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1 **Development and Assessment of a Water Pressure Reduction System** 2 **for Lining Invert of Tunnels in Saturated Grounds**

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14

15 **Abstract**

16 In this study, the feasibility of a novel bottom-up drainage and water pressure reduction
17 system for reducing the secondary lining external water pressure on tunnels has been
18 validated by conducting laboratory evaluations. The tunnels environment including
19 surrounding rock, lining, bottom drainage system and other supplementary components
20 have been simulated to investigate the working pattern and efficiency of this drainage
21 system. The drainage system has been further optimized by analyzing the measured

22 water pressure and flow rate. Experimental results indicate that the designed draining
23 system is feasible for reducing the secondary lining external water pressure in the
24 bottom of tunnels and the water pressure has been reduced significantly with high
25 efficiency. The capacity of the proposed system to control the rapid water inflow in
26 tunnel construction region can be guaranteed. The factors affecting the performance of
27 the system such as the diameter of the drainage pipe and the inlet water pressure are
28 also discussed in this paper.

29 **1 Introduction**

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

48 Many researchers have investigated how to control the external water pressure on
49 the tunnel lining. Arjnoi et al. (2009) conducted theoretical analysis and numerical

50 simulation to study the effect of drainage conditions on pore water pressure
51 distributions and lining stresses in a drained tunnel with two different boundary
52 conditions. Wang et al. (2008) presented a theoretical model to predict the distribution
53 of water pressure on tunnel lining by laboratory test and field evaluation. Fang et al.
54 (2016) developed an apparatus to apply the appropriate external water pressure by
55 evacuating the inner space of the tunnel and applying external air pressure to the liner
56 to act as the water pressure. Stripple et al. (2016) presented a new design of drainage
57 system for rock tunnels. Yee et al. (2015) and Yee (2015) analyzed the influence
58 between magnetic fields and calcium carbonate deposition through laboratory tests and
59 field evaluations to prevent clogging. Besides, wave vibrations (Xin et al., 2018),
60 Quantum Stick (Jung et al., 2013) and geosynthetic (Jang et al., 2015), etc. were also
61 investigated. Choi et al. (2015) proposed an optimal lightweight-foamed mortar mix
62 suitable for composite lining method to facilitate tunnel drainage. The lightweight-
63 foamed mortar replaces the traditional initial support, and the drainage system works
64 more efficiently due to its porous structure. The current studies mainly focus on the
65 porewater pressure distributions on the whole tunnel lining or the water pressure that
66 applies to the upper structure of the tunnel. There is still much research needs on the
67 solution of the problems occurred on tunnel invert caused by high water pressure.

68 To prevent the damage of the tunnel invert caused by water pressure, Li et al. (2018)
69 developed a novel bottom-to-up drainage and water pressure reduction system (Fig. 1)
70 to reduce the water pressure that applies on the secondary lining. Such system includes

71 a transverse catchment system, a longitudinal water conducting system, and a bottom-
72 to-up water drainage system. Series of numerical analyses has been conducted to
73 evaluate its drainage performance. Better waterproof and drainage function can be
74 achieved on the entire tunnel by combining the new and existing technologies.

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

80 **2 Experimental setup**

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

91 **2.1 Water supply system**

92 The water supply system (Fig.4) consists of 6 parts, providing power to make
93 water flow and receiving water from the drainage system. Water tank(I) is a steel
94 cylinder, which is 1.2m high with an inner diameter of 0.6m and a 2mm-thick wall. The
95 Water pump(II) is the main power supply of the experiment to make water flow, which
96 is 1.1m-long with a flow of 3 m³/h. Intake pipe(III) connects the water supply system
97 and the simulating drainage system. There are two tees in the intake pipe(III), the first
98 tee divides the flow path into two: one connects inlet valve(VI) to make water flow into
99 the simulating drainage system, the other connects return valve(V) and return pipe(IV)
100 to make water flow back into water tank(I); the second tee divides the other flow path
101 into two to connect testing chamber as there are two intakes on both sides of the testing
102 chamber.

103 The following two flow paths were designed in this experiment:

- 104 1. Path 1 is 1-water tank →2-water pump →3-intake pipe →the first tee →5-
105 return valve →4-return pipe →1-water tank;
- 106 2. Path 2 is 1-water tank →2-water pump →3-intake pipe →the first tee →the
107 second tee →6-inlet valve →the simulating drainage system →1-water tank.

108 The volume of water flowing into the testing chamber can be controlled by
109 regulating 5-return valve and 6-inlet valve, the water pressure in the testing
110 chamber can also be controlled if superadding regulating 22-ball valve.

111 2.2 Drainage system

112 The drainage system makes up the testing chamber and the components in it. The

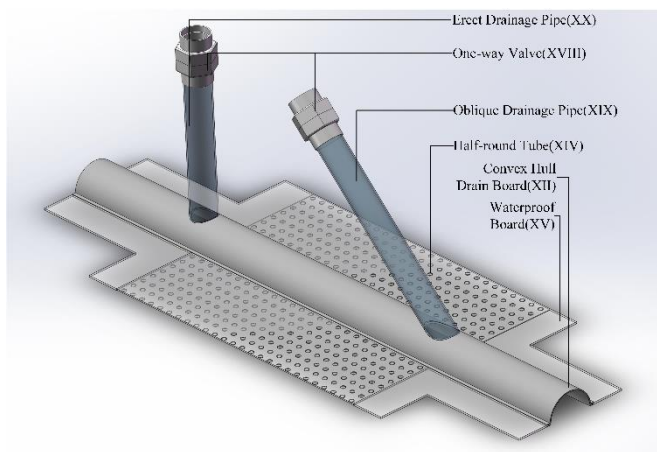
113 testing chamber is a cuboid steel box with a size of $3\text{m}\times 1\text{m}\times 0.65\text{m}$ (length \times width \times
114 height), which is used to simulate the tunnel invert structure and groundwater shows in
115 [Fig.5](#). There is a buffer box(VIII) in each side of the testing chamber, and the size of
116 the buffer box(VIII) is $0.2\text{m}\times 1\text{m}\times 0.65\text{m}$ (length \times width \times height). The surplus space
117 of the testing chamber is the main container of simulating tunnel invert. The size of the
118 testing chamber is $2.6\text{m}\times 1\text{m}\times 0.65\text{m}$ (length \times width \times height). There is a pressure
119 gauge(VII-a) connected to the top of each buffer box(VIII). The Cover plate(XVII) is
120 installed on the top of the testing chamber by screws. The Cover plate(XVII) is
121 manufactured with two parts to reduce the weight for easy transport. On each plate,
122 there is a hole corresponding to the erect drainage pipe and oblique drainage pipe.

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

134 space between the cast-in-place concrete filling(XIII) and cover plate(XVII) and
135 transfers force if necessary.

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

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



151 Fig. 7.

152 **3 Monitoring and data acquisition system**

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

155 **3.1 Pore water pressure monitoring**

156 There are two types of pore pressure sensors: HC-25 micropore pressure sensor
157 (0.2% in precision) and HCYB-25 micropore pressure sensor (0.5% in precision).
158 HCSC-16 data acquisition equipment and YBY-2001 strain acquisition instrument were
159 used for data acquisition. There are 3 tiers of pore pressure sensors installed at different
160 heights (see Fig.). The Bottom Tier Sensors is placed in the gravel filling(X) to monitor
161 the pore pressure representing surrounding rock. The Medium Tier Sensors is placed
162 between precast concrete boards(XI) and waterproof board to monitor the pore pressure
163 that representing simulating secondary lining. The Top Tier Sensors is placed in each
164 drainage pipe which is 15cm higher than the medium tier. The horizontal arrangement
165 of each tier of pore pressure sensors is shown in Fig. . No.1~No.9 sensors are HCYB-
166 25 micro pore pressure sensors, and No.10~No.22 sensors are HC-25 micro pore
167 pressure sensors.

168 **3.2 Water discharge monitoring**

169 Water discharge monitoring system consists of a water container, an electronic
170 scale, and a stopwatch. The weight of the water container was measured before the
171 experiment. When adding water into the container, the corresponding elapsed time was

172 also monitored. The water discharge of each drainage pipe was obtained by calculating
173 the mass of the water in the container and the elapsed time. For better accuracy, 3 was
174 used as an average value of water discharge in each experimental condition.

175 **4 Experimental programme**

176 **4.1 The process of installation of experimental equipment**

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

207 Fig. shows the entire experimental system.

208 **4.2 Simulations**

209 The following experiments will be discussed in this section.

210 **(1) Steady seepage test**

211 The distribution of water pressure in steady seepage will be analyzed in this study.

212 When performing the experiment, all intake pipes and 4-return pipe will be opened

213 except the drainage pipes, which are controlled by the ball valves(XXII). It includes

214 three conditions:

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

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

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

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

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

235 drainage pipe opened to 15° and 10° , and ball valve(XXII) of oblique drainage pipe
236 opened to 30° , 15° , and 10° .

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

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

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

249 **5 Results and analysis**

250 **5.1 Water pressure distribution of steady seepage**

251 In Fig. (a) and Fig. (b), the water discharge of the erect drainage pipe
252 approximately equals to that of the oblique drainage pipe. The exact water discharge
253 values measured from an erect drainage pipe and oblique drainage pipe are 1384.64g/s
254 and 1248.97g/s respectively. The water discharge of erect drainage pipe is slightly
255 greater than that of the oblique pipe. Fig. (c) shows the water discharge of both drainage

256 pipes during draining. The measured water discharges of erect and oblique drainage
257 pipe are 695.82g/s and 387.24g/s respectively. It is found that, under the same test
258 condition of intake water pressure and opening angles of ball valves, the drainage
259 efficiency of the erect drainage pipe is better than the oblique pipe. It may be due to the
260 difference of the drainage paths since the drainage path of the erect drainage pipe is
261 much shorter than the oblique drainage pipe.

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

272 From each tier of sensors, the water pressure measured has a similar trend. It
273 indicates that the water pressure is well distributed and changed synchronously, which
274 proves that the bottom-to-up drainage and water pressure reduction system is effective
275 to reduce water pressure at the bottom of the tunnel. Since the average values of water
276 pressure under each test condition are different, the standard deviation is unable to

277 validate the data. Therefore, the coefficient of variation (“CV,” the ratio of the standard
278 deviation to average value) is chosen to validate the collected data. Only the CV values
279 of the Bottom Tier Sensors in each test condition are more than 10%, which means that
280 the water pressure at the bottom of the testing chamber flutters obviously. The
281 maximum CV value of the Medium and Top tier is 6.10%, which means that the water
282 pressure values in the position of each tier are almost not fluctuant, proving the good
283 distribution of water pressure in another way. The reasons of such fluctuation can be
284 concluded as: 1) The water flow paths are disordered and the flow rate is not as uniform
285 as the bottom tier of pore pressure sensors placed in gravel filling, in which there are
286 plenty disordered interspace; 2) The data measured by the bottom and the top tier of
287 sensors have much better accuracy than the bottom tier.

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

295

296 **5.2 Influence of the diameter of the drainage pipe**

297 The water pressure of the secondary lining of the tunnel is primarily affected by

298 the water pressure reduction system. The water pressure measured by No.10~No.22
299 pore pressure sensors is more accurate than No.1~No.9. Therefore, the water pressure
300 data measured by No.10~No.22 sensors will be mainly discussed in this part. The
301 measured water pressure is shown in Table 4. Due to the error of the data acquisition
302 system, the water pressure measured by the 7-pressure gauge varies slightly around
303 20kPa, which should maintain stable at 20kPa accurately without system error.

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

314 The reduction of water pressure due to the influence of drainage pipe diameter is
315 shown in Fig.. When 22-ball valve is opened to about 45° (the equivalent diameter is
316 63mm), the water flow is in a critical state between whole pipe flow and partly-filled
317 pipe-flow, which indicates that the water pressure state approaches to that of opening
318 ball valve about 90°. So the water pressure data of fully opened ball valve will be

319 regarded as that of 45° . And the angle of 0° means the ball valves fully closed, i.e.,
320 water pressure will not decrease.

321 In Fig., with the increase of the equivalent diameter of the drainage pipe, the water
322 pressure reduction ratio gradually increases and tends to be stabilized. For the case that
323 the initial pressure about 20kPa, the water pressure reduction ratio is approximately
324 60%. If the equivalent diameter is larger than 63mm, the whole pipe flow in each pipe
325 will switch to partly-filled pipe-flow. It indicates the water pressure will not decrease
326 any more even if increasing the diameter of the drainage pipe if the initial pressure is
327 20kPa. Therefore, the effect of reducing water pressure on tunnel secondary lining will
328 be better with the increase of drainage pipe diameter as long as it is whole pipe flow.
329 For a certain tunnel region, the whole pipe flow will become partly-filled pipe-flow
330 when the diameter of drainage pipe increases to a certain extent, which means the effect
331 of pressure reduction will not get better any longer. Therefore, for a safe tunnel structure,
332 in the design of the bottom drainage system for the tunnel, the drainage pipe should be
333 large enough for the water inflow of the tunnel construction region.

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

339 The data of No.15 pore pressure sensor monitoring water pressure decreasing

340 process is shown in Fig.. The water pressure decreasing process of both erect and
341 oblique drainage pipe is great, which lasting about 2~3s, when the equivalent diameters
342 are 47mm and 27mm. The water pressure of the pipe with an equivalent diameter of
343 18mm decreases very slowly, after about 50s the water pressure still shows some trend
344 to decrease. This experimental phenomenon indicates that a large enough cross-section
345 area of the drainage pipe contributes to a more rapid water pressure reduction process,
346 which is helpful to deal with the sudden increase of water pressure like a sudden rainfall.
347 Contrarily, if the diameter of the drainage pipe is too small, the water pressure decreases
348 rapidly at first and then very slow, which leads to a long drainage process with little
349 effect. Thus, it is critical to have a large enough drainage pipe to satisfy the requirement
350 of the tunnel structure. It is not necessary to use a partly-filled pipe-flow while a whole
351 pipe flow can reduce water pressure on the secondary lining of a tunnel efficiently. The
352 changing curve of water pressure with a time of 27mm-equivalent-diameter erect
353 drainage pipe and 27mm-equivalent-diameter oblique drainage pipe is shown in Fig..
354 With a comprehensive consideration of security, cost-effectiveness, etc., it is
355 recommended that the drainage capacity should be designed for a partly-filled pipe-
356 flow for the dry season and a whole pipe flow for the rainy season.

357

358 **5.3 Influence of inlet water pressure**

359 The relationship between water pressure and intake water pressure is shown in
360 Fig.. The water pressure increases linearly with the increase of intake pressure, which

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

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

382 of the water inflow more efficiently. Therefore, the erect type of drainage pipe is more
383 effective than the oblique type in the water flow rate analysis.

384

385 **6 Summary and Conclusion**

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

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

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

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

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

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

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

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

415

416 **Acknowledgments**

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420

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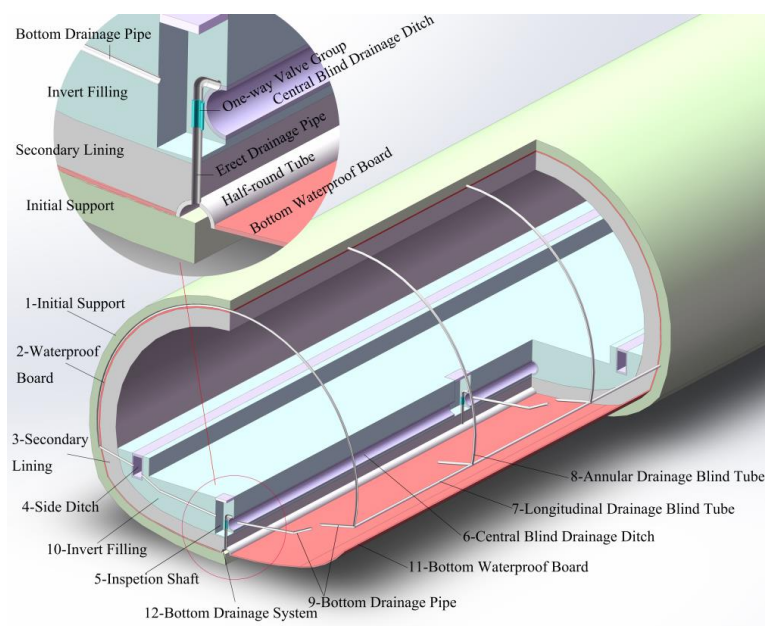
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Appendix A. Figures

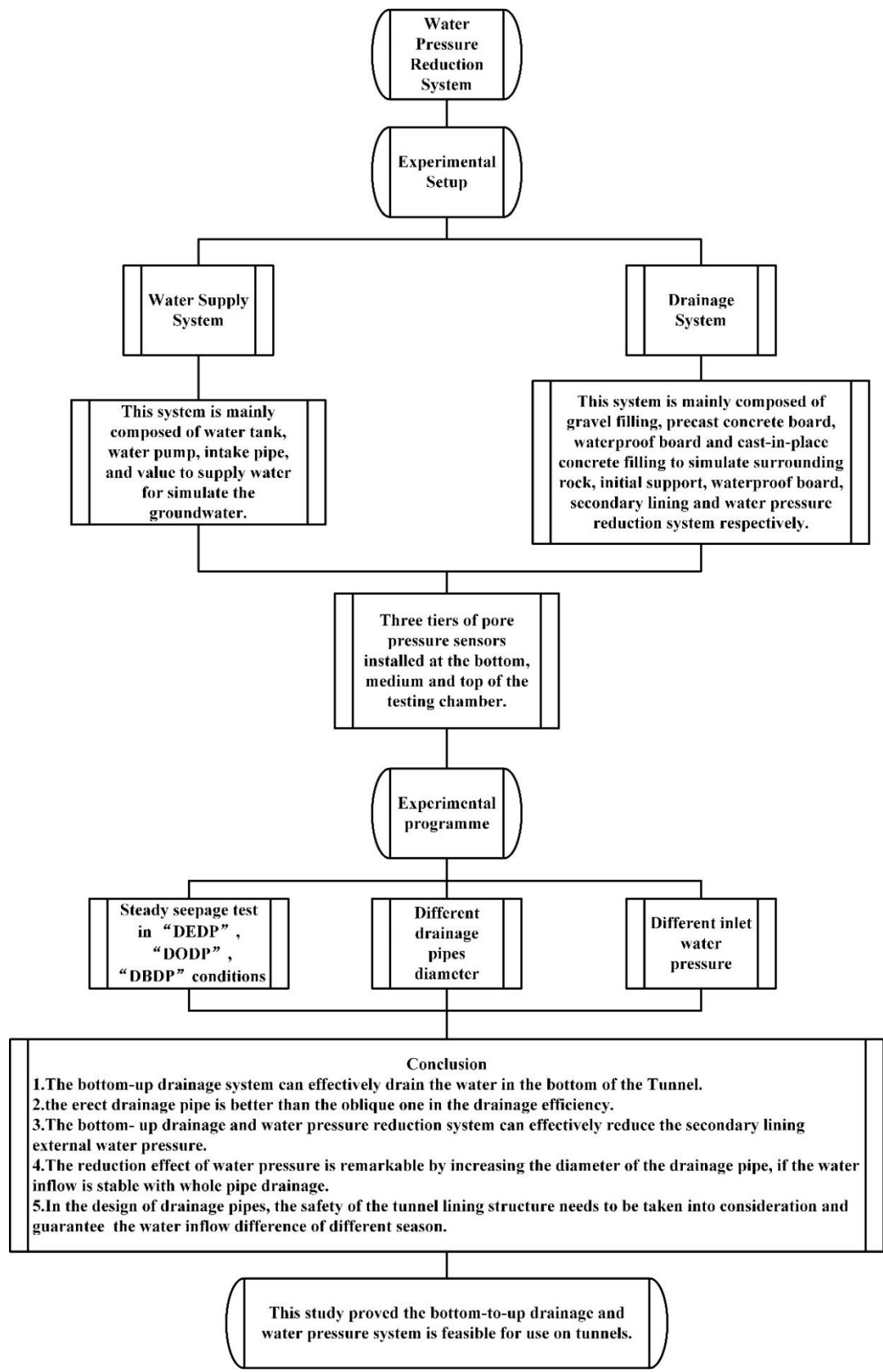


472

473 **Fig. 1. “bottom-to-up” drainage and pressure reduction system at the bottom of railway**

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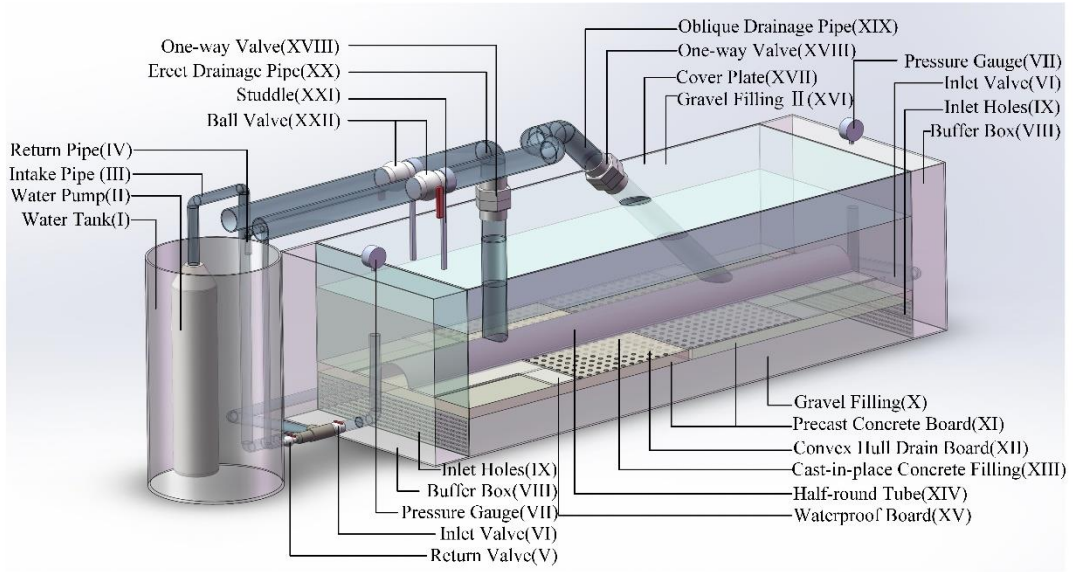
tunnels (Li et al., 2018)



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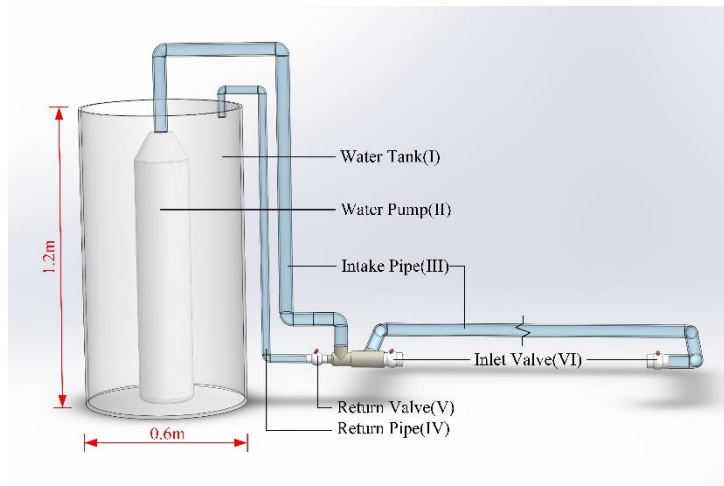
Fig. 2. The overall idea flowchart



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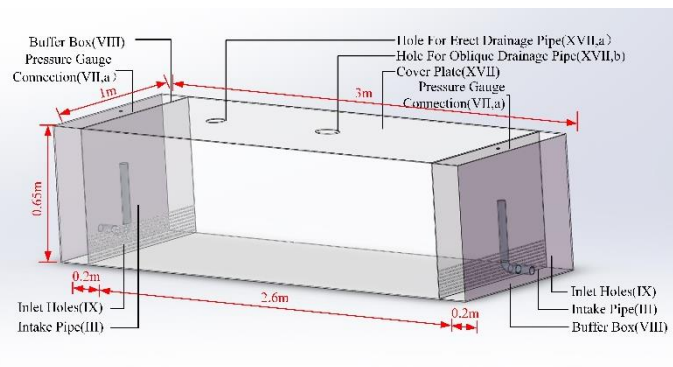
Fig. 3. Sketch of the experimental drainage system



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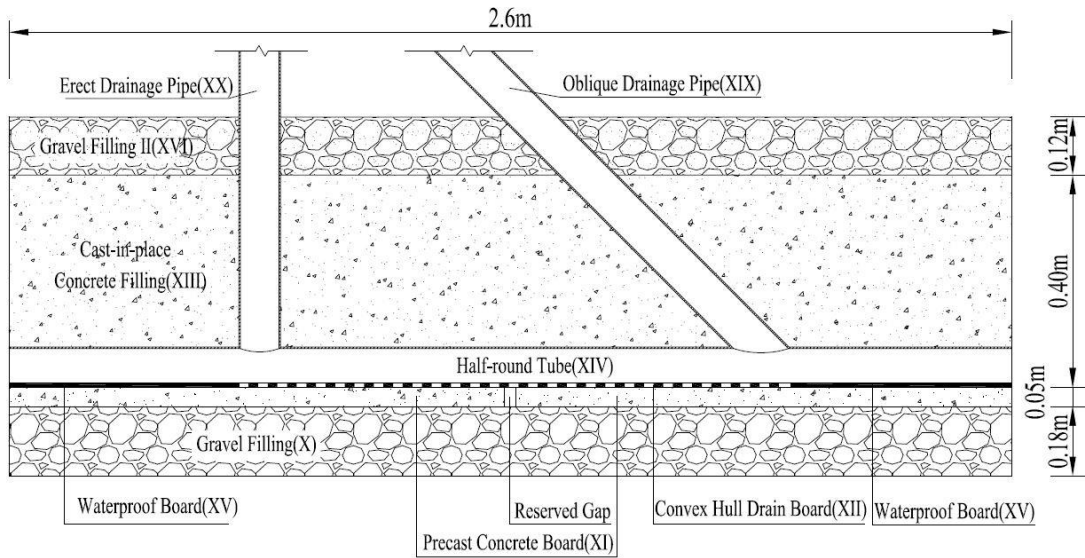
Fig. 4. Sketch of the water supply system



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Fig. 5. Sketch of the testing chamber



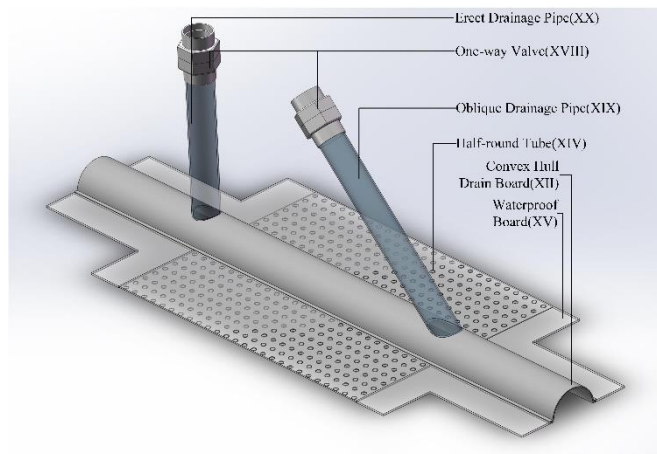
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Fig. 6. Sketch of the simulating tunnel invert structure and drainage system in the testing

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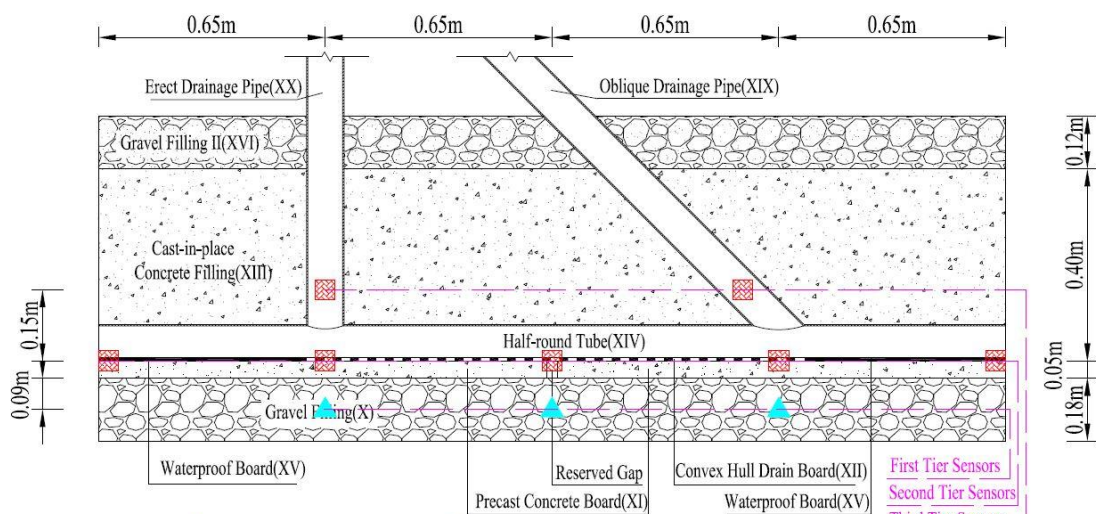
chamber



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Fig. 7. Sketch of the waterproof and drainage measures

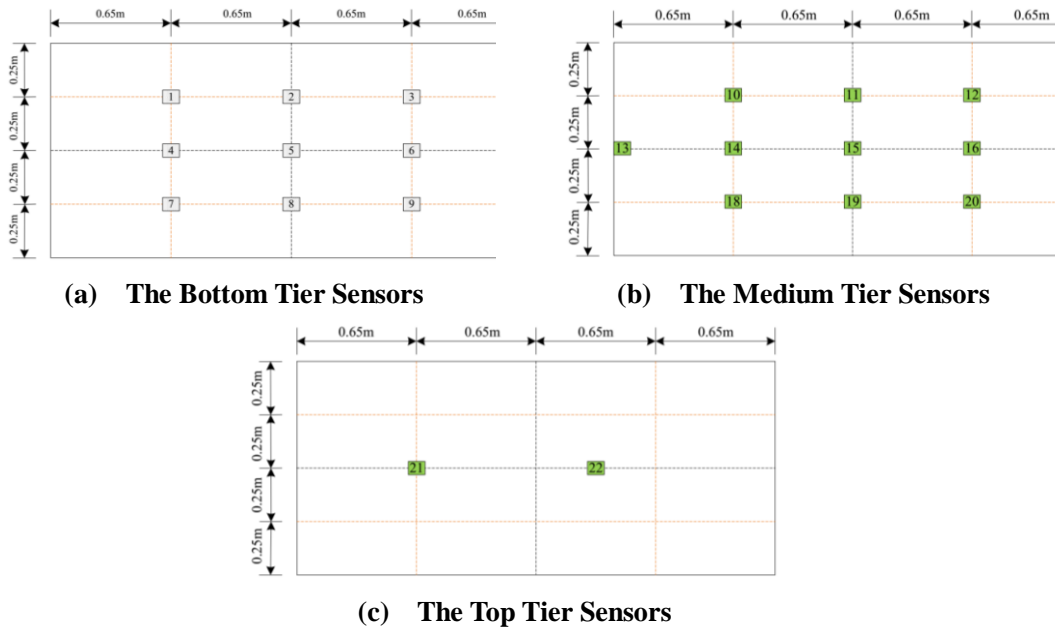


Appendix: 1, ▲ -HCYB-25 water pressure sensor, ■ -HC25 water pressure sensor;
 2, The sensor icon is not in scale.

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



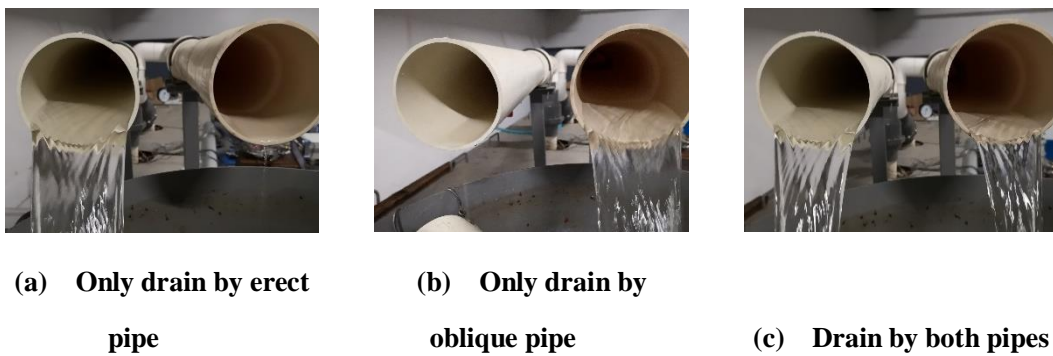
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Fig. 9. The horizontal arrangement of each tier of the pore pressure sensor



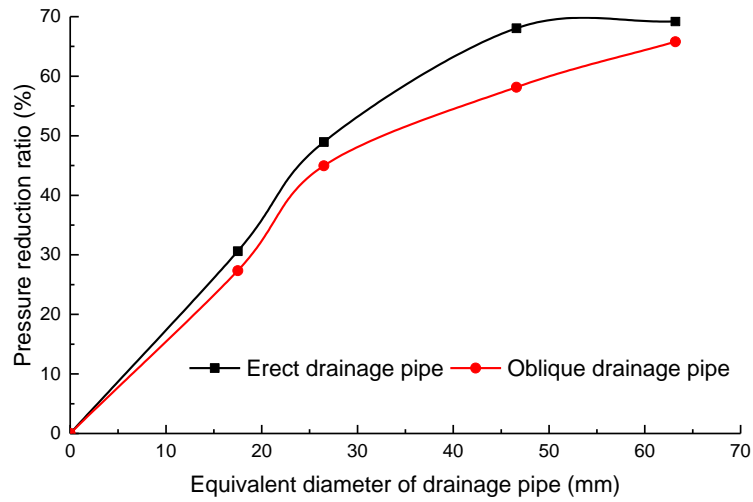
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Fig. 10. Photo of the whole prepared experimental equipment



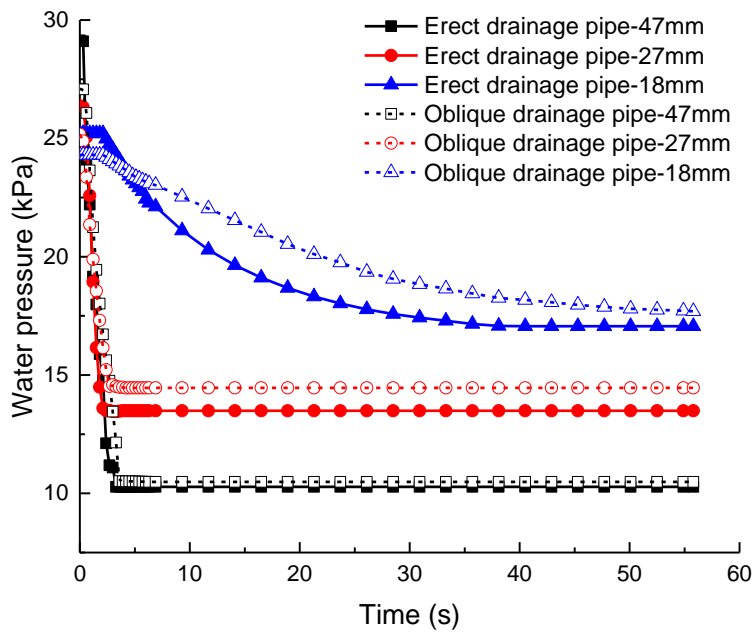
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Fig. 11. Water discharge of the drainage pipe in different test conditions



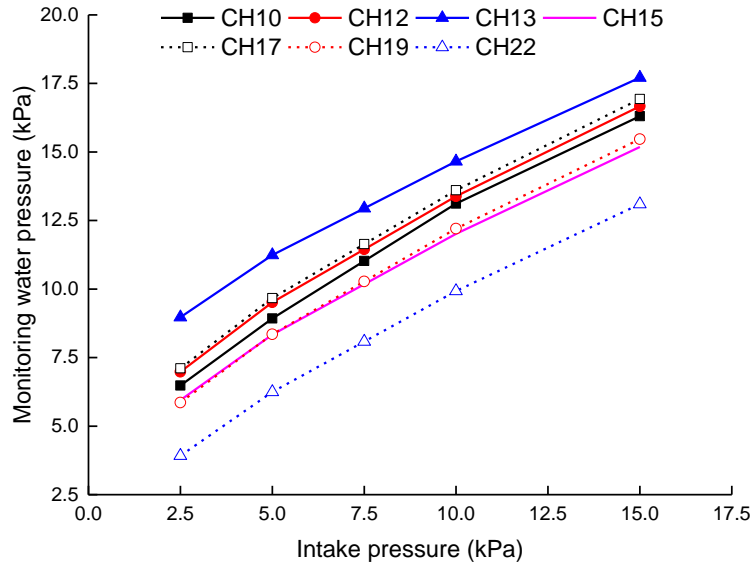
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Fig.12. The curve of the water pressure reduction and the equivalent diameter of the drainage pipe



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

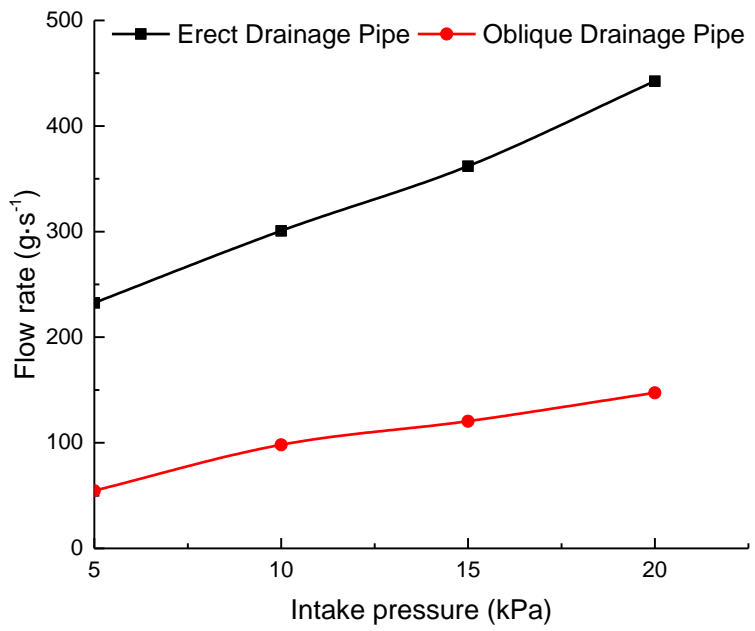


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Fig.14. Relation curve of monitoring water pressure and inlet water pressure

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

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Appendix B.

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

Item	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	Average	Standard deviation	Coefficient of variation
	/kPa	/kPa	/kPa	/kPa	/kPa	/kPa	/kPa	/kPa	/kPa	/kPa	/kPa	/%
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

513 * : “/” means no available data because of sensor damage.

514

515

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

Item	CH10	CH11	CH12	CH13	CH14	CH15	CH16	CH17	CH18	CH19	CH20	Average	Standard deviation	Coefficient of variation
	/kPa	/kPa	/kPa	/kPa	/kPa	/kPa	/kPa	/kPa	/kPa	/kPa	/kPa	/kPa	/kPa	/%
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

516 * : “/” means no available data because of sensor damage.

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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

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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	

18	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	
	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%