Experimental Investigation on the Sand Deposit Foundation of an Immersed Tube Tunnel by Using a Sand Flow Model

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Abstract. Sand flow is a mainstream construction method to treat the foundation of immersed tunnel. The characteristics of the sand deposit foundation, including its size and compactness, as well as fullness degree, are key indicators for estimating the effect of foundation treatment on the immersed tube tunnel. In this study, three series of model tests were conducted. The characteristics of fullness degree and compactness were elaborated. In addition, tunnel uplift and its prevention, the effect of surface roughness of tunnel on the compactness and size of sand deposit, and the effects of different injection sequences on the fullness degree were investigated. Valuable practical suggestions were drawn from the test results. First, the incidence of tunnel uplift can be avoided by monitoring the hydraulic pressure under the bottom of tunnel with water pressure gauges. Second, the surface roughness of tunnel should be decreased to allow for a sand deposit with a large radius and consequently enhance construction efficiency. Third, the difference in injection sequences barely influences the fullness degree of sand deposit; therefore, injection sequences can be flexibly designed to provide convenience for construction.

Keywords. Sand flow, full-scale model, sand deposit foundation, compactness, fullness degree.

1. Introduction

Tunnel foundation treatment is a key step in the process of tunnel construction for it is directly related to the quality of tunnel and the subsequent operation safety [1-2]. Currently, the commonly used methods for foundation treatment of immersed tube tunnel are scraping, pile foundation, grouting, sand injection, and sand flow [3-4]. Among these methods, sand flow has become one of the mainstream construction methods because of its superiority [1, 5].

The sand flow method was first used in the Vlake Tunnel of Holland; the corresponding mechanisms and related construction parameters of this method were explored by performing model tests [6]. Chen et al. (2002) [7] shared their design experience and emphasized that the characteristics of the sand deposit foundation, including its size and compactness, as well as the fullness degree of the bottom of the tunnel element, are directly related to the foundation treatment efficiency and effectiveness. However, the design of a single sand deposit foundation and the determination of its size mainly rely on engineering experiences because an effective method has not yet been developed. The uplift of tunnel elements, which renders subsequent construction difficult, occurs frequently in
engineering, such as in the Pearl River Tunnel of Guangzhou and the Western Harbour Tunnel of Hongkong [8]. Furthermore, the sand deposit foundation under tunnel load undergoes a certain post-settlement, which often leads to excessive and differential settlements. For example, in the External Ring Tunnel of Shanghai, the maximum and differential settlements of the tunnel elements reached 310 and 245 mm, respectively, from 2001 to 2003 [8]. Thus, a complete understanding of the characteristics of the sand deposit foundation is imperative to avoid these problems.

The characteristics of the sand deposit foundation connected with the whole sand flow processes are affected by sand flow boundaries. The commonly used waterproofing systems for immersed tube tunnels are structural and outsourcing waterproofing systems [9-10]; these systems provide tunnel elements with different degrees of surface roughness. The bottom of tunnel element is a main boundary of sand–water flow [11-12]; thus, its surface roughness significantly affects the transport resistance of sand–water flow and may consequently affect the size and compactness of sand deposit foundation. As the direction of sand-water flow changes when the expanded radius of sand deposit approaches that of a well-formed sand deposit foundation or trench baffle, a particular injection sequence can change the shape of single sand deposit foundation and consequently may influence the fullness degree of the bottom of tunnel element. However, thus far, tunnel designers and builders have not fully determined the effects of the abovementioned factors.

Recently, several model tests on sand flow have been conducted in China. Li (2001) [13] established an experimental model for the Pearl River Tunnel and recorded the final fullness degree of sand deposit and pressure near the injection opening. Wang et al. (2009) [14] performed model tests of a 1:5 scale for the Shengwudao–Daxuecheng Tunnel of Guangzhou, obtained the average void ratio of sand deposit and verified the sand–water mass ratio of the original design. These tests, which adopt scale models, are conducted to inspect the design parameters and provide technical guidance for construction mainly. Owing to the complexity of a model system for sand flow, achieving a high similarity between the prototype and the model and accurately capturing parameters, such as particle size, sand–water ratio, and various boundary conditions, are difficult. Thus, using a scale model to guide the design and construction exhibits a certain limitation; as a consequence, the authenticity of the test results is decreased.

In this study, three series of full-scale model tests were conducted to simulate the whole sand flow processes. The characteristics of fullness degree and compactness were further elaborated. In addition, the cause and prevention of tunnel element uplift, the effect of surface roughness of tunnel element on the compactness and size of sand deposit, and the effects of different injection sequences on the fullness degree of the bottom surface of tunnel element were investigated. The results of this study can provide a detailed reference data set for the design and construction of sand deposit foundation and a basis for the future research on the settlement and anti-seismic property of foundation.

2. Test Model and Experimental Materials

2.1. Zhoutouzui Immersed Tunnel

In this study, the Zhoutouzui Tunnel of Guangzhou in China is taken as the background. The tunnel is located in the Pearl River main channel at the junction of three rivers, and its total length is 340 m. Numbers E1 and E4 are variable cross-section tunnel elements. The standard spacing of the designed injection points in the floor slab is 10.0 m, and the effective diameter of the designed sand deposit foundation is 15.0 m. A sectional view of tunnel element E4 and the layout of the designed injection points are shown in figure 1.
2.2. Test Model

The model should meet certain design principles to simulate the formation and expansion of a single sand deposit foundation accurately and obtain highly reliable test results [12]; these principles are the conditions of the top boundary of fluid, the lateral boundary conditions within the scope of the tested sand deposit, the underwater environment conditions of rivers, the consistency of test equipment with construction equipment, the non-effect of the measuring systems on the experimental results, the close relationship of the grades of the test sand and the construction sand in the same category, and similar sand–water mass ratio used in tests in engineering practice.

A full-scale model within a sand deposit foundation range was constructed to simulate the injection into a single opening; this model is represented by the area enclosed by the thick dashed line in figure 1(a) in accordance with the given model design principles. The test system includes a model board, an experimental tank, injection equipment system, sand deposit detectors, and hydraulic pressure gauges, as shown in figure 2. The model board is connected to the shore set in the experimental tank. The height of the shore is 1.0 m, and the model board size is 8.2 m (width)/8.7 m (width) × 15.2 m (length). An

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Figure 1. Tunnel element of an immersed tube tunnel. (a) Schematic layout and (b) Sectional view of the tunnel element (unit: cm).

Figure 2. Test model. (a) Schematic of the test model and (b) Physical map (unit: cm).
Injection opening is set at the center of the model board and connected to the test equipment by a steel-wired hose. The sand–water mixture, which is driven by the injection equipment system [12], is injected underneath the model board through the injection opening to simulate the whole sand flow processes. The real-time measurement data of the model test are acquired by using the sand deposit detector, hydraulic pressure gauge, and displacement benchmarks; these components are prearranged on the model board. The detailed configurations are described in section 3.

2.3. Test Materials

Vibrations from earthquakes and trains [15-16] are likely to cause the liquefaction of the sand in a sand deposit foundation. Thus, the sand in an artificial sand deposit foundation should be well graded, without chemical admixture and pollutants from the environment [13-14]. The test sand is screened to comply with the design principles for a full-scale model test. The content of the sand with a particle size greater than 0.5 mm is 68.4% (> 50.0%) and that with a particle size greater than 2 mm is 20.6% (< 25.0%). Therefore, the particle size distribution of the sand meets the requirements for test materials, as shown in figure 3.

![Figure 3. Particle size distribution of the test sand. (unit: cm).](image)

3. Measurement Methods

The measurements in this study comprise synchronous and follow-up measurements. The synchronous measurements include the hydraulic pressure at the bottom of model board, the expanded height of sand deposit, and the uplift amount of model board. The follow-up measurements include the final radius in all directions of sand deposit and its compactness.

3.1. Hydraulic Pressure Measurement

3.1.1. Hydraulic pressure Measurement. Hydrodynamic gauges (0–0.1 MPa) are installed along the E, S, W, and N axes on the bottom surface of the model board, as shown in figure 2 and table 1. The time-history curves of hydraulic pressure at different measurement points are obtained by measurement at time intervals of 5 min.

| Measurement point | Axis | E | S | W | N |
|-------------------|------|---|---|---|---|
| 1                 |      | 0.5 | — | 0.5 | — |
| 2                 |      | 2.0 | 2.0 | 2.0 | 2.0 |
| 3                 |      | 3.5 | 3.5 | 3.5 | 3.5 |
| 4                 |      | 6.5 | — | 6.5 | — |

3.1.2. Height Measurement of the Sand Deposit. The self-designed sand deposit detector is installed along the W, M, S, F, and T axes, as shown in figure 2. The measurement points along the axes are
shown in table 2. The time-history curves of the height of the sand deposit are obtained by measurement at time intervals of 3 min. A detailed introduction on the sand deposit detector was provided in the paper of Li et al. (2013) [11].

| Measurement point | W   | M   | S   | F   | T   |
|-------------------|-----|-----|-----|-----|-----|
| 1                 | 0.9 | 2.0 | 1.0 | 1.0 | 2.0 |
| 2                 | 2.0 | 3.1 | 2.0 | 2.0 | 3.0 |
| 3                 | 3.0 | 4.1 | 3.0 | 3.0 | 4.0 |
| 4                 | 3.8 | 5.1 | 3.8 | 4.0 | 5.0 |
| 5                 | 4.8 | 6.1 | —   | 5.0 | —   |
| 6                 | 5.7 | 7.1 | —   | 6.0 | —   |
| 7                 | 6.5 | 8.0 | —   | 7.1 | —   |
| 8                 | 7.5 | —   | —   | 8.0 | —   |

3.1.3. Observations on Model Board Uplift. A vertical displacement benchmark is installed around the model board, as shown in figure 2. The time-history curves of the model board uplift are acquired by taking the readings every 10 min.

3.2. Follow-up Measurements

3.2.1. Final Radius of the Sand Deposit. After completing the injection and draining the water from the experimental tank, the radius of the sand deposit in all directions is obtained using measurement scales, and the fullness degree of the bottom surface of the model board is obtained by calculation.

3.2.2. Compactness of the Sand Deposit. The dry density of the sand deposit is obtained by adopting conventional compactness detection methods, including light dynamic penetration test and sand replacement method. The measurement points lie along the W axis, as shown in figure 2. The sand deposit is divided into three layers: bottom (0–30 cm), middle (30–60 cm), and top (60–90 cm). The compactness distribution over the radial cross section of the sand deposit is obtained by sampling measurement every 1 m.

4. Test Parameters

Sand–water mass ratio and the height of foundation trench gap are the primary factors that directly influence foundation treatment. According to previous research results, the reasonable sand–water mass ratio ranges from 1:9 to 1:7, and the height of foundation trench gap is approximately 1.0 m [13-14]. Therefore, the test parameters are as follows: sand-water mass ratio of 1:8 or 1:9; height of foundation trench gap of 1.0 m. In addition to the influences of the two factors, the effects of tunnel element uplift, tunnel element surface roughness, and different injection sequences on sand deposit characteristics should be considered.

For the exploration of the cause and prevention of tunnel element uplift, the shore is not fixed on the bottom of the experimental tank to ensure that the model board can be freely uplifted. Accordingly, the entire process of tunnel element uplift can be simulated.

Two model tests are conducted to explore the effects of the surface roughness of tunnel element on the compactness and size of sand deposit. The first test is performed on a steel–concrete material with a rough and uneven surface (figure 4(a)). The friction coefficient of the wet surface of this steel–concrete material is 0.24. The object of the second test is initially flattened by grinding and then smoothed by brushing with a waterproof material [9], as shown in figure 4(b). The friction factor of the wet surface of the waterproofed steel–concrete material is 0.16.
Two additional experiments are conducted to explore the effects of different injection sequences on fullness degree. As shown in figure 5(a), if sand deposit 2# is constructed after sand deposit 1#, then sand deposit 1# becomes a unilateral obstacle boundary of sand deposit 2#. Subsequently, sand deposits 1# and 2# become bilateral obstacle boundaries of sand deposit 5#. The dam board is set on side S of the Model board to simulate the effects of a unilateral obstacle boundary, as shown in figure 5(b). The dam boards are set on sides E and S of the model board to simulate the effects of bilateral obstacle boundaries, as shown in figure 5(c).

Figure 4. Physical mapping of the roughness of the bottom surface of the model board. (a) Concrete with rough surface and (b) Concrete with smooth waterproofed surface.

Figure 5. Schematic of the obstacle boundary of the tunnel element model. (a) Schematic of the construction sequence of sand deposits, (b) Schematic of the unilateral obstacle boundary and (c) Schematic of the bilateral obstacle boundary.
### Table 3. Test parameters.

| Test No. | Sand–water mass ratio | Foundation trench gap (m) | Obstacle boundary case | Roughness | Shore |
|----------|-----------------------|---------------------------|------------------------|-----------|-------|
| SFMT-1   | 1:9                   | 1.0                       | NO                     | Coarse    | Not fixed |
| SFMT-2   | 1:8                   | 1.0                       | NO                     | Coarse    | Fixed   |
| SFMT-3   | 1:8                   | 1.0                       | NO                     | Smooth    | Fixed   |
| SFMT-4   | 1:8                   | 1.0                       | Side S                 | Coarse    | Fixed   |
| SFMT-5   | 1:8                   | 1.0                       | Sides S and E          | Coarse    | Fixed   |

Five sets of model test parameters are formed on the basis of the given test parameters and the analysis of the test conditions. The test parameters are listed in table 3. The model tests on the sand flow method are denoted by SFMT-X, where X is the number of model test. All tests are divided into three groups and then compared and analyzed as follows:

1. SFMT-1 simulates tunnel element uplift.
2. SFMT-2 and SFMT-3 simulate the surface roughness of tunnel element.
3. SFMT-2, SFMT-4, and SFMT-5 simulate the sequences of injection.

### 5. Test Results and Analysis

#### 5.1. Characteristics of Fullness Degree

The distance from the center (injection point) of sand deposit to the edge point is defined as the expanded radius. The isochrones of the expanded radius of the sand deposit are illustrated in figure 6. The shape of the sand deposit is concentric circles when its radius is less than 3.8 m, that is, the sand deposit has expanded in all directions nearly uniformly at the initial stages of sand flow. When the radius of the sand deposit is more than 3.8 m, the sand deposit is noncircular; this phenomenon indicates the uneven expansion of the sand deposit in the different directions. This non-uniformity becomes remarkable with the increase in the sand deposit radius. Finally, the shape of the sand deposit approximates a rectangle, and the bottom of the model board is nearly filled by the sand deposit.

![Figure 6. Isochrones of the expanded radius of the sand deposit in SFMT-2.](image)

On the basis of the time-history curves characteristics of sand deposit height [11-12], the sand flow process can be divided into three stages: formation, gap flow, and chute flow. The formation spans from the beginning of the test to the end of the increase in the height of sand deposit. Typical sand deposit profiles on W–E axis are obtained by connecting the data point of sand deposit height at each time instants, as shown in figure 7. The gap flow is that the sand–water mixture injected into the splash pour out through the gap existing between the top of the sand deposit and the bottom of the model board (figures 8 and 9(a)). The sand-water flow is weakly affected by the model boundaries. The accumulation of sand particles around the periphery of the sand deposit is relatively uniform; thus, the
sand deposit expands uniformly in all directions. The chute flow shows that the clearance between the top of the sand deposit and the bottom of the model board becomes very small and forms chutes, as shown in figure 9(b). The sand–water flows are easily affected by many boundaries, including model board bottom, edges, and the top of sand deposit. Thus, the chutes are easily blocked, breached, and detoured. Subsequently, the distribution of the chute exits around the periphery of the sand deposit is inhomogeneous, and the expansion velocities of the sand deposit in all directions differ. Random variations in the positions of the chute exits initially occur along the length of the model when the chutes are short and then gradually shift to the direction of the width of the model. Furthermore, the expansion of the sand deposit is also initially relatively fast along the length of the model, and it then gradually shifts to the width of the model. Finally, the shape of the sand deposit is nearly a rectangle; consequently, the bottom of the model board is nearly filled by the sand deposit.

After the sand flow test, the above-mentioned results are confirmed by follow-up measurements. The fullness degrees of the bottom of the tunnel element in all directions are obtained using measurement

Scales, as shown in table 4. The minimum of all the obtained values is 83% in WN. In ES and WS, the two other directions that are not completely filled, the fullness degrees reach 98% and 95%, respectively. According to the results, the overall fullness degree of the model board bottom is 95.9%. According to the layout of the sand deposit in figure 1, the fullness degree at the bottom of the model board exceeds 85%, thereby ensuring a 100% fullness degree at the tunnel element. Therefore, the layout of the sand deposit in figure 1 satisfies the requirements of fullness degree. In fact, the number of injections can be appropriately decreased by increasing the standard spacing of injection points in
floor slab to improve the construction efficiency, or the designed radius of single sand deposit can be appropriately reduced to decrease the buoyancy force of tunnel.

Table 4. Final fullness degrees in eight directions in SFMT-2 (%).

| Test No. | N | EN | E | ES | S | WS | W | WN |
|----------|---|----|---|----|---|----|---|----|
| SFMT-2   | 100 | 100 | 100 | 98 | 100 | 95 | 100 | 83 |

5.2. Characteristics of Compactness

The compactness contour of the sand deposit along the W axis is presented in figure 10. Overall, the compactness characteristics at different layers are as follows: the bottom layer is loose, the middle layer is slightly dense, and the top layer presents moderate and low density. The compactness of the top layer is significantly higher than those of the middle and bottom layers. The compactness characteristics at different radii are as follows: loose inside and outside and dense in the middle. In relation to sand flow processes, two major factors affect the distribution of compactness, namely, particle size distribution and pressure at the top of sand deposit.

The carrying capacities of water flows and the settling velocities of sand particles differ [17-18]; thus, the deposition of sand particles under water is a process of sorting, that is, the coarse particles are deposited before fine particles. At the formation stage, the content of coarse particles close to the injection points is higher than that far from the injection points. At the gap and chute flows, the content of the coarse particles at the top layer is more than that at the bottom layer. The reason is attributed to that coarse particles are deposited before fine particles in the upper slope of the periphery of the sand deposit. This analysis shows that the compactness of sand deposit is roughly consistent with its particle size distribution. The sand deposit presents a high compactness in the area where the content of coarse particles is high. The particle size distributions along the crater and W axis in the sand deposit are compared with that of the test sand, as shown in figure 11. The content of coarse particles in the crater is significantly higher than that of the test sand, and the content of the coarse particles along the W axis is slightly lesser than that of the test sand. These results fully verify that the deposition of sand particles is a process of sorting.

Figure 10. Compactness contour of the sand deposit along the W axis. This contour is obtained by conventional light dynamic penetration test. The evaluation indexes of this test are as follows: number of hammering = < 10, loose sand; number of hammering = 10–20, slightly dense sand; number of hammering = 21–30, close-grained sand between the middle and low levels; number of hammering = 31–35, moderately dense sand.

Figure 11. Particle size grading curve of the sand particles in the sand deposit.
Figure 10 also shows the existence of high-density areas, that is, transition zone of the gap to the chute. In this zone, the radius of the top layer of the sand deposit is from 3.0 m to 4.5 m. In relation to the sand flow processes, the top of the sand deposit at the gap flow stage does not contact the bottom of the model board. Moreover, the weight of the model board is mainly loaded by the shore, buoyancy, and hydraulic pressure. At the chute flow stage, few sand particles accumulate on top of the sand deposit; as a result, the transport resistance of the sand-water flow increases with the increase in the radius of the sand deposit, and the thickness of the gap between the top of the sand deposit and the bottom of the model board decreases with the increase in the radius of the sand deposit. Consequently, a small portion of the region on top of the sand deposit starts to contact the bottom of the model board, and they form a mutual extrusion under the weight of the model board. The stress caused by this mutual extrusion increases with the increase in the sand deposit radius and the accumulation of the sand particles, thereby forming an area of high stress at the transition zone of the gap to the chute to support the weight of the model board. As a result, a high compactness area is achieved.

In this section, the distribution characteristics of sand deposit compactness are shown for the first time, and its formation mechanisms are discussed in detail. The results presented in this section can provide a basis for the future research on the settlement and anti-seismic property of a foundation.

5.3. Tunnel Element Uplift and Its Prevention

The anti-floating safety factor (1.04–1.05) of an immersed tube tunnel is small during construction; thus, the tunnel element is easily uplifted because of the increase in the hydraulic pressure of the tunnel element bottom surface, which is detrimental to maintaining the stability of the tunnel element. A model test is conducted in SMFT-1 to simulate the entire process of tunnel element uplift and thus explore the cause and prevention of tunnel element uplift. The results of the uplift of the model board are shown in figure 12, and the typical time-history curves of the sand deposit height at the measurement points along the F axis are presented in figure 13. The uplift of the model board starts at 430 min given that the expanded radius of the sand deposit reaches 5.4 m.

Figure 12. Time-history curves of the uplift of the model board.

Figure 13. Typical time-history curves of the sand deposit height.

Figure 13 shows that the increase in the height of the sand deposit decelerates from F-6 to F-8, and the trench gap cannot always be filled. This finding indicates that a large amount of the injected sand particles can fail to transfer to the periphery of the sand deposit when the expanded radius of the sand deposit is greater than 5.4 m and can accumulate at the top of the sand deposit. As a result, the weight carrier of the model board is gradually transferred to the sand deposit and hydraulic pressure from the shore. Finally, the model board is constantly supported by the hydraulic pressure and the sand deposit. The time-history curve of hydraulic pressure in the plash by SFMT-1 is presented in figure 14. The hydraulic pressure reaches its maximum value at the initiation of model board uplift; subsequently, the hydraulic pressure is slightly reduced. This result indicates that the effective radius of the sand deposit no longer increases after the model board uplift. That is, the sand particles that accumulated at the top of the sand deposit only induces the rearrangement of chute flows, but the total length of the chute flows remains constant. This result is ascribed to the linear relationship between the hydraulic pressure in the plash and the expanded radius of sand deposit [12]. Therefore, tunnel element uplift is caused by
the tunnel element reaching the limit equilibrium state and the sand particles continuously accumulating at the top of sand deposit.

Figure 14 also shows that the magnitudes of hydraulic pressure remain unchanged from 0 min to 30 min, indicating that the sand flow is at the formation stage. From 30 min to 290 min, the hydraulic pressure in the crater presents a continuous rise, indicating that the sand flow is at the gap flow stage. From 290 min to 430 min, the curve of the hydraulic pressure in the crater shows apparent volatility, indicating that the sand flow enters the chute flow stage. After 430 min, hydraulic pressure is slightly reduced and undulant.

![Figure 14. Time-history curve of the hydraulic pressure in the crater by SFMT-1.](image)

![Figure 15. Distribution curves of hydraulic pressure.](image)

The distribution curves of the hydraulic pressure at different times in the radial direction are presented in figure 15. The hydraulic pressure at any time presents a nonlinear attenuation from the center of the sand deposit to its outer edge. The hydrostatic pressure is approximately 0.0075 MPa, which indicates that the area between the curves of hydraulic pressure and the hydrostatic pressure line is a sphere of influence of the hydraulic pressure at each time. That is, the hydraulic pressure acting on the bottom surface of the model board is conically distributed.

The analysis in this section shows that the model board at the limit equilibrium state is constantly supported by the hydraulic pressure and the sand deposit of a constant value. On the basis of the linear relationship between the hydraulic pressure in the crater and sand deposit radius [12], the hydraulic pressure distribution in figure 15, and the limit equilibrium state of the model board, the hydraulic pressure and the supporting force of the sand deposit can be determined by the weight and volume of the tunnel element if all the other conditions remain unchanged. Thus, water pressure gauges can be installed at the bottom of the tunnel to monitor hydraulic pressure changes during construction. The hydraulic pressure changes can be used to judge the state of sand flow and determine whether the sand deposit has expanded to the designed radius. Then, tunnel element uplift can be prevented by ensuring that the hydraulic pressure in the crater does not exceed its peak value, as monitored by water pressure gauges.

5.4. Effect of Surface Roughness

Immersed tube tunnels with structural and outsourcing waterproofing systems [9-10] present different surface roughness degrees. The surface roughness of tunnel element significantly affects the transport resistance of sand–water flow and consequently affects the expanded radius of single sand deposit foundation and the compactness characteristics of foundation. In this study, a rough surface model (SFMT-2) and a smooth surface model (SFMT-3) are tested to investigate the effects of surface roughness on the compactness and size of a single sand deposit foundation. The measured results of the sand deposit compactness are presented in figure 16. The test results of the hydraulic pressure are shown in table 5.

Figure 16 shows that, in SFMT-2, the points of compactness higher than 0.33 account for 89.5% of all the testing points, whereas the points only account for 66.7% in SFMT-3. The sand deposit compactness in SMFT-2 is slightly higher than that in SMFT-3. This phenomenon is induced by the sand–water mixture passing through the gap flow and chute flow to the periphery of the sand deposit;
the sand–water flow is comparable to a pressurized pipe flow. The surface of the model board in SFMT-2 is concave–convex; thus, it functions as a radial vortex generator and impedes the sand–water flow. On a macro level, this phenomenon resembles the frictional effect called “circular confinement” boundary, which causes the sand particles to pile up at the connecting area between the gap flow and the chute flow. As a result, this area bears the weight of the model board. In conclusion, a comparatively small connecting area between the gap flow and the chute flow bears the weight of the model board. This area is a high-stress area in the sand deposit, and it is relatively concentrated and that it forms a sand deposit with relatively high compactness. In SMFT-3, the tested model board is smooth and thus presents less friction on the top boundary of the sand–water flow; such condition does not slow down the accumulation of sand in the connecting area between the gap flow and the chute flow but transfers the sand to the periphery of the sand deposit. Therefore, the high-stress area at the top of the sand deposit is relatively uniform, and its compactness is relatively low.

![Figure 16. Sand deposit compactness frequency chart including the (a) top and (b) middle layers of the sand deposit.](image)

Table 5 shows that the hydraulic pressures at different radii of the sand deposit in SMFT-3 are 0.002 MPa lower than those in SMFT-2. This result is attributed to the sand–water mixture exiting through the inside section between the bottom of the model board and the top of the sand deposit. This section narrows with the expansion of the sand deposit. As the inside section is narrow, the surface roughness of the model board affects the transport resistance of the sand–water flow. If the surface of the model board is smooth, that is, the sand–water flow has a smooth top boundary, then the radial swirl of the sand–water mixture that occurs at the bottom becomes weak and minor, thereby reducing the turbulent flow and backflow collision of the sand–water mixture. As a result, the outflow of the sand–water mixture is relatively unhindered. Thus, the hydraulic pressure at the bottom of the model board in SMFT-3 is 0.002 MPa less than that in SMFT-2 at the same expanded radius of the sand deposit. Therefore, a smooth surface of the tunnel allows for a sand deposit with a large radius or the simultaneous operation of more multiple pieces of injection equipment.

| Table 5. Hydraulic pressures at the different radii of the sand deposit (MPa). |
|-------------------|---|---|---|
| Radius (m)        | 2.0 | 3.5 | 6.5 |
| SFMT-2            | 0.022 | 0.020 | 0.014 |
| SFMT-3            | 0.020 | 0.018 | 0.012 |
To date, the effects of surface roughness of tunnel element, which depends on the waterproofing system used, on the design and construction parameters and foundation treatment effect have not been thoroughly studied. The measurement results show that, in practical engineering, bottom surface roughness should be reduced to allow for a sand deposit with a large radius or the simultaneous operation of multiple pieces of injection equipment to enhance the construction efficiency. Adopting outsourcing waterproof not only improves the waterproof performance of tunnel but also facilitates the construction of sand flow. The results in this section provide a useful reference for the selection between structural and outsourcing waterproofing systems and a basis for design and construction.

5.5. Effects of Obstacle Boundary

The direction of sand–water flow changes when the expanded radius of sand deposit approaches that of a well-formed sand deposit foundation or trench baffle; thus, the shape of single sand deposit foundation is affected by different injection sequences, which then affect the fullness degree of the bottom of tunnel element. In this study, a unilateral obstacle boundary (SFMT-4) and a bilateral obstacle boundary (SFMT-5) are tested to investigate the effects of different injection sequences on the fullness degree at the bottom of the model board. The fullness degree results in eight directions are presented in figure 17. The fullness degrees in the eight directions are nearly full in each test, with 80 % being the minimum. Among all the three tests, SMFT-2 presents the lowest overall fullness degree (95.9%), with three directions incompletely filled. By contrast, SFMT-4 presents the highest overall fullness degree of 99.7%, followed by SFMT-5, which exhibits an overall fullness degree of 99.3%. These results indicate that obstacle boundaries exert no detrimental effect on fullness degree but rather improve it.

![Figure 17. Fullness degrees for the sand deposit radii in all directions (%). Note: In N-410, N means the direction of the model board, and 410 means that the distance from the external rim of the model board to injection point is 410 cm. The directions are denoted as follows: N—north, E—east, S—south, W—west, EN—northeast, ES—southeast, WS—southwest, and WN—northwest.](image)

In relation to the sand deposit expansion, the sand particles deposit and accumulate uniformly in all directions of the periphery of the sand deposit when the expanded radius of the sand deposit is relatively small. Even if the periphery of the sand deposit is close to the obstacle boundary (for example, R≥3.8 m), the sand–water flow at the top of the sand deposit near the obstacle boundary is affected by the obstacle boundary, but it does not stop; only the direction of the sand–water flow changes. The sand deposit size can expand continually on this side, as shown in figure 18(a). When the top surface of the sand deposit reaches the obstacle boundary, the sand–water flows from multiple chute flows converge to form a “channel flow,” as shown in figure 18(b). The sand–water flows are then transported along the “channel flow” and circled by the obstacle boundary. Subsequently, the sand–water flows continue to be transported. Finally, the exit of the obstacle boundary is filled by sand particles. This “chute flow–channel flow” trend keeps the sand–water flows smooth near the obstacle boundary, thereby allowing the sand particles to fill the obstacle boundary from inside out completely.
Therefore, the fullness degree on the bottom surface of the model board is unaffected by the obstacle boundary.

To date, designers and constructors do not have a definitive knowledge of the effects of obstacle boundaries, which result from different injection sequences, on the expansion of a sand deposit and its final state. They emphasize that the sequences of injection should avoid artificial obstacle boundaries. However, the results in this section show that the effects of artificial obstacle boundaries on the final state of the sand deposit are nearly negligible. The sequence of injection can be flexibly changed during design and construction without affecting the fullness degree of tunnel element. As a result, the utilization efficiency of the construction equipment can be improved and using multiple sand flow systems during construction becomes convenient.

![Figure 18. Sand deposit characteristics in the obstacle boundary. (a) Direction of chute flow and (b) Channel flow.](image)

6. Conclusions

Three series of full-scale model tests were conducted to simulate the whole sand flow processes. The characteristics of fullness degree and compactness were elaborated. Discussion on these topics allows for a better understanding of the characteristics of sand deposit foundation and provides a basic background for the future research on the differential settlement and anti-seismic property of a foundation. Furthermore, the effects of the surface roughness of tunnel element on the compactness and size of sand deposit and those of different injection sequences on the fullness degree of tunnel element bottom were investigated. The following are the main conclusions drawn from the analysis of the experimental data.

Water pressure gauges can be installed at the bottom of tunnel to monitor the change in hydraulic pressure during construction. These monitored pressure changes can be used to assess the state of sand flow and determine whether the sand deposit has expanded to the designed radius.

The compactness is from dense to loose from the top layer to the bottom layer of the sand deposit. In a radial direction, the sand deposit compactness shows a nearly normal distribution. These distribution characteristics of compactness are determined by the particle size distribution and the tunnel element pressure on the top surface of sand deposit. These results can also provide a basis for the future research on the settlement and anti-seismic property of foundation.

3) During the uplift of the tunnel element, the hydraulic pressure of the model board bottom reaches its maximum value, and the effective radius of the sand deposit no longer increases. Furthermore, the weight carrier of the model board is constantly supported by the hydraulic pressure and the sand deposit. Ensuring that the hydraulic pressure in the crater does not exceed its peak value by monitoring with water pressure gauges can prevent tunnel element uplift.

4) The surface roughness of tunnel element slightly affects the compactness of sand deposit and influences the design radius of sand deposit. In practical engineering, bottom surface roughness should be decreased to allow for a sand deposit with a large radius or the simultaneous operation of multiple pieces of injection equipment and consequently enhance construction efficiency. These results provide a useful reference for the selection between structural and outsourcing waterproofing systems and offer a basis for design and construction.
(5) The obstacle boundaries caused by different injection sequences barely affect the fullness degree of the bottom surface of tunnel element. Thus, injection sequence can be flexibly designed to increase the utilization efficiency of the construction equipment and using multiple sand flow systems during construction becomes convenient.

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