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Development and Assessment of a Water Pressure Reduction System for Lining Invert of Tunnels in Saturated Grounds

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Abstract

In this study, the feasibility of a novel bottom-up drainage and water pressure reduction system for reducing the secondary lining external water pressure on tunnels has been validated by conducting laboratory evaluations. The tunnels environment including surrounding rock, lining, bottom drainage system and other supplementary components have been simulated to investigate the working pattern and efficiency of this drainage system. The drainage system has been further optimized by analyzing the measured water pressure and flow rate. Experimental results indicate that the designed draining system is feasible for reducing the secondary lining external water pressure in the bottom of tunnels and the water pressure has been reduced significantly with high efficiency. The capacity of the proposed system to control the rapid water inflow in tunnel construction region can be guaranteed. The factors affecting the performance of the system such as the diameter of the drainage pipe and the inlet water pressure are also discussed in this paper.

1 Introduction

Water penetration and dripping are always critical problems for tunnels in the water-saturated ground. The groundwater in the tunnels are typically treated in two ways: waterproofed or drained (Yoo, 2016). The waterproofed tunnel doesn't allow the groundwater to penetrate the secondary lining as the waterproof boards are set along the circumferential direction to form a complete. This issue very common in urban tunnel constructions due to the low groundwater discharging rate. A drained tunnel usually allows groundwater into the tunnel, which is finally discharged along with the various measures in such tunnel. Usually, the waterproof and drainage system of a drained tunnel consists of initial support, secondary lining, waterproof boards, blind tubes, and central drainage ditches. Existing waterproof and drainage system for tunnels is mainly designed to deal with the groundwater pressure applied on the upper structure of the tunnel (Yuan et al., 2000; Shin et al., 2009). The water pressure applied is supposed to be bearded by the tunnel invert. Unfortunately, it's been proved that the current design is not able to solve the problems due to the potential damages on the ballast bed, including uplift, mud pumping, cracking and so on (Butscher et al., 2017). Among the four causes (Gamisch et al., 2005) of these damages, the groundwater plays a much more important role than the other factors, such as construction defection, long-term train vibration load, and poor surrounding rock.

Many researchers have investigated how to control the external water pressure on the tunnel lining. Arjnoi et al. (2009) conducted theoretical analysis and numerical simulation to study the effect of drainage conditions on pore water pressure distributions and lining stresses in a drained tunnel with two different boundary conditions. Wang et al. (2008) presented a theoretical model to predict the distribution of water pressure on tunnel lining by laboratory test and field evaluation. Fang et al. (2016) developed an apparatus to apply the appropriate external water pressure by evacuating the inner space of the tunnel and applying external air pressure to the liner to act as the water pressure. Stripple et al. (2016) presented a new design of drainage system for rock tunnels. Yee et al. (2015) and Yee (2015) analyzed the influence between magnetic fields and calcium carbonate deposition through laboratory tests and field evaluations to prevent clogging. Besides, wave vibrations (Xin et al., 2018), Quantum Stick (Jung et al., 2013) and geosynthetic (Jang et al., 2015), etc. were also investigated. Choi et al. (2015) proposed an optimal lightweight-foamed mortar mix suitable for composite lining method to facilitate tunnel drainage. The lightweight-foamed mortar replaces the traditional initial support, and the drainage system works more efficiently due to its porous structure. The current studies mainly focus on the porewater pressure distributions on the whole tunnel lining or the water pressure that applies to the upper structure of the tunnel. There is still much research needs on the solution of the problems occurred on tunnel invert caused by high water pressure.

To prevent the damage of the tunnel invert caused by water pressure, Li et al. (2018) developed a novel bottom-to-up drainage and water pressure reduction system (Fig. 1) to reduce the water pressure that applies on the secondary lining. Such system includes a transverse catchment system, a longitudinal water conducting system, and a bottom-to-up water drainage system. Series of numerical analyses has been conducted to evaluate its drainage performance. Better waterproof and drainage function can be achieved on the entire tunnel by combining the new and existing technologies.

This paper presents an experiment-based study on the bottom-to-up drainage and water pressure reduction system. The performance of the proposed system will be validated by experiments. The drainage efficiency of different types of drainage pipe and the influence to seepage field caused by the pipe diameter will also be analyzed. The overall idea of this article is shown in flowchart 2.

2 Experimental setup

The equipment setup is shown in Fig. 3 including the structure of tunnel invert, the bottom-to-up drainage, water pressure reduction system and surrounding rock with groundwater, which simulates the structure part highlighted in Fig. 1. According to functions of the components, they can be divided into two systems: water supply system and drainage system. (Water tank(I), Water pump(II), Intake pipe(III), Return pipe(IV), Return valve(V), Inlet valve(VI), Pressure valve(VII), Buffer box(VIII), Inlet holes(IX), Gravel filling(X), Precast concrete board(XI), Convex hull drainboard(XII), Cast-in-place concrete filling(XIII), Half-round tube(XIV), Waterproof board(XV), Gravel filling Ⅱ(XVI), Cover plate(XVII), One-way valve(XVIII), Oblique drainage pipe(XIX), Erect drainage pipe(XX), Studdle(XXI), Ball valve(XXII).)

2.1 Water supply system

The water supply system (Fig.4) consists of 6 parts, providing power to make water flow and receiving water from the drainage system. Water tank(I) is a steel cylinder, which is 1.2m high with an inner diameter of 0.6m and a 2mm-thick wall. The Water pump(II) is the main power supply of the experiment to make water flow, which is 1.1m-long with a flow of 3 m^3/h. Intake pipe(III) connects the water supply system and the simulating drainage system. There are two tees in the intake pipe(III), the first tee divides the flow path into two: one connects inlet valve(VI) to make water flow into the simulating drainage system, the other connects return valve(V) and return pipe(IV) to make water flow back into water tank(I); the second tee divides the other flow path into two to connect testing chamber as there are two intakes on both sides of the testing chamber.

The following two flow paths were designed in this experiment:

1. Path 1 is 1-water tank →2-water pump →3-intake pipe →the first tee →5-return valve →4-return pipe →1-water tank;
2. Path 2 is 1-water tank →2-water pump →3-intake pipe →the first tee →the second tee →6-inlet valve →the simulating drainage system →1-water tank. The volume of water flowing into the testing chamber can be controlled by regulating 5-return valve and 6-inlet valve, the water pressure in the testing chamber can also be controlled if superadding regulating 22-ball valve.

2.2 Drainage system

The drainage system makes up the testing chamber and the components in it. The testing chamber is a cuboid steel box with a size of 3m×1m×0.65m (length × width × height), which is used to simulate the tunnel invert structure and groundwater shows in Fig.5. There is a buffer box(VIII) in each side of the testing chamber, and the size of the buffer box(VIII) is 0.2m×1m×0.65m (length × width × height). The surplus space of the testing chamber is the main container of simulating tunnel invert. The size of the testing chamber is 2.6m×1m×0.65m (length × width × height). There is a pressure gauge(VII-a) connected to the top of each buffer box(VIII). The Cover plate(XVII) is installed on the top of the testing chamber by screws. The Cover plate(XVII) is manufactured with two parts to reduce the weight for easy transport. On each plate, there is a hole corresponding to the erect drainage pipe and oblique drainage pipe.

The components in the testing chamber are shown in Fig.6. From bottom to top, there are gravel filling(X), precast concrete board(XI), convex hull drainboard(XII), cast-in-place concrete filling(XIII), half-round tube(XIV), waterproof board(XV) and gravel filling Ⅱ(XVI), corresponding to the simulation of surrounding rock, initial support, convex hull drainboard, secondary lining, half-round tube and waterproof board on the edge in the bottom-to-up drainage and water pressure reduction system respectively. The permeability of initial support is relatively high in the tunnel because it is usually fabricated by shotcrete. It is very difficult to reproduce the shotcrete support in the laboratory with the same permeability performance. Therefore a gap about 3cm wide is put between two 11-precast concrete boards for water flowing through to reach a permeability similar to the real condition. Gravel filling Ⅱ(XVI) is used to fill the space between the cast-in-place concrete filling(XIII) and cover plate(XVII) and transfers force if necessary.

There are two types of bottom-to-up drainage pipes: oblique drainage pipe(XIX) and erect drainage pipe(XX). The performance of the drainage pipe can be analyzed through the data of water discharge and water pressure reduction, which helps to improve the design of bottom-to-up drainage and water pressure reduction system in tunnels.

The diameter of the half-round tube(XIV) is 200mm, and that of oblique drainage pipe(XIX) and erect drainage pipe(XX) is 100mm. There are convex parts on both sides of convex hull drainboards(XII). When convex hull drainboard（XII） is set on precast concrete boards(XI), there are plenty of flowing paths under the convex hull drainboard, and the depression area will be filled by cast-in-place concrete to meet the force-bearing demand. The half-round tube is connected to drainage pipes with a tee and waterproof glue. The edges of the waterproof board, half-round tube, and testing chamber will be connected to each other by waterproof glue. The whole structure of the waterproof board, half-round tube, and drainage pipe are shown in

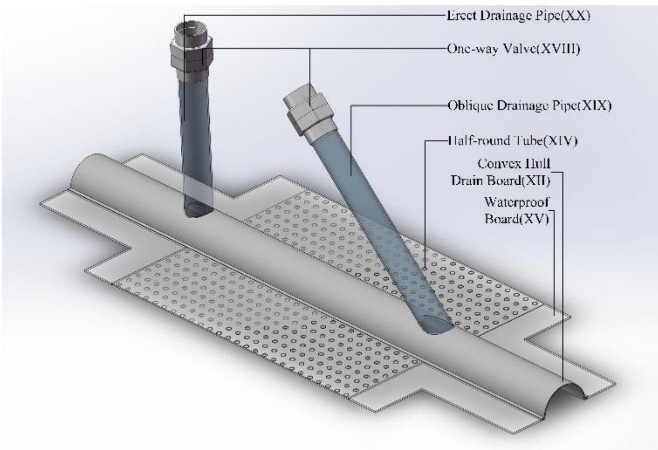

Fig. 7.

3 Monitoring and data acquisition system

In this experiment, the pore water pressure and flow charge of drainage pipes are investigated.

3.1 Pore water pressure monitoring

There are two types of pore pressure sensors: HC-25 micropore pressure sensor (0.2% in precision) and HCYB-25 micropore pressure sensor (0.5% in precision). HCSC-16 data acquisition equipment and YBY-2001 strain acquisition instrument were used for data acquisition. There are 3 tiers of pore pressure sensors installed at different heights (see Fig.). The Bottom Tier Sensors is placed in the gravel filling(X) to monitor the pore pressure representing surrounding rock. The Medium Tier Sensors is placed between precast concrete boards(XI) and waterproof board to monitor the pore pressure that representing simulating secondary lining. The Top Tier Sensors is placed in each drainage pipe which is 15cm higher than the medium tier. The horizontal arrangement of each tier of pore pressure sensors is shown in Fig. . No.1~No.9 sensors are HCYB-25 micro pore pressure sensors, and No.10~No.22 sensors are HC-25 micro pore pressure sensors.

3.2 Water discharge monitoring

Water discharge monitoring system consists of a water container, an electronic scale, and a stopwatch. The weight of the water container was measured before the experiment. When adding water into the container, the corresponding elapsed time was also monitored. The water discharge of each drainage pipe was obtained by calculating the mass of the water in the container and the elapsed time. For better accuracy, 3 was used as an average value of water discharge in each experimental condition.

4 Experimental programme

4.1 The process of installation of experimental equipment

The process of installing the bottom-to-up drainage and water pressure reduction system for tunnels include filling gravel material, arranging and setting pore pressure sensors, installing drainage pipes, pouring concrete for simulating tunnel invert secondary lining, installation of inlet/outlet pipes and valves, testing of data acquisition equipment and so on. The detailed process is as follows:

(1) Transporting and fix the testing chamber and water tank etc. in the prepared testing field;

(2) Laying some non-woven fabric to cover the inlet holes to prevent any gravel getting into the buffer box;

(3) Filling gravel in the bottom of testing chamber with a thickness of 18cm, tamping to dense the gravel;

(4) Placing the Bottom Tier Sensors according to the prepared arrangement;

(5) Placing two precast concrete boards into the testing chamber and reserve a 3cm gap between them, seal the edge of the boards with waterproof glue;

(6) Placing the Medium Tier Sensors and gather all the wires of the sensors with a tarp;

(7) Installing half-round tube, convex hull drainboard, waterproof board and so on, connect and seal with waterproof glue;

(8) Installing the erect drainage pipe and oblique drainage pipe, set the Top Tier Sensors;

(9) Pouring self-compacting concrete with a thickness of 40cm, tamping gently and complete maintenance;

(10) Filling the upper gravel with a thickness of 10cm and tamping;

(11) Installing the cover plate and connecting it to the testing chamber with screws;

(12) Installing one-way valve, ball valves and other pipes;

(13) Installing intake pipe, valves, water pump and so on, connect the water supply system and the testing chamber;

(14) Installing the pressure gauges on both sides of the testing chamber, connecting sensors and the data acquisition equipment, debugging facilities, and prepare to carry out the experiment.

Fig. shows the entire experimental system.

4.2 Simulations

The following experiments will be discussed in this section.

(1) Steady seepage test

The distribution of water pressure in steady seepage will be analyzed in this study. When performing the experiment, all intake pipes and 4-return pipe will be opened except the drainage pipes, which are controlled by the ball valves(XXII). It includes three conditions:

Only the ball valve of erect drainage pipe is opened, and the draining is conducted using erect drainage pipe (called “DEDP” for short);

Only the ball valve of oblique drainage pipe is opened, and the draining is conducted using oblique drainage pipe (called “DODP” for short);

Both ball valves are opened, and the draining is conducted using drainage pipes (called “DBDP” for short).

(2) Influence of the drainage pipes diameter on the effect of water pressure reduction

The effect of the water pressure reduction system will be evaluated, and the influence of the diameter of the drainage pipe will also be investigated. Due to the limitation of the laboratory instrumentation, the drainage pipe was not able to be replaced directly to complete the experiment of the diameter of the drainage pipe. Different opening angles of the ball valve(XXII) result in different drainage discharge of the drainage pipe, which is similar to draining with different diameters of drainage pipes. In the experiment, return valve(V) was opened, and the inlet valve(VI) and the ball valve(XXII) was closed. The water pump(II) and the inlet calve(VI) opened gradually to increase the water pressure of the pressure gauge(VII) until 20kPa. The ball valve(XXII) of erect drainage pipe was then opened to about 30°, and the water pressure was measured during the process of the water pressure reduction. This process was repeated, and the water pressure was recorded with ball valve(XXII) of erect drainage pipe opened to 15° and 10°, and ball valve(XXII) of oblique drainage pipe opened to 30°, 15°, and 10°.

It is found that the inner diameter of the drainage pipe is 10cm when the ball valve(XXII) is opened to about 30°, 15°, and 10°. The equivalent diameters of the drainage pipe are 47mm, 27mm, and 18mm, respectively.

(3) Influence of inlet water pressure on the seepage field

In this section, the water pressure and water discharge will be discussed. The cross-section area of the two types of drainage pipe is as identical as possible to make the inlet water pressure the only variable. In the experiment, the return valve(V) was opened first, then the inlet valve(VI) was closed, and the ball valves(XXII) was then opened to about 10°. The water pump(II) was then started, and the inlet valve(VI) was opened gradually to make the water pressure to reach 5kPa, 10kPa, 15kPa, and 20kPa, which is monitored by pressure gauge(VII). Then the pore water pressure and water discharge of each pressure is obtained.

5 Results and analysis

5.1 Water pressure distribution of steady seepage

In Fig. (a) and Fig. (b), the water discharge of the erect drainage pipe approximately equals to that of the oblique drainage pipe. The exact water discharge values measured from an erect drainage pipe and oblique drainage pipe are 1384.64g/s and 1248.97g/s respectively. The water discharge of erect drainage pipe is slightly greater than that of the oblique pipe. Fig. (c) shows the water discharge of both drainage pipes during draining. The measured water discharges of erect and oblique drainage pipe are 695.82g/s and 387.24g/s respectively. It is found that, under the same test condition of intake water pressure and opening angles of ball valves, the drainage efficiency of the erect drainage pipe is better than the oblique pipe. It may be due to the difference of the drainage paths since the drainage path of the erect drainage pipe is much shorter than the oblique drainage pipe.

The water pressure values measured by each tier of sensors are shown in **Error! Reference source not found.**, 2, and 3. Comparing to the value monitored by each sensor under different test conditions, the water pressure of most DEDP is less than that of DODP. It means that the water pressure reduction effect of the erect drainage pipe is greater than the oblique drainage pipe, which agrees well with the result proved by water discharge analysis. The water pressure values of most DODP are less than that of the DEDP since the active drainage area of DODP is larger than that of DEDP or DODP. It shows that in a certain range, multiple drain outlets are more conducive to reduce water pressure than a single drain outlet. It indicates that the distance between the two drain outlets needs rational design.

From each tier of sensors, the water pressure measured has a similar trend. It indicates that the water pressure is well distributed and changed synchronously, which proves that the bottom-to-up drainage and water pressure reduction system is effective to reduce water pressure at the bottom of the tunnel. Since the average values of water pressure under each test condition are different, the standard deviation is unable to validate the data. Therefore, the coefficient of variation ("CV," the ratio of the standard deviation to average value) is chosen to validate the collected data. Only the CV values of the Bottom Tier Sensors in each test condition are more than 10%, which means that the water pressure at the bottom of the testing chamber flutters obviously. The maximum CV value of the Medium and Top tier is 6.10%, which means that the water pressure values in the position of each tier are almost not fluctuant, proving the good distribution of water pressure in another way. The reasons of such fluctuation can be concluded as: 1) The water flow paths are disordered and the flow rate is not as uniform as the bottom tier of pore pressure sensors placed in gravel filling, in which there are plenty disordered interspace; 2) The data measured by the bottom and the top tier of sensors have much better accuracy than the bottom tier.

Under the same condition, the average pore pressure measured from the bottom tier sensors is the highest. The one from the medium tier is lower than the bottom tier, and the one from the top tier is the lowest. The difference of the data measured by the bottom tier and the medium tier, the medium tier, and the top tier is 0.961kPa, 0.896kPa, respectively. The difference is almost the same as the hydrostatic pressure of the sensors in the different height of, which indirectly proves the correctness of these water pressure data.

5.2 Influence of the diameter of the drainage pipe

The water pressure of the secondary lining of the tunnel is primarily affected by the water pressure reduction system. The water pressure measured by No.10~No.22 pore pressure sensors is more accurate than No.1~No.9. Therefore, the water pressure data measured by No.10~No.22 sensors will be mainly discussed in this part. The measured water pressure is shown in Table 4. Due to the error of the data acquisition system, the water pressure measured by the 7-pressure gauge varies slightly around 20kPa, which should maintain stable at 20kPa accurately without system error.

Table 4 shows that when the equivalent diameters are 47mm, 27mm, and 27mm, the water pressure decrease for about 60%, 45%, and 30%, respectively, which indicates that the water pressure decreases with the increase of the equivalent diameter of drainage pipe. This result proves that if the drainage capacity of the drainage and water pressure reduction system is enough for a tunnel, the water pressure on the secondary lining will not increase too much, which agrees with the conclusion of Li (2018). If the drainage capacity of the drainage pipe for a tunnel is not enough for the water inflow of the construction region, the effect of the bottom-to-up drainage and water pressure reduction system will decrease, and it may even result in the damage of the tunnel due to the additional drainage measures in the bottom of the tunnel.

The reduction of water pressure due to the influence of drainage pipe diameter is shown in Fig.. When 22-ball valve is opened to about 45° (the equivalent diameter is 63mm), the water flow is in a critical state between whole pipe flow and partly-filled pipe-flow, which indicates that the water pressure state approaches to that of opening ball valve about 90°. So the water pressure data of fully opened ball valve will be regarded as that of 45°. And the angle of 0° means the ball valves fully closed, i.e., water pressure will not decrease.

In Fig., with the increase of the equivalent diameter of the drainage pipe, the water pressure reduction ratio gradually increases and tends to be stabilized. For the case that the initial pressure about 20kPa, the water pressure reduction ratio is approximately 60%. If the equivalent diameter is larger than 63mm, the whole pipe flow in each pipe will switch to partly-filled pipe-flow. It indicates the water pressure will not decrease any more even if increasing the diameter of the drainage pipe if the initial pressure is 20kPa. Therefore, the effect of reducing water pressure on tunnel secondary lining will be better with the increase of drainage pipe diameter as long as it is whole pipe flow. For a certain tunnel region, the whole pipe flow will become partly-filled pipe-flow when the diameter of drainage pipe increases to a certain extent, which means the effect of pressure reduction will not get better any longer. Therefore, for a safe tunnel structure, in the design of the bottom drainage system for the tunnel, the drainage pipe should be large enough for the water inflow of the tunnel construction region.

The data of Table 4 and Fig. shows that both the erect and oblique drainage pipe has good performance in water pressure reduction. However, under the same test condition, the water pressure reduction ratio of the erect drainage pipe is more than the oblique drainage pipe for about 4%. It indicates that the drainage effect of erect drainage pipe is better than the oblique drainage pipe to some extent.

The data of No.15 pore pressure sensor monitoring water pressure decreasing process is shown in Fig.. The water pressure decreasing process of both erect and oblique drainage pipe is great, which lasting about 2~3s, when the equivalent diameters are 47mm and 27mm. The water pressure of the pipe with an equivalent diameter of 18mm decreases very slowly, after about 50s the water pressure still shows some trend to decrease. This experimental phenomenon indicates that a large enough cross-section area of the drainage pipe contributes to a more rapid water pressure reduction process, which is helpful to deal with the sudden increase of water pressure like a sudden rainfall. Contrarily, if the diameter of the drainage pipe is too small, the water pressure decreases rapidly at first and then very slow, which leads to a long drainage process with little effect. Thus, it is critical to have a large enough drainage pipe to satisfy the requirement of the tunnel structure. It is not necessary to use a partly-filled pipe-flow while a whole pipe flow can reduce water pressure on the secondary lining of a tunnel efficiently. The changing curve of water pressure with a time of 27mm-equivalent-diameter erect drainage pipe and 27mm-equivalent-diameter oblique drainage pipe is shown in Fig.. With a comprehensive consideration of security, cost-effectiveness, etc., it is recommended that the drainage capacity should be designed for a partly-filled pipe-flow for the dry season and a whole pipe flow for the rainy season.

5.3 Influence of inlet water pressure

The relationship between water pressure and intake water pressure is shown in Fig.. The water pressure increases linearly with the increase of intake pressure, which is similar to the results of the study by Li et al. (2018). It shows that the secondary lining external water pressure increase approximately identically as the increase of water head height of the vault. Since the pore pressure sensors and the pressure gauges are placed at different locations in this study, the data measured from them be used to validate each other. All the water pressure values are shown in Fig. have a similar trend which indicates that there is no sudden change of pressure observed in the experiment. It demonstrates that the simulation of the steady seepage and monitoring methods of water pressure change in this study is feasible, and the water pressure is well distributed with no serious fluctuation.

The influence of intake pressure on the flow rate is shown in Fig.. The flow rate is measured in the steady flow, and the cross-section area of both types of drainage pipes are the same, meaning the difference of flow rate should only be caused by the drainage pipe types. Fig. shows a linear relation of the flow rate and the inlet water pressure. The flow rate increases with the increase in intake pressure. The flow rate of the erect drainage pipe is two times higher than the oblique drainage pipe with the same intake pressure. Therefore, it can be concluded that with the same cross-section area and whole pipe flow, the flow rate of the erect drainage pipe is about two times greater than the oblique drainage pipe. Furthermore, the slope of the flow rate curve of the erect drainage pipe is much larger than the oblique drainage pipe. It indicates that the water discharge of the erect drainage pipe would increase rapidly with the increase of the intake pressure. In other words, the erect drainage pipe can manage the sudden change of the water inflow more efficiently. Therefore, the erect type of drainage pipe is more effective than the oblique type in the water flow rate analysis.

6 Summary and Conclusion

This paper presents a study on assessing the feasibility of bottom-up drainage and water pressure reduction system for railway tunnels by simulation and analyzing the pressure reduction effect. The experiment equipment consists of two main parts: the water supply system and the drainage system. The experiment was set up imitating the bottom structure of the tunnel with the bottom drainage system under three test conditions: water pressure distribution of steady seepage in a regular working state; the influence of the change of the drainage pipes diameter on the effect of water pressure reduction; and inlet water pressure on the seepage field. The results of the experiment can be summarized as follows:

(1) The bottom-up drainage system can effectively drain the water in the bottom of the tunnel by the difference of natural hydraulic pressure.

(2) It is discovered that the erect drainage pipe is better than the oblique one in the drainage efficiency, flow rate, and percentage reduction of water pressure.

(3) The bottom-up drainage and water pressure reduction system can effectively reduce the secondary lining external water pressure, and there will be a well water pressure distribution at the bottom of the tunnel.

(4) If the water inflow is stable with whole pipe drainage, the reduction effect of

water pressure is remarkable by increasing the diameter of the drainage pipe. In other words, if the drainage pipes are incapable of draining the water at the bottom of tunnels, the reduction effect of water pressure on the secondary lining is unremarkable, and the reduction process is very long.

(5) In the design of drainage pipes, the safety of the tunnel lining structure needs to be taken into consideration and guarantee as well as the water inflow difference of rainy season and dry season. Therefore, the design of partly-pipe flow in the dry season and whole pipe flow in the rainy season is recommended.

This study proved the bottom-to-up drainage and water pressure system is feasible for use on tunnels. Due to the difference between the construction site and laboratory test, more field test data is necessary to validate and optimize the performance of the proposed drainage system.

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Appendix A. Figures

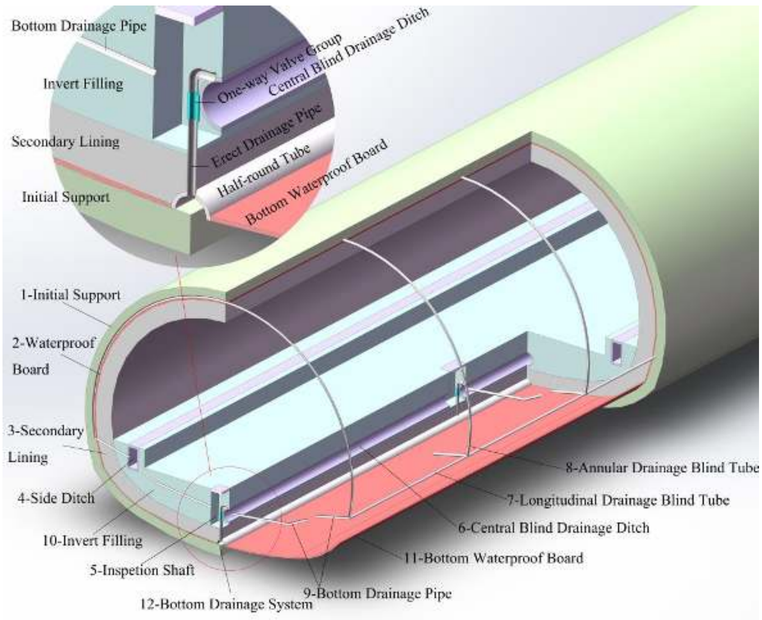


Fig. 1. "bottom-to-up" drainage and pressure reduction system at the bottom of railway tunnels (Li et al., 2018)

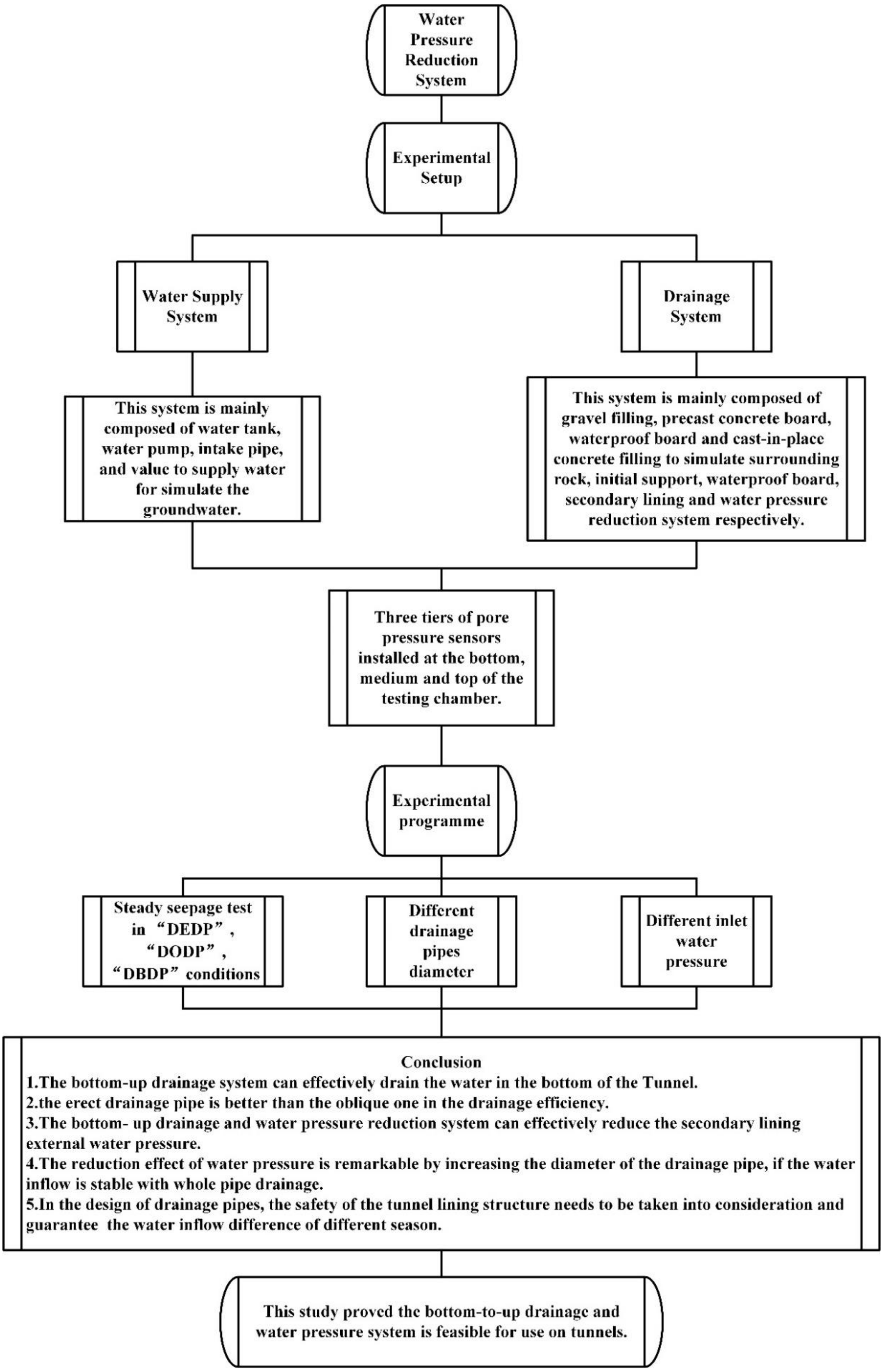


Fig. 2. The overall idea flowchart

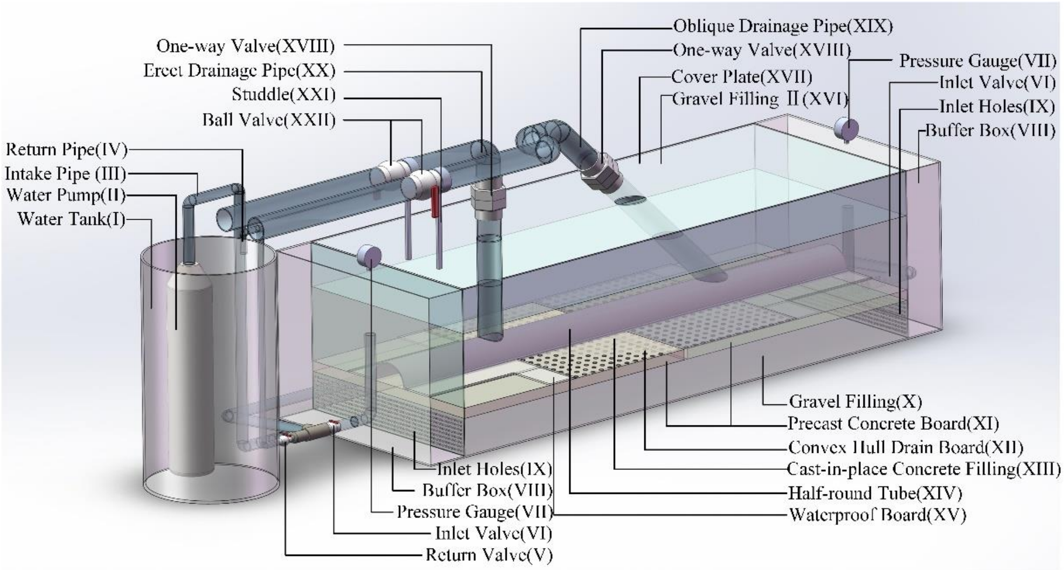


Fig. 3. Sketch of the experimental drainage system

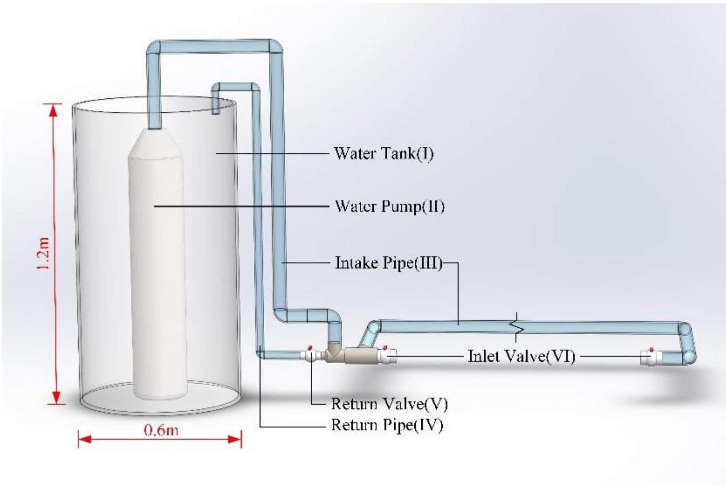


Fig. 4. Sketch of the water supply system

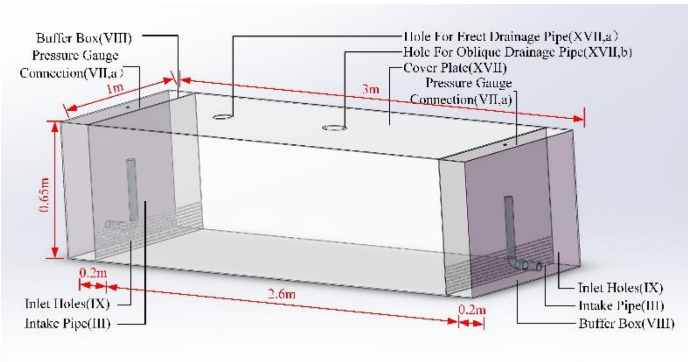


Fig. 5. Sketch of the testing chamber

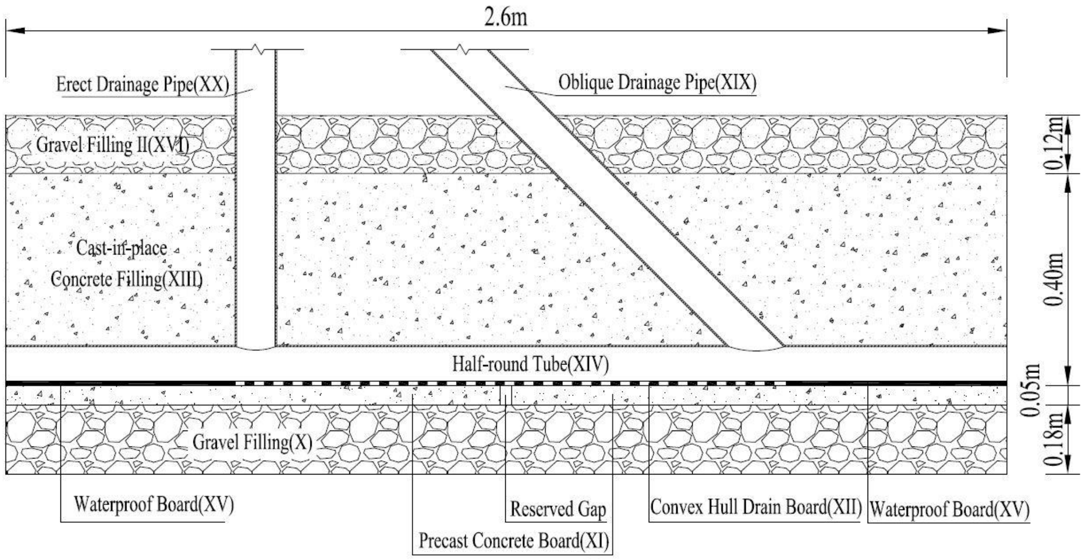


Fig. 6. Sketch of the simulating tunnel invert structure and drainage system in the testing chamber

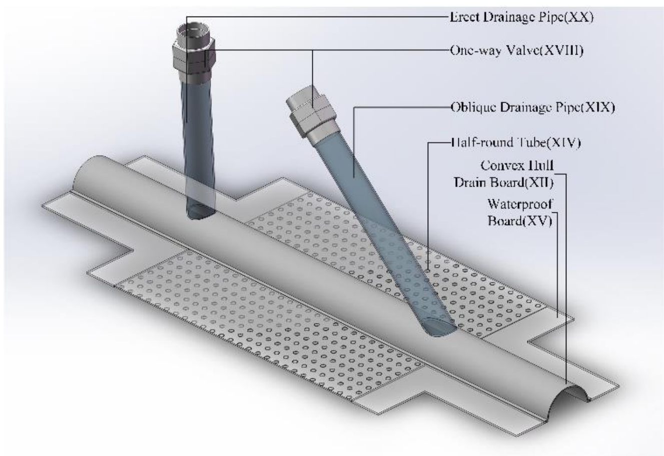


Fig. 7. Sketch of the waterproof and drainage measures

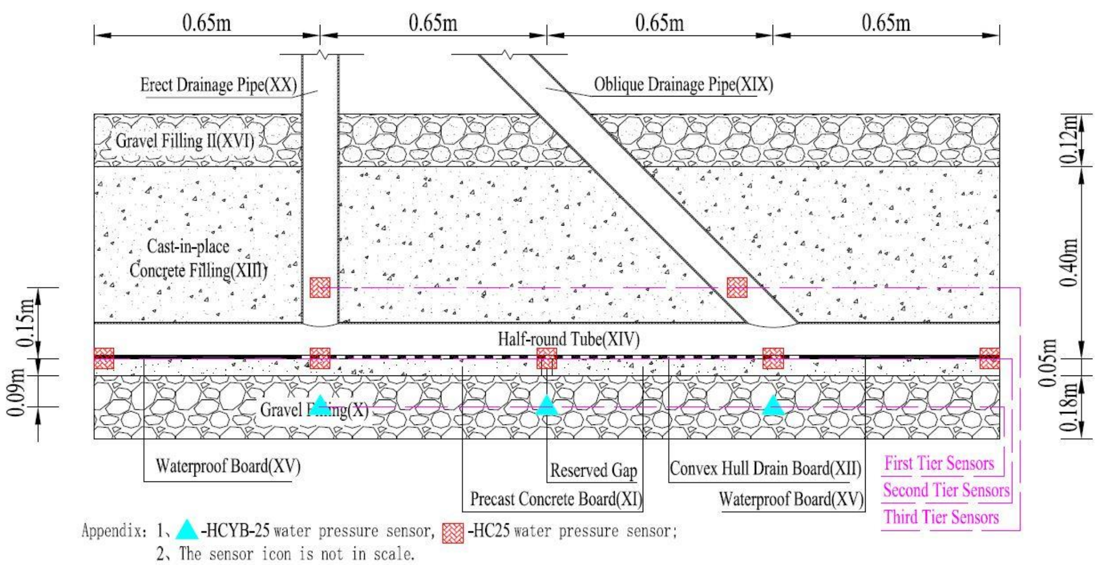
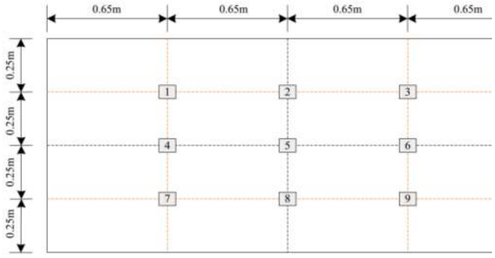
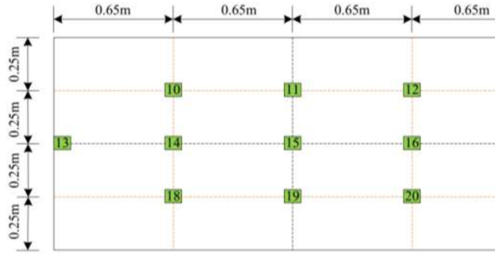


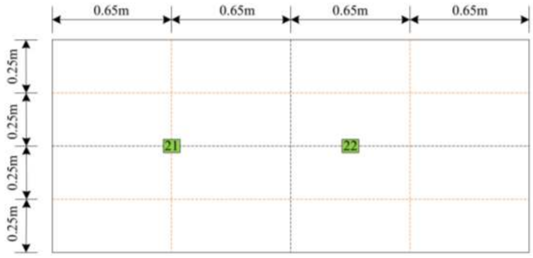
Fig. 8. Vertical sectional profile of the arrange of the pore pressure sensor



(a) The Bottom Tier Sensors



(b) The Medium Tier Sensors



(c) The Top Tier Sensors

Fig. 9. The horizontal arrangement of each tier of the pore pressure sensor

Fig. 10. Photo of the whole prepared experimental equipment

(a) Only drain by erect pipe

(b) Only drain by oblique pipe

(c) Drain by both pipes

Fig. 11. Water discharge of the drainage pipe in different test conditions

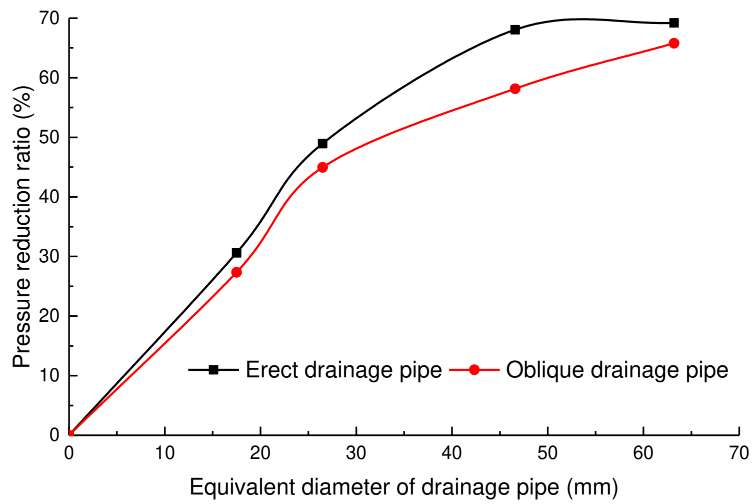


Fig.12. The curve of the water pressure reduction and the equivalent diameter of the drainage pipe

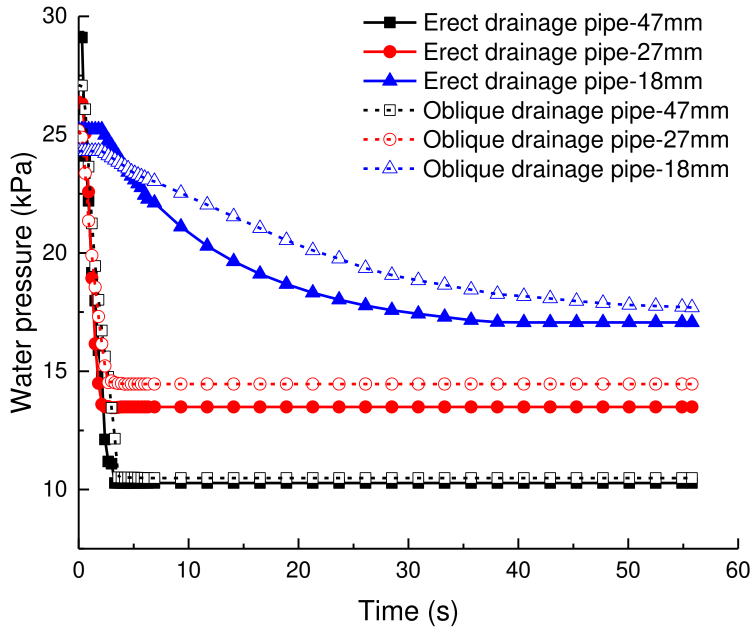


Fig.13. The curve of the water pressure reducing process monitoring by No.15 sensor

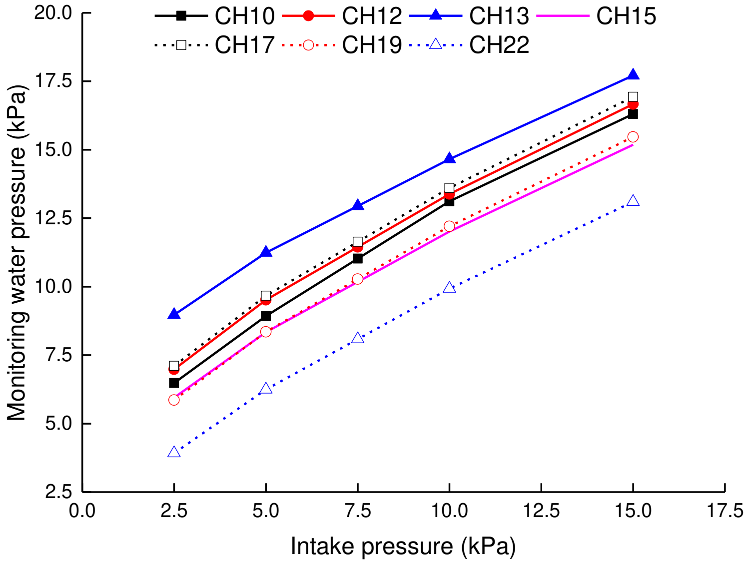


Fig.14. Relation curve of monitoring water pressure and inlet water pressure

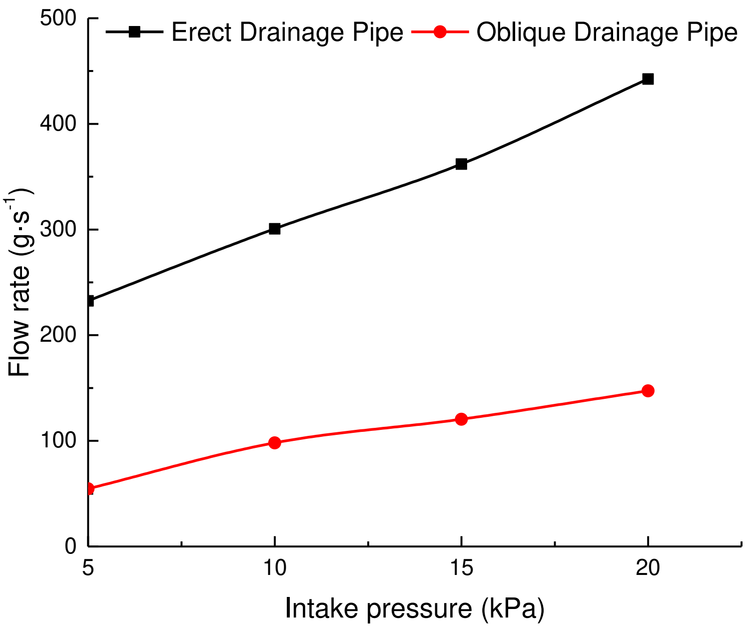


Fig.15. Relation curve of flow rate and inlet water pressure

Appendix B.

Table 1 Water pressure measured by the first tier of pore pressure sensors

Item	CH1 /kPa	CH2 /kPa	CH3 /kPa	CH4 /kPa	CH5 /kPa	CH6 /kPa	CH7 /kPa	CH8 /kPa	CH9 /kPa	Average /kPa	Standard deviation /kPa	Coefficient of variation /%
DBDP	10.694	10.161	/*	9.985	11.925	8.490	10.153	10.206	12.044	10.457	1.138	10.88
DEDP	11.450	10.094	/	9.989	10.749	8.204	10.153	10.305	12.047	10.374	1.139	10.98
DODP	13.383	9.835	/	10.212	11.934	9.327	10.389	10.653	10.695	10.804	1.287	11.92

*: "/" means no available data because of sensor damage.

Table 2 Water pressure measured by the second tier of pore pressure sensors

Item	CH10 /kPa	CH11 /kPa	CH12 /kPa	CH13 /kPa	CH14 /kPa	CH15 /kPa	CH16 /kPa	CH17 /kPa	CH18 /kPa	CH19 /kPa	CH20 /kPa	Average /kPa	Standard deviation /kPa	Coefficient of variation /%
DBDP	9.748	9.664	9.653	9.323	9.666	9.361	9.363	9.638	8.575	9.681	/*	9.467	0.351	3.70
DEDP	9.889	9.809	9.798	9.407	9.817	9.588	9.590	9.791	8.197	9.823	/	9.571	0.505	5.28
DODP	10.072	9.987	9.961	9.619	10.000	9.733	9.716	9.962	8.084	10.005	/	9.714	0.592	6.10

*: "/" means no available data because of sensor damage.

Table 3 Water pressure measured by the third tier of pore pressure sensors

Item	CH21 /kPa	CH22 /kPa	Average /kPa	Standard deviation /kPa	Coefficient of variation /%
DBDP	8.629	8.392	8.510	0.167	1.96
DEDP	8.751	8.657	8.704	0.067	0.77
DODP	8.949	8.753	8.851	0.139	1.57

Table 4 Water pressure value and pressure decrease percentage in different diameter of drainage pipe

Equivalent diameter /mm	**Drain pipe**	**Item**	**CH10**	**CH11**	**CH12**	**CH13**	**CH14**	**CH15**	**CH16**	**CH17**	**CH18**	**CH19**	**CH20**	**CH21**	**CH22**	**Average**
47	Erect drainage pipe	Before	30.766	30.455	30.814	24.736	35.486	29.202	29.083	29.781	28.998	31.228	/*	31.579	27.526	
		After	10.055	9.910	9.901	9.356	10.012	10.276	11.023	10.019	6.776	9.945	/	8.827	8.334	
		Percentage	67.32%	67.46%	67.87%	62.18%	71.79%	64.81%	62.10%	66.36%	76.63%	68.15%	/	72.05%	69.72%	68.04%
	Oblique drainage pipe	Before	28.324	27.997	28.257	23.572	31.171	26.903	26.869	27.641	25.386	28.522	/	28.340	25.036	
		After	10.596	12.050	12.052	11.266	12.169	12.021	12.749	12.137	8.916	12.084	/	10.984	10.046	
		Percentage	62.59%	56.96%	57.35%	52.20%	60.96%	55.32%	52.55%	56.09%	64.88%	57.63%	/	61.24%	59.87%	58.14%
27	Erect	Before	28.564	27.582	27.716	24.605	28.639	26.314	26.560	27.724	/	27.803	/	26.928	24.522	

	drainage	After	14.816	14.253	14.234	13.752	13.851	13.477	13.780	14.552	/	14.216	/	12.941	11.668	
	pipe	Percentage	48.13%	48.33%	48.64%	44.11%	51.63%	48.78%	48.12%	47.51%	/	48.87%	/	51.94%	52.42%	48.95%
	Oblique	Before	26.883	26.190	26.372	22.715	28.192	25.094	25.200	26.114	/	26.558	/	25.945	23.281	
	drainage	After	15.024	14.589	14.603	13.559	14.790	13.852	14.075	14.741	/	14.644	/	13.522	12.049	
	pipe	Percentage	44.11%	44.30%	44.63%	40.31%	47.54%	44.80%	44.15%	43.55%	/	44.86%	/	47.88%	48.24%	44.94%
	Erect	Before	26.739	25.905	26.020	22.996	27.099	24.722	24.935	25.976	/	26.067	/	25.255	22.933	
	drainage	After	18.713	18.091	18.111	16.683	18.329	17.178	17.446	18.290	/	18.079	/	17.004	15.394	
18	pipe	Percentage	30.02%	30.16%	30.39%	27.45%	32.36%	30.52%	30.04%	29.59%	/	30.65%	/	32.67%	32.87%	30.61%
	Oblique	Before	26.356	25.518	25.618	22.742	26.581	24.336	24.568	25.610	/	25.655	/	24.813	22.532	
	drainage	After	19.286	18.636	18.668	17.194	18.885	17.704	17.974	18.847	/	18.634	/	17.569	15.921	
	pipe	Percentage	26.83%	26.97%	27.13%	24.39%	28.95%	27.25%	26.84%	26.41%	/	27.37%	/	29.19%	29.34%	27.33%

*: "/" means no available data because of sensor damage.