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Experimental study on seepage erosion induced by pipeline damage under full pipe flow condition

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Abstract: Aiming at the problems of ground settlement induced by the underground pipeline damage in water-rich sand layer, a set of visualization experimental device was designed. For these cases of 11 kinds of sand samples with particle size of soil d_{90}=1.45~8.45mm and 5 kinds of full pipe flow velocity, the behavior of ground settlement induced by seepage erosion was studied. Research showed that: (1) There are three modes of seepage erosion induced by pipeline damage: only water inrush without settlement, soil arching formation with settlement, and sand crushing with settlement; (2) The particle size of soil , damaged mouth size and thick-span ratio are the main factors determining the seepage erosion mode of soil; (3) When the soil arching or sand crushing is formed in the soil above the damaged mouth of pipeline, the relationship between the particle size of soil d_{90} and the thick-span ratio r is that: when $8.0 \geqslant r \geqslant 4.2$, the d_{90} decreases parabolically with the increase of r; when $12.5 \geqslant r \geqslant 8.0$, d_{90} remains unchanged; (4) When the soil arching or sand crushing is formed in the soil above the damaged mouth of pipeline, the initial settlement radius and settlement depth with the flow velocity of 0 are determined by the ratio (D/d_{50}) of the damaged mouth diameter D and the average particle size of soil d_{50} ; the settlement radius and depth increase linearly with the increase of full pipe flow velocity; when the soil arching is formed, the expansion velocity (V_L、V_H) of settlement radius and settlement depth with the increase of flow velocity is logarithmic to D/d_{50}; When the sand crushing is formed, the expansion velocity V_L of settlement radius with the increase of flow velocity is that, when $23.0 \geqslant D/d_{50} \geqslant 6.0$, it increases linearly with the increase of D/d_{50}; when $42.0 \geqslant D/d_{50} \geqslant 23.0$, it decreases logarithmically with the increase of D/d_{50}.

Keywords: seepage erosion; settlement; thick-span ratio; flow velocity; particle size

1 Introduction

In recent years, the collapse accidents of urban road have increased dramatically. The reason is mainly the loss of soil and water below the surface, resulting in concealed cavity. When the soil above the cavity cannot bear the overlying load, surface subsidence or even ground collapse will occur, which seriously threatens the safety of ground traffic, construction and pedestrians[1]. According to the statistics of domestic road collapse cases, seepage erosion induced by underground pipeline damage is one of the main causes of underground cavity[2]. In China, the ability of deformation resistance of underground pipeline is poor, the early laid pipeline is seriously corroded and generally damaged, which provides a new way for soil erosion. If the prevention and control is not effective, the surface subsidence or even collapse is very easy to occur under the action of external load. Such accidents often are sudden, harmful and unpredictable[3].

At present, the research on seepage erosion induced by underground pipeline damage mainly focuses on the detection of underground cavity by engineering geophysical exploration, such as geological radar detection[4,5]. There are few researches on the mechanism of disaster development and its influencing factors. Because of the concealment of underground pipeline, the evolution process of seepage erosion induced by pipeline damage is difficult to observe on site. Therefore, the method of indoor model experiment is mostly adopted by scholars at home and abroad.

Jones et al.[6-7] based on a large number of field investigations, qualitatively stated that the size of damaged mouth of pipes, the groundwater level, the full pipe flow velocity and the nature of soil are the main factors for the seepage erosion induced by the pipeline damage, and the probability of seepage erosion is the highest in the sandy stratum. Reiko et al.[8], through the experiment of circulation erosion sand channel and unidirectional seepage erosion sand channel of underground pipeline damage, found that, in the uniform-graded fine sand, when seepage erosion is induced by pipeline damage, the erosion range extends from the damaged mouth to the soil surface. Guo et al.[9] studied the erosion process of the sand layer induced by the damage of underground pipeline in the uniform-graded fine sand through the indoor experiment, and deduced the calculation formula of the erosion pit induced by the seepage erosion of soil. Tang et al.[10] simulated the process of soil erosion induced by pipeline damage in uniform-graded fine sand by indoor experiment and numerical simulation, and found that the loss of particles will form a soil arch around the damaged mouth. When the damaged

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mouth is further expanded, the soil arch will damage and intensify the loss of water and sand. The objects of the above researches are mainly the uniform-graded fine sands. In the actual stratum, the most common is the uneven graded sand layer mixed with coarse and fine particles. The seepage erosion mechanism of the sand layer with coarse soil skeleton is obviously different from that of the homogeneous fine sand without coarse soil skeleton[11-12].

He et al.[13] used the self-designed experimental device to simulate the seepage erosion of the soil at the damaged mouth under the condition of partially-filled flow of the pipeline, and analyzed the influence of sand gradation, groundwater level, the size of the damaged mouth and other factors on the seepage erosion of the soil. It was found that under the partially-filled flow condition, there are three erosion failure modes of soil, namely, no erosion, stable hole formation, and complete fluidization. The particle size and the size of the damaged mouth have important influence on the occurrence condition of the failure mode and the size of the erosion pit. Zhang et al. [14], through model experiment, simulated the seepage erosion process of uneven graded sand due to pipeline damage under the partially-filled flow condition, analyzed the development of soil erosion and erosion area, and revealed that the erosion process of discontinuous graded sand can be divided into three stages: fast erosion, stable erosion and convergence. The above study only aims at the special working condition of the pipeline without full pipe flow. The field investigation shows that: when the pipeline is full of flowing water (i.e. full flow), the probability of soil seepage erosion will increase, and the full pipe flow velocity is an important factor affecting soil seepage erosion[6-7].

In reality, the flow velocity of the underground pipeline under the full flow condition often fluctuates obviously due to the change of rainfall infiltration, drainage and so on. Under the condition of rainstorm, the full pipe flow velocity will increase obviously, which will aggravate the soil loss at the damaged mouth, and then induce ground settlement or collapse. However, there are few reports about the research of full pipe flow velocity on the seepage erosion of soil induced by the pipeline damage. For this reason, a self-designed visualization experimental device was used to simulate the process of seepage erosion induced by pipeline damage under different full pipe flow velocities, and the behavior of settlement induced by seepage erosion of damaged pipelines under different full pipe flow velocities was studied, in order to provide reference for the prediction and prevention of surface subsidence induced by pipeline breakage.

2 Experimental device and methods

2.1 Experimental device

The self-designed experimental device is shown in Fig. 1, which was composed of main test chamber, simulated underground pipeline, full pipe flow simulation system, water supply system and water sand collection system.

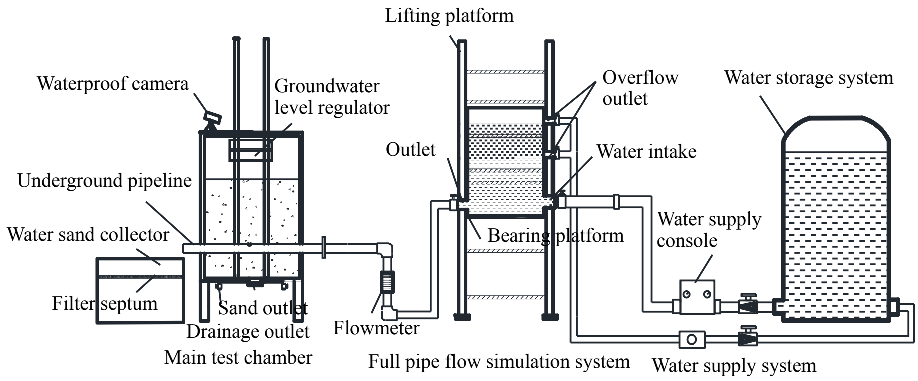

Fig.1 Experimental device system

The main test chamber is shown in Fig. 2, firstly, a skeleton with length, width and height of 1000mm, 600mm and 1200mm was made of 5mm thick steel plate, and then the tempered glass with thickness of 15mm was tightly pasted on the inner wall of the test box with bolts to form a visual window, which was convenient to observe the seepage and erosion process of soil. The main test chamber was divided into soil tank simulating seepage erosion and water tank simulating groundwater recharge. The two tanks were separated by permeable plates only allowing water to pass through. By controlling the water level regulator, the water level of the test water tank and the soil tank can be kept consistent. The length, width and height of the test soil tank were 600mm, 600mm and 800mm respectively, which was used for filling the test soil samples. A circular hole with a diameter of 50mm was opened at the place 150 mm from the front center to the bottom of the model tank, and the underground pipeline was laid. The horizontal distance from the center line of the underground pipeline to the boundary of both sides was greater than $5D_l$ (D_l was the pipe diameter), so as to reduce the influence of boundary effect on the experimental results [15].

As shown in Fig. 2, both sides of the test soil tank containing underground pipeline in the model were permeable plates, and the water can flow freely from both sides. During the experiment, the water level of the test water tank remained unchanged, so the boundary of the left and right sides was the horizontal stable infiltration boundary. The front and rear sides of the test soil tank were glass plates, which were impermeable

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boundaries.

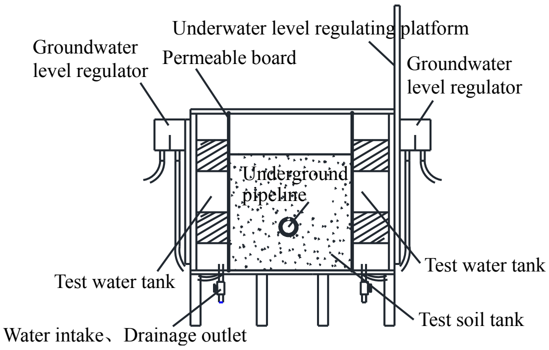


Fig.2 Main test chamber

The PVC pipe with a diameter of 50 mm was used to simulate the underground pipeline. The actual damaged mouths of pipelines are usually round holes, and most of them are located on the top of the pipeline[5-7]. Therefore, the damaged mouth was set on the top of the pipeline (as shown in Fig. 3), and the diameter can be adjusted within 4-26 mm and 2mm for each stage. In order to overcome the influence of the model size effect on the test results, according to the regulation [15], during the experiment, firstly, the damaged mouth was adjusted to the middle of the soil tank, so that the distance between the damaged mouth and the boundary of the soil box was greater than 3*D* (*D* was the diameter of damaged mouth), and then the influence of the model boundary on the seepage can be reduced. Secondly, applying Vaseline on the inner surface of soil tank can eliminate the influence of side wall effect.

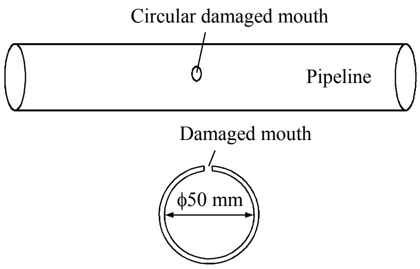


Fig.3 Underground pipeline

The full pipe flow simulation system used in this experiment can provide full flow of different flow rates for the pipeline. The system was composed of a movable water tank and a lifting platform, as shown in Fig.1. The height of the mobile water tank was changed by the lifting platform to provide the full pipe flow with different constant velocity for the pipeline. The water supply system provided the water source for the full pipe flow simulation system of the pipeline, which was composed of the water supply console and the water storage tank. By controlling the pressure regulating valve and water pump, the water in the water storage tank can be supplied to the water tank of the full pipe flow simulation system of the pipeline. During the experiment, as long as the overflow outlet of the water tank in the full flow simulation system of the pipeline continuously flowed out, the water level can be ensured to be constant, and then the flow velocity of the pipeline can be ensured to be stable.

Most of the urban drainage pipelines are the non-pressure pipelines, and the water flow in the pipelines is mainly dominated by gravity, which is characterized by gravity flow. Its characteristics are obviously different from the pressure flow driven by pipeline pressure [9]. For the partially-filled flow, the free water surface on the upper part of the fluid was in direct contact with the atmosphere, which had the characteristics of non-pressure flow. As the reason of that the diameter of damaged mouth was much smaller than that of the pipeline, it can be realized by adjusting the height of the movable water tank during the experiment that the water flow was not full of the pipeline and was in the partially-filled flow state during the groundwater seepage along the damaged mouth. Similarly, during the experiment, the water surface of the movable tank can be adjusted to be basically flat with the top surface of the pipe and slightly lower than the top surface of the pipeline, so that the pipeline can basically reach the state of no pressure and full pipe flow.

For the gravity full pipe flow, the pipeline was filled with fluid, and the pipeline boundary was affected by the full pipe flow pressure, which belonged to the pressurized pipe flow. The water pressure in the pipeline changes with the change of full pipe flow velocity, and the relationship between these two is as follows [15]:

$$P = \frac{u^2 \rho g L}{C^2 R} \tag{1}$$

where *P* is the water pressure in the pipe; *u* is the full pipe flow velocity; *C* is the Chézy coefficient of the pipe; *L* is the length of the pipe; ρ is the fluid density; g is the acceleration of gravity; *R* is the hydraulic radius of the pipe.

It can be seen from Eq.(1) that: the water pressure in the pipe is directly proportional to the square of the full pipe flow velocity, and the full pipe flow velocity can also reflect the water pressure in the pipe. The effect of water pressure on the experiment has been comprehensively reflected by the full pipe flow velocity. In the experiment, the height of the moving water tank can be adjusted by the lifting platform, which can provide the full pipe flow of different design velocity for the pipeline.

2.2 Experimental soil samples

In this experiment, the coarse sand with the particle size of 2-10 mm was selected as the coarse particle, and the standard sand with the particle size of 0.075-2 mm was selected as the fine particle. In the experiment, the experimental soil samples with different gradations (No.: A-K) were prepared with 100%, 90%, 80%, 70%, 60%, 50%, 40%, 30%, 20%, 10% and 0% of fine sand content respectively. The grading curves of soil samples were shown in Fig.4, and the main physical parameters were shown in Table 1. The thickness of the experimental soil layer was 250 mm, and the thickness of the soil layer over the damaged mouth was 100 mm.

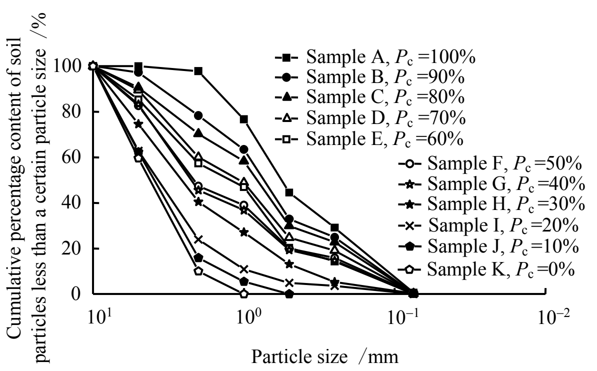


Fig.4 Grading curves of experimental soil samples

Table 1 Physical and mechanical parameters of soil samples

Soil specimen	P_c /%	γ' /(kN • m^{-3})	e	d_{50} /mm	d_{90} /mm	C_u	C_c
A	100	13.8	0.60	0.56	1.45	6.38	0.88
B	90	14.3	0.55	0.73	3.56	7.65	1.40
C	80	13.4	0.57	0.82	4.98	9.33	1.15
D	70	13.8	0.53	1.09	5.05	14.18	1.72
E	60	13.0	0.58	1.24	6.26	12.41	1.10
F	50	14.2	0.57	2.14	6.70	17.92	1.20
G	40	14.1	0.57	2.22	6.73	17.14	1.21
H	30	13.9	0.58	2.57	7.64	8.94	1.03
I	20	13.6	0.56	3.64	8.31	5.14	1.26
J	10	14.5	0.58	3.96	8.41	3.63	1.10
K	0	14.9	0.61	4.17	8.45	2.49	0.84

Note: γ' is the bulk density of soil sample; e is the void ratio; d_{50} is the average particle size, representing the size of particles below which 50% of the total soil weight of sample lies; d_{90} is the skeleton particle size, representing the size of particles below which 90% of the total soil weight of sample lies; C_u is the uneven coefficient of soil sample; C_C is the curvature coefficient of soil sample.

2.3 Experimental scheme and steps

The main purpose of the experiment was to study the influence of full pipe flow velocity, thick-span ratio and soil gradation on seepage erosion and settlement induced by pipeline damage. Therefore, the experiment was designed as follows:

(1) In Experiment 1, under the condition of fixed water level and no full pipe flow, different sizes of damaged mouth and soil gradation were selected to study the influence of the thick-span ratio (i.e. the ratio of the thickness of the overburden layer of the damaged mouth to the diameter of the damaged mouth[16]), the soil gradation and the size of the damaged mouth on the seepage erosion. The details of the experimental scheme are shown in Table 2.

(2) On the basis of Experiment 1, by setting different full pipe flow velocity, the influence of full pipe flow velocity on the occurrence conditions of soil seepage erosion and the influence law on soil settlement were studied. See Table 3 for the experimental scheme.

Field investigation showed that: when the groundwater level is higher than that of the stratum under the condition of water-rich sand layer or rainstorm, it will aggravate soil erosion and surface subsidence[5-7]. With reference to the research results of Guo, He, Zhang and other scholars [9, 13, 14], the designed hydraulic gradient of this experiment was 3, namely, the underground water level was 3 times the thickness of soil layer.

According to the Code for design of building water supply and drainage[17], the full pipe flow velocity in the pipeline shall not exceed 3.0 m/s. Therefore, the full pipe flow velocity set in the experiment was 0.6, 1.4, 1.8, 2.4 and 3.0 m/s, respectively. See Table 3 for details.

Table 2 Experimental scheme 1

Thick-span ratio r	Fine sand content P_c/%	Thick-span ratio r	Fine sand content P_c/%
25.0	100	6.3	100, 90, 80, 70, 60, 50, 40, 30, 20, 10, 0
16.7	100, 90	5.6	100, 90, 80, 70, 60, 50, 40, 30, 20, 10, 0
12.5	100, 90, 80	5.0	100, 90, 80, 70, 60, 50, 40, 30, 20, 10, 0
10.0	100, 90, 80	4.6	100, 90, 80, 70, 60, 50, 40, 30, 20, 10, 0
8.3	100, 90, 80	4.2	100, 90, 80, 70, 60, 50, 40, 30, 20, 10, 0
7.2	100, 90, 80	3.9	100, 90, 80, 70, 60, 50, 40, 30, 20, 10, 0

Note: The thick-span ratio r is the ratio of the thickness of the overlying soil layer to the diameter of the damaged mouth[17].

Table 3 Experimental scheme 2

Fine sand content P_c/%	Thick-span ratio r	Full pipe flow velocity u /(m • s^{-1})
100	8.3, 7.2, 6.2, 5.6, 5.0, 4.6, 4.2	0.6, 1.4, 1.8, 2.4, 3.0
80		
50		
20		
10		

According to the geotechnical test procedures, the test operations were as follows:

(1) Experimental preparation: check the experimental equipment, install the underground pipelines needed for the experiment, and close the damaged mouth.

(2) Preparation of soil samples: according to the experimental scheme, the soil samples of different gradations were arranged, and the soil samples were fully mixed and then scattered in the soil trough through the rain fall method, and then compacted to the proposed layer height in layers.

(3) Experimental process: according to the hydraulic gradient designed in the experiment, the groundwater level regulator was controlled to make the water level of the experimental soil tank and water tank reach the designed water level and keep stable. While the experiment was started, the damaged mouth would be opened, the soil seepage and erosion process can be observed and photographed, the main

phenomena in the experiment process can be recorded, and the lost soil samples from the underground pipeline can be collected and measured.

(4) Data analysis: at the end of the experiment, the radius and depth of land subsidence were measured by measuring needle method; the gradation of soil samples was tested to analyze the gradation change after soil loss.

3 Experimental phenomenon and result analysis

3.1 Seepage erosion mode of soil and its occurrence conditions

3.1.1 Seepage erosion mode of soil

It was found that: there are three modes of seepage erosion induced by pipeline damage under different full pipe flow velocities:

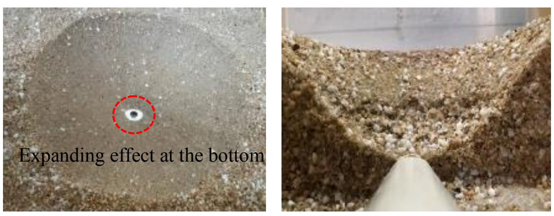
(1) Only water inrush without settlement: only water inrush, no sand inrush and no settlement of soil mass occur at the damaged mouth.

(2) Soil arching with settlement: water gushing and sand gushing firstly occur at the damaged mouth, then the amount of sand gushing gradually reduces, and finally only water gushing occurs. The soil above the damaged mouth forms a settlement similar to a cone. The settlement plane of the soil mass is approximately circular, the section is approximately triangular, and there is a stable soil arch in the soil layer above the damaged mouth, as shown in Fig. 5.

(3) Sand crushing with settlement: a large amount of water and sand flows into the pipeline through the damaged mouth until the overburden of the damaged mouth is completely lost. The settlement plane of the soil is approximately circular, the section is approximately trapezoid. No soil arch is found near the damaged mouth. The settlement radius is large and the damaged mouth at the bottom is clearly visible, as shown in Fig. 6.

(a) Settlement overlook (b) Settlement profile

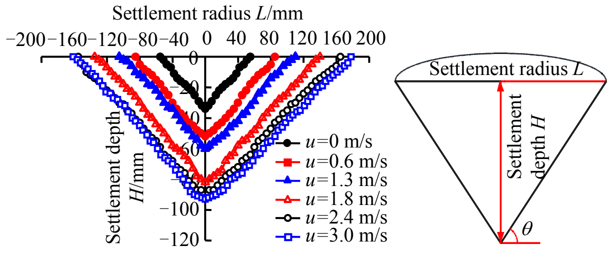
Fig.5 The mode of soil arching formation with settlement



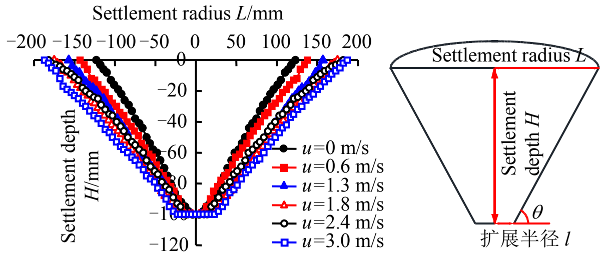
(a) Settlement overlook (b) Settlement profile

Fig.6 The mode of sand crushing with settlement

The settlement curves of the soil arch formed above the damaged mouth and sand crushing are shown in Fig. 7. As can be seen from Fig. 7:



(a) Settlement shape of soil arching formation



(b) Settlement shape of sand crushing

Fig.7 Settlement curves of soil arching formation and sand crushing under different full pipe flow velocities

(1) When the soil arch is formed with settlement at different full pipe flow velocities, the settlement profile is approximately triangular, and the settlement radius and depth increase with the increase of flow velocity;

(2) When the sand crushing with settlement occurs, the settlement profile is approximately trapezoid, and the settlement depth is the thickness of soil layer. The settlement radius and the extension radius of the bottom damaged mouth increase with the increase of flow velocity.

3.1.2 Occurrence conditions of three modes for seepage erosion of soil in partially-filled flow

The soil particles above the damaged mouth formed soil arch as shown in Fig. 8. It can be seen from Fig.8 that: coarse particles in uneven graded soil sample participate in arching and play a role of skeleton. The skeleton particle size d_{90} represents the size of particles below which 90% of the total soil weight of sample lies, which can effectively reflect the particle size of the skeleton in the sand [18].

Fig.8 Arching photo of coarse particles above the damaged mouth

According to the arrangement of the experimental results of scheme 1 in Table 2, the seepage erosion mode and skeleton particle size range of the soil under the condition of partially-filled flow were obtained, as shown in Table 4.

Table 4 The skeleton particle size range of failure modes of soil under partially-filled flow condition

Thick-span ratio r	Skeleton particle size d_{90} /mm			Critical sand crushing	Soil arching formation
	Failure mode 1	Failure mode 2	Failure mode 3	D/d_{90}	D/d_{90}
>12.5	only water inrush with no settlement			—	—
12.5	>3.56	1.45-3.56	0-1.45	5.51	2.25-5.51
10.0	>3.56	1.45-3.56	0-1.45	6.89	2.81-6.89
8.3	>3.56	1.45-3.56	0-1.45	8.28	3.37-8.28
7.2	>4.98	1.45-4.98	0-1.45	9.66	2.81-9.66
6.3	>4.98	3.56-4.98	0-3.56	4.49	3.21-4.49
5.6	>6.26	5.05-6.26	0-5.05	3.56	2.88-3.56
5.0	>8.41	6.70-8.41	0-6.70	2.99	2.37-3.56
4.6	>8.45	7.64-8.45	0-7.64	2.88	2.60-2.88
4.2	>8.45	8.41-8.45	0-8.41	2.85	2.84-2.85
<4.2	occur sand crushing without forming stable soil arching			—	—

Note: The thick-span ratio r is the ratio of the thickness of the overlying soil layer to the diameter of the damaged mouth[17].

Table 5 Occurrence conditions of various seepage erosion modes of soil under partially-filled flow condition

Failure mode of soil	Occurrence conditions of failure modes of soil		
	r	d_{90} /mm	D/d_{90}
only water inrush without settlement	>12.5	⩾1.45	0-5.50
only water inrush without settlement	8.3-12.5	⩾3.56	0-2.50
only water inrush without settlement	4.2-8.3	4.98-8.45	0-2.88
soil arching formation with settlement	8.3-12.5	1.45-3.56	⩾3.37-5.51
soil arching formation with settlement	4.2-8.3	1.45-8.45	⩾2.37-9.66
sand crushing with settlement	8.3-12.5	0-1.45	⩾5.51-8.28
sand crushing with settlement	4.2-8.3	1.45-8.41	⩾2.85-9.66
sand crushing with settlement	<4.2	0-8.45	>2.85

As can be seen from Table 4:

(1) Under the condition of partially-filled flow, there are three failure modes of seepage erosion induced by pipeline damage. The main factors affecting the seepage erosion mode are the thick-span ratio r, the diameter of the damaged mouth D and the diameter of the skeleton d_{90}.

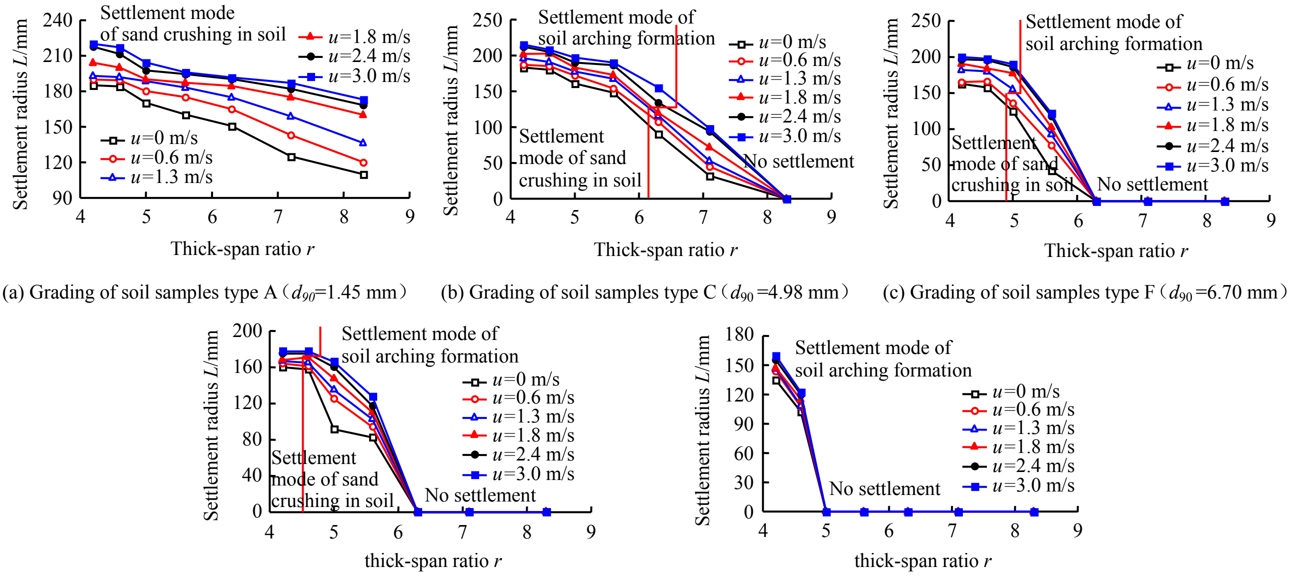
(2) Under different thick-span ratios, different soil seepage erosion modes will appear when the ratio of the diameter of the damaged mouth D to the diameter of the particle skeleton d_{90} (i.e. D/d_{90}) exceeds the limit value. Therefore, according to the thick-span ratio, the diameter of the damaged mouth and the particle size of the skeleton, the occurrence conditions of seepage erosion mode of soil under the condition of partially-filled flow can be divided, as shown in Table 5.

3.1.3 Influence of full pipe flow velocity on seepage erosion model of soil

The experimental results of settlement of different graded soil at different full pipe velocities are shown in Fig. 9. According to the experimental results, the occurrence conditions of three seepage erosion modes of soil under different full pipe flow velocities were sorted out, as shown in Table 6.

It can be seen from table 6 and Fig. 9 that:

(1) The settlement of soil is mainly affected by the thicknessspan ratio r, the diameter of the damaged mouth D, the diameter of the skeleton d_{90} and the full pipe flow velocity u; the thick-span ratio r, the diameter of the damaged mouth D and the diameter of the skeleton d_{90} are the main factors determining the seepage erosion mode and the occurrence conditions of soil.



(a) Grading of soil samples type A (d_{90}=1.45 mm) (b) Grading of soil samples type C (d_{90} =4.98 mm) (c) Grading of soil samples type F (d_{90} =6.70 mm)

(d) Grading of soil samples type I (d_{90} =8.31 mm) (e) Grading of soil samples type K (d_{90} =8.45 mm)

Fig.9 The relation curve between the settlement radius and thick-span ratio under different full pipe-flow velocities

Table 6 The occurrence conditions of various failure modes of soil under different full pipe-flow velocities

Grading of soil samples	Thick-span ratio r	D/d_{90}	Falure modes
Type A (d_{90}=1.45 mm)	4.2~8.3	8.3~16.6	sand crushing with settlement
	>8.3	<2.4	only water inrush without settlement
Type C (d_{90}=4.98 mm)	6.3~8.3	2.4~3.2	soil arching formation with settlement
	4.2~6.3	3.2~4.8	sand crushing with settlement
	>6.3	<2.4	only water inrush without settlement
Type F (d_{90}=6.70 mm)	5.0~6.3	2.4-2.9	soil arching formation with settlement
	4.2~5.0	2.9-3.6	sand crushing with settlement
	>6.3	<1.9	only water inrush without settlement
Type I (d_{90}=8.31 mm)	4.6~6.3	1.9-2.6	soil arching formation with settlement
	4.2~4.6	2.6-2.9	sand crushing with settlement
Type K (d_{90}=8.45 mm)	5.0~8.3	1.4-2.4	only water inrush without settlement
	4.2~5.0	2.4-2.8	soil arching formation with settlement

(2) Full pipe flow velocity is an important factor affecting the settlement range. Under the same thick-span ratio, the settlement radius of soil increases with the increase of full pipe flow velocity; relatively speaking, when the full pipe flow velocity is less than 1.8 m/s, the increase trend of settlement radius with the increase of flow velocity is more obvious than that when the flow velocity is 1.8~3.0 m/s.

It can be seen from the comparison of table 5 and table 6 that: the occurrence conditions (thick-span ratio r, skeleton particle size d_{90} and D/d_{90}) of three seepage erosion modes of soil under full pipe flow condition are basically the same as those under no full pipe flow condition; the full pipe flow velocity has little influence on the occurrence conditions of seepage erosion mode of soil.

3.2 Relationship between the thick-span ratio and the particle size of soil skeleton when settlement occurs

Relatively speaking, the harm of surface subsidence is greater. Therefore, the following focused on the study of the behavior of two modes of soil arching formation with settlement and sand crushing with settlement above the damaged mouth of the pipeline.

In case of sand crushing with settlement, the curve of skeleton particle size of soil changing with thick-span ratio is shown in Fig. 10. It can be seen from Fig. 10 that: in case of sand crushing settlement, when $8.3 \geqslant r \geqslant 4.2$, the skeleton particle size d_{90} and the thick-span ratio r show a parabola decline relationship; when $12.5 \geqslant r > 8.3$, the skeleton particle size d_{90} is unchanged, and the fitting relationship between them is as follows:

$$d_{90}=\begin{cases}0.223r^2-4.486r+23.246, & 8.3\geqslant r\geqslant 4.2\\ 1.45, & 12.5\geqslant r\geqslant 8.3\end{cases} \quad (2)$$

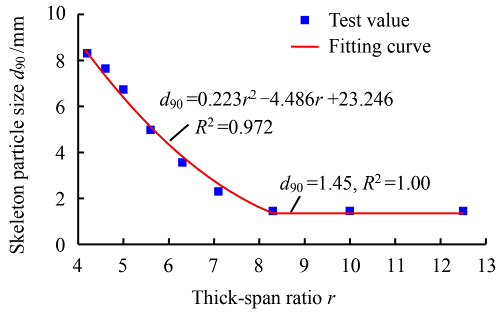


Fig.10 The relation between the skeleton particle size and thick-span ratio under the condition of sand crushing settlement

When the soil above the damaged mouth formed soil arch with settlement, the curve of the average particle size of soil skeleton with the thick-span ratio is shown in Fig. 11. As can be seen from Fig. 11:

(1) In case of the soil arching formation with settlement, when $8.3 \geqslant r \geqslant 4.2$, the interval average value of soil skeleton size d_{90} decreases parabola with the thick-span ratio r; when $12.5 \geqslant r > 8.3$, the interval average value of soil skeleton size d_{90} remains unchanged. Their fitting relations are:

$$d_{90}=\begin{cases}0.193r^2-3.941r+21.806, & 8.3\geqslant r\geqslant 4.2\\ 2.51, & 12.5\geqslant r\geqslant 8.3\end{cases} \quad (3)$$

(2) In case of the soil arching formation with settlement, when $8.0 \geqslant r \geqslant 4.2$, The change range of particle size of soil skeleton d_{90} (see the upper and lower horizontal lines of Fig. 11) increases with the increase of thick-span ratio r; when $12.5 \geqslant R \geqslant 8.0$, the change range of skeleton particle size basically maintains the maximum value with the change of thick-span ratio r.

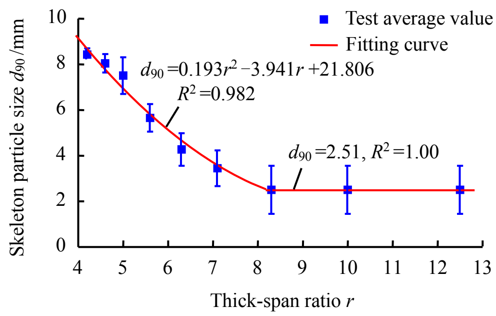


Fig.11 The relation between the skeleton particle size and thick-span ratio under the condition of soil arching formation

3.3 The behavior of soil settlement when forming soil arch

3.3.1 Influence of full pipe flow velocity on settlement

The average particle size d_{50} is the size of particles below which 50% of the total soil weight of sample lies, which can effectively reflect the average particle size in sand. According to the experimental results, when the ratio (D/d_{50}) of the diameter D of the damaged mouth to the average diameter d_{50} of the soil sample is 19.51, 17.07, 8.57, 5.76, 5.49 and 5.28 respectively, the relationship between the settlement radius, settlement depth and full pipe flow velocity is shown in Fig. 12

and Fig. 13.

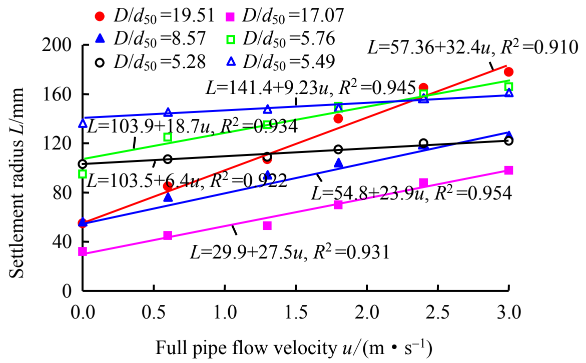


Fig.12 The relationship between settlement radius and full pipe-flow velocity under the condition of soil arching formation

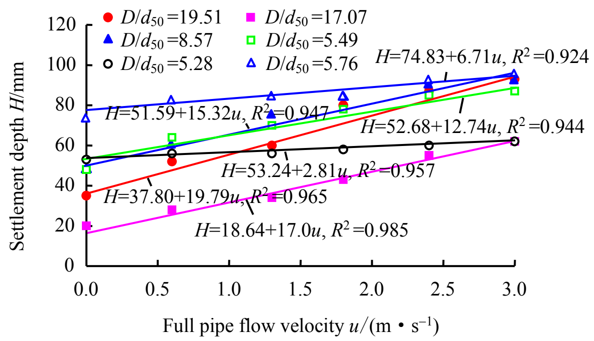


Fig.13 The relationship between settlement depth and full pipe-flow velocity under the condition of soil arching formation

It can be seen from Fig. 12 and Fig. 13 that:

(1) In case of the soil arching formation with settlement, When the velocity is 0, the initial settlement radius and settlement depth are determined by the ratio D/d_{50} between the diameter of the damaged mouth and the average particle size;

(2) Under the same D/d_{50} condition, the settlement radius L and the settlement depth H of soil formed soil arch with settlement increase linearly with the increase of full pipe flow velocity u.

3.3.2 Effect of full pipe flow velocity on the velocity of settlement expansion

It can be seen from Fig. 12 and Fig. 13 that: the settlement radius and depth change in a straight line with the change of full pipe flow velocity, but the slope of the straight line (the expansion speed of settlement radius and depth with the increase of flow velocity) is not the same. According to the experimental results in Fig. 12 and Fig. 13, the D/d_{50} was taken as the horizontal coordinate, and the expanding velocity V_L (the slope of straight line in Fig. 12), V_H (the slope of straight line in Fig. 13) of the settlement radius and settlement depth with the increase of flow velocity were respectively selected as the vertical coordinate, Thus, the relationship curves between V_L, V_H and D/d_{50} can be drawn, as shown in Fig. 14 and Fig. 15.

It can be seen from Fig. 14 and Fig. 15 that:

(1) In case of the soil arching formation, the expanding velocity V_L, V_H of the settlement radius and settlement depth with the increase of flow velocity increase with the increase of D/d_{50}.

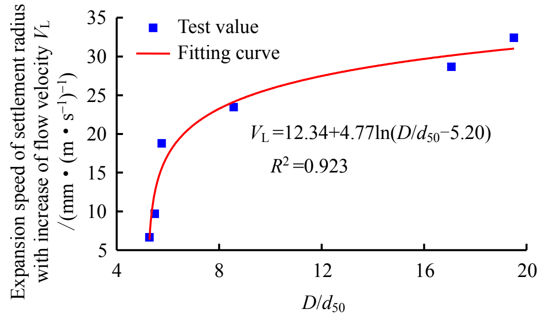


Fig.14 The relationship between the expansion velocity V_L of settlement radius with flow velocity and D/d_{50}

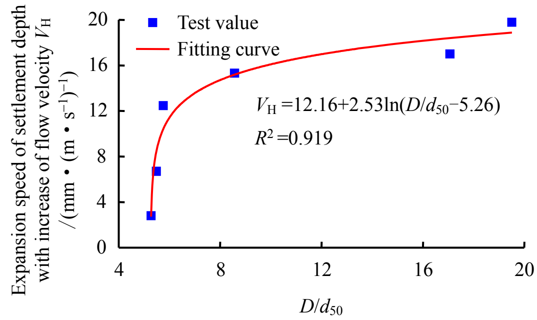


Fig.15 The relationship between the expansion velocity V_H of settlement depth with flow velocity and D/d_{50}

(2) When D/d_{50}=5~7, the expanding velocity V_L, V_H of the settlement radius and settlement depth with the increase of flow velocity increase sharply with the increase of D/d_{50}; When D/d_{50}>7, the increasing trend of expanding velocity V_L, V_H of the settlement radius and settlement depth with the increase of D/d_{50} is obviously slowed down.

Data fitting showed that: V_L、V_H and D/d_{50} have a good logarithmic relationship, and the fitting relationship is:

$$V_L = 12.34 + 4.77\ln\left(\frac{D}{d_{50}} - 5.20\right) \tag{4}$$

$$V_H = 12.16 + 2.53\ln\left(\frac{D}{d_{50}} - 5.26\right) \tag{5}$$

According to Eq. (4) and Eq. (5), when the soil above the damaged mouth formed soil arch with settlement, the calculation formulas of settlement radius L and settlement depth h can be obtained as follows:

$$L = 12.34u + 4.77u \cdot \ln\left(\frac{D}{d_{50}} - 5.20\right) + a \tag{6}$$

$$H = 12.16u + 2.53u \cdot \ln\left(\frac{D}{d_{50}} - 5.26\right) + b \tag{7}$$

Where: a, b are the initial settlement radius and settlement depth determined by D/d_{50} when the full pipe flow velocity is 0.

3.4 The behavior of soil settlement in case of sand crushing

3.4.1 Influence of full pipe flow velocity on settlement

According to the experimental results, when D/d_{50} = 6.59~42.9, the relationship between settlement radius and full pipe flow velocity in case of sand crushing can be sorted out, as shown in Fig. 16.

As can be seen from Fig. 16:

(1) when the sand crushing with settlement occurs in the soil above the damaged mouth, the initial settlement radius at the velocity of 0 is determined by the ratio D/d_{50} of the diameter of damaged mouth to the average particle size;

(2) Under the same D/d_{50} condition, the settlement radius L of soil occurred sand crushing with settlement increase linearly with the increase of full pipe flow velocity u.

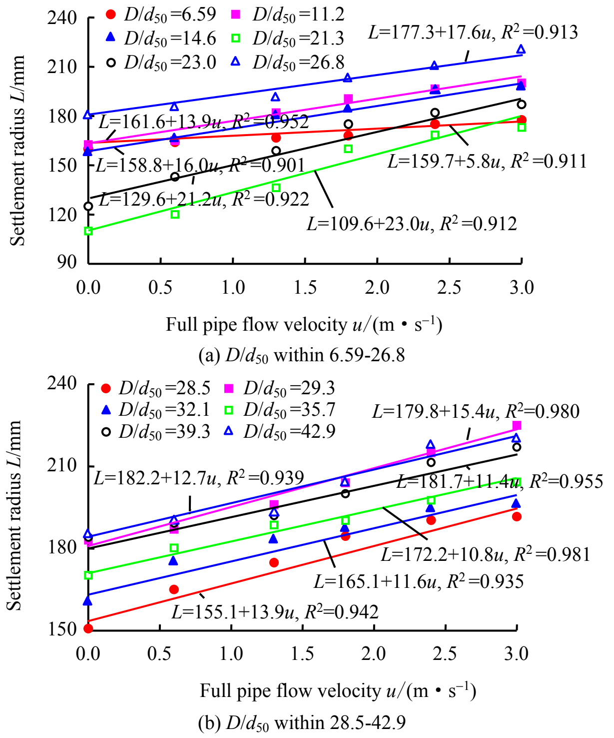


Fig.16 The relationship between settlement radius and the full pipe-flow velocity under the condition of sand crushing

3.4.2 Effect of full pipe flow velocity on the velocity of settlement expansion

According to the results in Fig. 16, the D/d_{50} was taken as the horizontal coordinate, and the expanding velocity V_L (the slope of straight line in Fig. 16) of the settlement radius with the increase of flow velocity was selected as the vertical coordinate, Thus, the relationship curves between V_L and D/d_{50} can be drawn, as shown in Fig. 17.

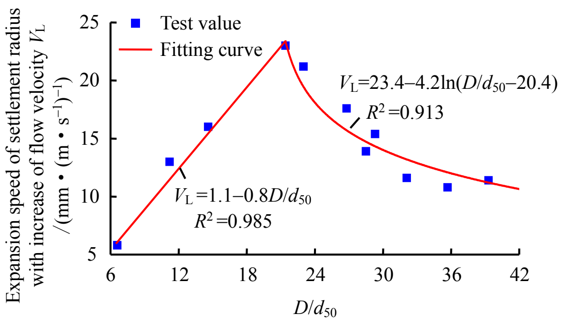


Fig.17 The relationship between the expansion velocity V_L of settlement radius with flow velocity and D/d_{50}

As can be seen from Fig. 17: when $23.0 \geqslant D/d_{50} \geqslant 6.0$, the expanding velocity V_L of the settlement radius with the increase of flow velocity increases linearly with the increase of D/d_{50}; when $42.0 \geqslant D/d_{50} \geqslant 23.0$, the expanding velocity V_L of the settlement radius with the increase of flow velocity decreases logarithmically with the increase of D/d_{50}.

$$V_L = \begin{cases} 1.1 - 0.8\dfrac{D}{d_{50}}, & 23.0 \geqslant \dfrac{D}{d_{50}} \geqslant 6.0 \\ 23.4 - 4.2\ln\left(\dfrac{D}{d_{50}} - 20.4\right), & 42.0 \geqslant \dfrac{D}{d_{50}} \geqslant 23.0 \end{cases} \quad (8)$$

According to Eq. (8), in case of the sand crushing with settlement, the calculation formula of settlement radius L can be obtained as follows:

$$L = \begin{cases} 1.1u - 0.8u\dfrac{D}{d_{50}} + a, & 23.0 \geqslant \dfrac{D}{d_{50}} \geqslant 6.0 \\ 23.4u - 4.2u\ln\left(\dfrac{D}{d_{50}} - 20.4\right) + b, & 42.0 \geqslant \dfrac{D}{d_{50}} \geqslant 23.0 \end{cases} \quad (9)$$

where: a is the initial settlement radius determined by D/d_{50} when the full pipe flow velocity is 0.

The ground settlement induced by underground pipeline damage is a complex geotechnical engineering problem[19]. Based on the research results of this paper, the following measures were proposed to prevent and weaken the ground settlement induced by pipeline damage:

(1) Strengthen the quality management of pipeline laying, especially the connection quality of pipeline interface, to avoid water seepage and sand leakage at the interface;

(2) It is better to lay geotextile on the top of the pipeline to reduce the settlement induced by the inflow of soil above the damaged mouth after pipeline damage;

(3) The filler around the pipeline should be coarse-grained soil with good grading, not fine-grained soil;

(4) In rainy season, the increase of flow velocity in the pipeline will aggravate the settlement of soil above the damaged mouth of the pipeline, thus, the inspection and maintenance of the pipeline should be strengthened.

4 Conclusions

(1) Under the condition of full pipe flow of damaged pipeline, there are three modes of seepage erosion of soil induced by pipeline damage, which are: only water inrush without settlement, soil arching formation with settlement and sand crushing with settlement. In case of the soil arching formation with settlement, the plane of the settlement area is circular, and the section is inverted triangle; in case of the sand crushing with settlement, the plane of the settlement area is circular, and the section is trapezoid with large up and small down.

(2) Whether it is full pipe flow or not, the particle size of soil skeleton, the size of damaged mouth and the thick-span ratio are the main factors that determine the mode of seepage erosion of soil induced by pipeline damage; the full pipe flow velocity has no effect on the mode of seepage erosion of soil,

which mainly affects the settlement range.

(3) Under the condition of full pipe flow of damaged pipeline, for the sand with skeleton size d_{90} =1.45~8.45 mm, when the thick-span ratio $r\geqslant 12.5$, The thick-span ratio plays a decisive role in the seepage erosion of soil. The larger the thick-span ratio is, the less likely the soil is to settle; when $12.5\geqslant r\geqslant 4.2$, The model of seepage erosion of soil is related to the diameter of the damaged mouth D and the diameter of the skeleton d_{90}, when the ratio D/d_{90} of the diameter D of the damaged mouth to the grain size of the skeleton d_{90} reaches the limit value, the mode of soil arching formation with settlement or sand crushing with settlement will occur; when $r<4.2$, the coarse particles in the soil can't form a stable soil arch at the damaged mouth, which will lead to sand crushing with serious settlement.

(4) When the soil arching formation or sand crushing occurs in the soil above the damaged mouth, the relationship between the particle size of soil skeleton d_{90} and the thick-span ratio r is: when $8.0\geqslant r\geqslant 4.2$, d_{90} decreases parabola with the increase of r; when $12.5\geqslant r\geqslant 8.0$, d_{90} remains unchanged.

(5) When the soil arching formation with settlement occurs in the soil above the damaged mouth, the initial settlement radius and settlement depth at the velocity of 0 are determined by D/d_{50}; The settlement radius and depth of soil increase linearly with the increase of full pipe flow velocity; the relationship between the expanding velocity V_L, V_H of the settlement radius and settlement depth with the increase of flow velocity and D/d_{50} are logarithmic.

(6) When the sand crushing with settlement occurs in the soil above the damaged mouth, the initial settlement radius at the velocity of 0 is determined by D/d_{50}; the settlement radius of soil increases linearly with the increase of flow velocity; the expanding velocity of the settlement radius with the increase of flow velocity: when $23.0\geqslant D/d_{50}\geqslant 6.0$, it increases linearly with the increase of D/d_{50}; when $42.0\geqslant D/d_{50}\geqslant 23.0$, it decreases logarithmically with the increase of D/d_{50}.

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