diameter, permeability of soil, reynolds number at leak hole and other factors, it is difficult to describe it in a unified formula [5,6]. Some scholars preliminarily analyzed the evolution of sand seepage process [7-9], but it is difficult to explain deeply its mechanism. Alsaydalani [10] found that a lifting cavity would occur in radical
direction in the leakage of underground water pipe model test when the pore water pressure reaches a critical value. However, the Alsaydalani model test adopted the vertical baffle, which made the leakage of seepage water in the soil basically consistent with the horizontal distribution hypothesis. Some experts and scholars found that leakage of underground water pipe flow is subject to radial seepage distribution in massive tests[11,12]. Obviously, the test model of Alsaydalani is difficult to accurately simulate the actual damage characteristics of sand.

In this paper, a set of related seepage model device and numerical simulation are used for researching on the effect of leakage diameter, water pressure and flow rate on the seepage failure of sand.

2 Model test
In the test model (see Figure 1), the rectangular box is made of polymethyl methacrylate material. The test device is distributed with 6 measuring tubes above the leakage vertically to measure pore water pressure. A drainage groove is arranged above the test box, and a pressure sensor and a flow meter are installed in the middle of the pipeline connecting the closed water tank and the water storage tank.

![Fig.1 Model test device](image)

The physical parameters of sand are shown in Table 1. Selection of leakage diameter is 1mm, 1.5mm and 3mm, and then increasing the water pressure from 0.01MPa to 0.05MPa in turn, and the head of 6 piezometer tubes was observed and recorded. Taking the leakage water pressure as the abscissa and the water head as the ordinate to draw a scatter diagram according to the test results, as shown in Figure 2.

| $d_{10}$/mm | $d_{30}$/mm | $d_{60}$/mm | $C_U$ | $C_C$ | Gs |
|-------------|-------------|-------------|-------|-------|----|
| 0.3         | 0.6         | 0.85        | 2.83  | 1.41  | 2.65 |
Figure 2 shows that different height of water head curve firstly increased and then declined with the increasing of leakage water pressure. In near the water head of leakage hole (especially 5cm) showed obvious peak. Cavity phenomenon occurred in the experiment process when the pressure of water leakage surpass the pressure corresponding to the peak. The test box can be observed in a full-water hole above the leakage orifice (see figure 3). The formation of the peak value is closely related to the cavity. The peak value is defined as the critical pressure. Leakage diameter is 1mm, the critical pressure is 0.03MPa; The critical water pressure is 0.02MPa at leakage diameter 1.5mm, 3mm. It shows that the smaller leakage diameter is, the greater critical water pressure is. Water head keep stable with the advancement of leakage water pressure, at the meantime, the soil skeleton of sample had been destroyed thoroughly.

3 Numerical simulation

3.1 Numerical model

As described in the previous section, a stable cavity was observed in the model test. In order to explore the internal mechanisms, there have carried out the numerical simulation of cavity formation to investigate the changes of flow field and the mechanism of cavity. The numerical model is established by FPS-BHAM to rebuild a granular bed submerged under water (see Figure 3), and detailed modeling methods and procedures are presented in document[11].
3.2 Pressure distribution
According to the test result, which is drawing the variation of bed height and water pressure at different flow rates (see Figure 4). Figure 4.a is the numerical simulation results, figure 4.b is Alsaydalani’s model experiment result[10]. The different height of pore water pressure change trend can be clearly seen that pore water pressure increases to a peak (at A point) along with the increase of flow rate, and the closer leakage distance is, the more obvious peak is. Once more than peak the corresponding to flow (at B point), pore water pressure began to decline, which is quite similar to the test law of the section 2. The leakage of a stable cavity occurred when the flow rates more than A, as shown in Figure 5. It represents a unique phenomenon that cavity is the leakage of underground water pipe caused by sand seepage failure.

3.3 Evolutionary process
The leakage of underground water pipe and the failure of sand seepage can be divided into 3 stages (non fluidization stage, stable cavity stage and fluidization stage).

The first stage: the non fluidization stage, the soil remains the same. In the early stage of the
leakage, the pore water pressure at the top of the leakage is accumulated until it reaches the seepage stability state, but it is always less than the critical value of the flow soil.

The second stage: stable empty stage, when the water leakage increased to a certain extent, the soil pore water pressure on the difference increases to a critical value. The cavity is formed at the place of leakage hole, then the cavity growing until reaches a steady state. The inside of cavity can be observed with the rotating vortex and moving soil particles.

The third stage: the fluidization stage, when the cavity continue to grow to the soil surface, a large number of soil particles are brought to the soil surface with the water pressure, the formation of a stable soil interaction in mixed flow at the leakage hole to the surface.

4 The mechanism of stable cavity
The inclination wedge angle of $\chi$ in the numerical model is drawing, as shown Figure 6, the upward drag forces (F) calculated by IMB are counted the whole particles within the wedge. Besides, the weigh of wedge(W) is also calculated by accumulating the weight of whole particles in the wedge.

![Image](a) Before fluidization occurs  \hspace{1cm} (b) After the cavity stabilizes

**Fig.6 A wedge drawn for force calculations**

Figure 7 shows the evolutionary process of F and W with different values of $\chi$. W undergoes a small increase between 4s and 5s. It is easily seen that there are a large number of particles within the wedge area at 5s compared with 4s by counting the number of particles. This is chiefly reason because of the cavity emergence, where the pressures on two sides are suddenly discharged in the lifting process and the particles beside the wedge come into it. Moreover, F initially increases to the peak value and declines till a stable state. It is deemed that the decrease is induced by the pressure decline in the nearby of the leakage hole during cavity evolutionary process.
As described in Section 2, there is an inclination angle of 62° in the real uplifting area. Seen from Figure 8.c, it is approved that there are reaching equal to one another between F and W during 4s and 5s when interstitial fluid is initialized, it verifies to exist a force balance in the evolution of seepage. Moreover, F begins to decline and become less than W. It is therefore said that a mechanism refers to the force balance so as to hamper the cavity from destruction due to the additional weight.

It is seen from Figure 8, the additional weight after the production of cavity that is the wedge angle of 62° is lower than that the wedge angle of 62°. Hence, it is obviously seen that the balance of force can be more easily achieved by the upward resistance forces. F is less than W during the all test process for a wedge with lower than 62°, Therefore, fluidization cannot be occurred. This is the reason why the wedge angle of 62° comes out a critical point for the test served for the numerical simulation.

5 Conclusion
This thesis aims to study the leakage of water-soil interaction, the conclusions are as follows:

(1) Experimental and numerical simulation results show that the different height of pore water pressures reach a peak with the increment of water pressure and flow rate, a stable cavity is formed above the leakage hole when the water pressure is greater than the peak. The cavity has been rising to the surface to dissipate when exceed the critical water pressure of sand, and then each height with pressures almost remain unchanged. The smaller leakage diameter is, the greater critical pressure is.

(2) The process of sand seepage failure caused by leakage of underground water pipe can be divided into 3 stages, i.e, non fluidization stage, cavity stage and fluidization stage. The stable cavity stage is the link between the soil seepage and the final soil skeleton destruction.

(3) In the numerical test of the wedge with an angle of 62°, it is found that the F and W become equal to each other at the beginning of the fluidization phenomenon. For wedges with an angle of less
than 62°, fluidization can not occur when F is less than W throughout the test period.

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References
[1] KOVACS G. Preparing test specimen using under compaction[J]. Geotechnical Testing Journal, 1981, 1: 16–23.
[2] Zhou Jian, Yao Zhixiong, Zhang Gang. Mesomechanical simulation of seepage flow in sandy soil[J]. Chinese Journal of Geotechnical Engineering, 2007, (07): 977-981.
[3] Li Xian, Chen Wenjun, Deng Yahong, et al. Formula Derivation of the Critical Condition of Sub-Ground Erosion[J]. Research of Soil and Water Conservation 2010, 17(5): 217-221
[4] Luo Yulong, Wu Qiang, Zhan Meili, et al. Development of seepage-erosion-stress coupling piping test apparatus and its primary application[J]. Chinese Journal of Rock Mechanics and Engineering, 2013, 32(10): 2108-2114
[5] Niven, R.K., Khalili, N. In situ fluidization by a single internal vertical jet[J]. Journal of Hydraulic Research, 1998, 36(2): 199-228.
[6] Van Zyl, J.E., Clayton C.R.I. The effect of pressure on leakage in water distribution systems[J]. Water Management, 2007, 160(WM2): 109-114.
[7] Rogers, C.D.F., Chapman, D.N., Royal, A.C.D. Experimental investigation of the effects of soil properties on leakage: final report[R]. University of Birmingham, Birmingham, 2008.
[8] Zoueshtiagh, F., Merlen, A. Effect of a vertically flowing water jet underneath a granular bed,[J]. Physical Review E, 2007, 75: 056313.
[9] Philippe, P., Badiane, M. Localized fluidization in a granular medium[J]. Physcial Review E, 2013, 87(4): 042206.
[10] Alsaydalani M. Internal fluidization of granular material[J]. Journal of Clinical Investigation, 2010, 54(2):316-325.
[11] Cui, X. Numerical simulation of internal fluidisation and cavity evolution due to a leaking pipe using the coupled DEM-LBM technique[D]. Birmingham: the University of Birmingham, 2012.
[12] Cui, X., Li, J., Chan, A., et al. Coupled DEM-LBM simulation of internal fluidisation induced by a leaking pipe[J]. Powder Technology, 2014, 254: 299-306. 2003.