Dynamic Behavior of Double Steel Sheet Pile Cofferdam under Different Wave Actions

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Abstract. Double-row steel sheet piles, which have good dynamic stability, strong deformability, high seepage resistance, and strong engineering adaptability, have been widely used as coastal defense structures. The paper investigates the dynamic behavior of the double-row steel sheet pile cofferdam under the actions of breaking-wave and standing-wave through large-scale flume model test. High-frequency optical fiber technology was applied to obtain the stress data on the steel sheet pile. It was found that the standing wave produced a cycle action of crest pressure and trough suction to the DSSP cofferdam, forming a scour pit at the toe of the seaside steel sheet pile. The breaking wave did not produce obvious reflection and suction against the DSSP but incurred huge crushing energy and large deformation on the DSSP cofferdam. The bending moment on the steel sheet pile under near the breaking wave is about 2 to 3 times that under the standing wave. The deformation of the steel sheet pile may cause leakage of the joint and soil erosion of the in-filled sands, even resulting in failure of the DSSP cofferdam.

Keywords. Wave breaking, standing wave, double steel sheet pile, cofferdam, water flume test
1. Introduction

The double-row steel sheet pile (DSSP) cofferdam is a composite structure composed of two rows of steel sheet piles, one or more rows of steel tie rods, and sand backfill between the piles. The DSSP structure has good dynamic stability, strong deformability, high seepage resistance, and strong engineering adaptability. It is increasingly used in important projects, such as seawall reinforcement and coastal repair. DSSP cofferdams in coastal areas are inevitably subjected to hydrodynamic pressures, such as periodic waves, and even extreme storm surges or tsunamis. When the wave height is large and water in front of the cofferdam is relatively shallow, the wave will break and generate high dynamic pressure against the cofferdam, threatening the safety and performance of the cofferdam and the permanent building behind it [1]. It is of great significance to investigate the dynamic behavior of DSSP cofferdams.

Hou et al. [2] conducted on-site monitoring of the DSSP cofferdam of a large-scale dock project in Shanghai and studied the deformation characteristics of the large-span DSSP cofferdam under construction conditions. Jiang et al. [3] analyzed the redundancy of the DSSP cofferdam structure and obtained the contribution of different structures to the overall safety. Zhu et al. [4] carried out the reliability analysis of DSSPs based on the Bayesian method and found that the Bayesian method can effectively integrate statistical data and site survey data. Mitobe et al. [5] reinforced the embankment using one and two rows of steel sheet piles against tsunami overflow and found that the double-wall case had much better performance though flume model test. Fujiwara et al. [6] installed partition walls perpendicular to sheet-piles and examined the dynamic the performance of the structure under earthquake through shaking table test and 2-D numerical simulation. Xue et al. [7] conducted stability analysis for cofferdams of pile wall frame structures via engineering test and 3D FEM numerical simulation and proposed a design method based on the limit equilibrium method. Although DSSP piles are widely used in engineering, the mechanical properties and dynamic behavior under the action of surge waves are insufficiently investigated.

This paper compares the different responses of the DSSP cofferdam under the action of breaking wave and standing wave through large-scale flume model test. High-frequency optical fiber technology is applied to obtain the stress data on the steel sheet pile. Combined with numerical analysis, dynamic response law of the DSSP cofferdam under the action of different wave types, is revealed.

2. Model test

2.1 Test equipment

This model test was conducted in the wave-flow water flume experiment platform at Tongji University. The water flume is 42 m long, 1.25 m high and 0.8 m wide (Figure 1). The wave-making system is composed of a wave pushing board, a servo motor, a servo driver, a servo controller, a motion control card, an AD/DA interface, a computer, and peripherals. There is a vertical energy dissipation net on the back of the wave maker and at the end of the trough to eliminate the influence of wave reflection. It can simulate regular waves, elliptical cosine waves, solitary waves, and other common frequency spectra. The wave height variation range is 0.02–0.3 m. The test used a high-speed camera and an optical fiber test system (Figure 2). Details on the test equipment refer to Peng et al. (2019, 2021) [8-9] on landslide dam breaching (Peng and Zhang, 2012 [10]; Shen et al., 2020 [11]).
2.2 Model test

The test prototype is the large-span DSSP cofferdam of a shipbuilding manufacturing base, named Shanghai Changxing. The geometric similarity ratio is 1:30. The length of the piles is 600 mm, the depth of the impact bed is 300 mm, the width of the fence is 300 mm, the shoulder width of the bed bone is 1000 mm, the foot of the rigid wall is 30°, and the thickness of the bed is 500 mm (Figure 1). The water depth in front of the weir is 650 mm, and the water depth in front of the double-row piles is 150 mm.

![Figure 1. Test equipment and the model cofferdam (in mm)](image)

The steel sheet pile in the model test is made of 1.5 mm thick Q235b steel sheet with a height of 600 mm, a water tank with a width of 800 mm, a rubber waterstop, and a steel plate with a width of 792 mm (Figure 2). On the top of the DSSPs, the steel tie rods are made of stainless steel tie rods. The backfill sand between the bed and the two rows of steel sheet piles is made of medium-density quartz sand with a particle size of 0.05–0.3 mm. U-shaped rubber is used to stop water between the steel plate and the glass on both sides of the sink.

The test is carried out according to the following steps:

1. Positioning points of DSSP cofferdams and positioning lines of layered sand filling, are drawn on the front and back sides of the tank wall, and the foundation bed is paved with quartz sand layer by layer, each with a thickness of 10 cm.

2. A pre-made optical fiber string is pasted with 5 measuring points in the middle of the steel sheet pile. Both the seaside steel sheet pile and the landside steel sheet pile are arranged on the front water surface, and the distance between the measuring points is 115 mm.

3. A single-point optical fiber strain gage is pasted on the two steel rods in the middle (Figure 2 top view). The single-point optical fiber needs to be spliced on site. After the fiber optic stress gage on the steel rod is fully dried, the sand is backfilled until the two rows of steel sheet piles are flush at the top.
Figure 2. Layout of the monitor devices (mm)

(4) The fiber string on the steel sheet pile and the single-point fiber on the tie rod are connected to the demodulator through a wire, and high-speed cameras are installed on the front and side of the steel sheet pile cofferdam.

(5) During the test, the water level rose to 65 cm and then stood for half an hour. Then cosine waves with the heights of 4 cm (Stage 1), 8 cm (Stage 2), and 12 cm (Stage 3) were applied for 10 minutes in a sequence.

3 Test results analysis

3.1 Wave action in front of weir

The high-speed camera captures the waveforms of the three working conditions of the wave advancing to the front of the steel sheet pile cofferdam, and obtains the topographic change rule of the foundation bed in front of the cofferdam.

(1) Stage 1 (wave height = 4 cm)

Figure 3 shows a complete wave travel cycle. At $t = 1s$, the wave surface reaches the maximum amplitude from bottom to top, forming a wave crest at the cofferdam, and then reflection occurs. At $t = 2s$, the water quality point moves from top to bottom to reach the maximum amplitude, forming a wave trough. At $t = 3s$, the water quality point reaches the wave crest again, and partially overlaps with the reflected wave, forming a higher wave crest than at $t = 1s$. Under the continuous action of waves, wavy uniform sand patterns appear on the foundation bed. In Stage 1, the double-row steel sheet pile cofferdam has no obvious visible deformation. The seaside base bed presents wave-like sand patterns.
Figure 3. Standing waves in front of the DSSP cofferdam (Stage 1 with wave height of 4 cm)

(2) Stage 2 (wave height = 8 cm)

The difference from Stage 1 is that the increase in wave height leads to more obvious wave reflection and superposition effect (Figure 4). The suction of larger wave troughs produces obvious erosion at the baseboard skirting near the seaside steel sheet pile, thereby reducing the insertion depth of the steel sheet pile.

Figure 4. Standing waves in front of the DSSP cofferdam (Stage 2 with a wave height of 8 cm)

(3) Stage 3 (wave height = 12 cm)

When the wave height is 12 cm, a breaking wave is formed in front of the cofferdam (Figure 5). At \( t = 1 \) s, the wave produces a large shock wave pressure at the steel sheet pile. At \( t = 2 \) s, the wave breaks and retreats. At \( t = 3 \) s, the wave produces a large impact on the steel sheet pile again, forcing the outside. The row of steel sheet piles is inclined toward landside, the soil on the landside is deformed landside due to compression, and the soil on the seaside is pressed against the steel sheet pile to deform landside. However, due to the restraint of the outer soil, the deformation of the steel sheet pile cannot recover even though the stress level is in the elastic stage. Although the wave height of the breaking wave of 12 cm is not as large as the wave height of the Stage 2 after the superposition of the standing wave is 16 cm, the deformation is significantly larger than that of the Stage 2 under the huge impact energy.
The standing wave produced a cycle action of crest pressure and trough suction to the DSSP cofferdam, forming a scour pit at the toe of the seaside steel sheet pile. The breaking wave did not produce obvious reflection and suction against the DSSP. The breaking wave convolved the sediment upward and forward, and deposited in the area adjacent to the DSSP. It seems that the insertion depth of the seaside row of piles increased. But the added part of the sand is very low in density, which cannot be regarded as the true increase in the insertion depth of the seaside row of piles.

3.2 Stress of steel sheet piles

The seaside of the cofferdam is subjected to earth pressure, hydrodynamic pressure with periodically changing water head, wave force (cycle action of crest pressure and trough suction when standing waves occur in front of the cofferdam; cycle wave pressure when breaking waves occur). The landside of the cofferdam is subjected to earth pressure and hydrostatic pressure.

Due to the water depth in the three sets of tests, the water depth in front of the cofferdam remains unchanged, thus the seaside earth pressure, landside hydrostatic pressure, and earth pressure remain the same. The key loads that affect the force characteristics of the cofferdam are the periodic hydrodynamic pressure and wave force. The wave force of standing-wave crests, troughs, and breaking waves are calculated with the methods shown in Figure 6.

The wave pressure at the bottom of the standing wave crest $P_d$ is calculated as follows:
When the wave crest occurs (Figure 6a), the wave pressure at the water level of the standing wave $P_s$ is calculated as

$$P_s = (P_d + \gamma d) \frac{H + h_s}{d + H + h_s}$$

(2)

The wave pressure at the top of the embankment $P_b$ is calculated as follows:

$$P_b = P_s - (P_s - P_d) \frac{d_1}{d}$$

(3)

When wave trough occurs (Figure 6b), the wave pressure at the water level of the standing wave $P'_s$ is calculated as follows:

$$P'_s = \gamma (H - h_s)$$

(4)

The wave pressure at the top of the embankment $P'_b$ is calculated as follows:

$$P'_b = P'_s - (P'_s - P'_d) \frac{d_1 + h_s - H}{d + h_s - H}$$

(5)

When near break wave occurs (Figure 6c), the wave pressure at the water level of the standing wave $P'_s$ is calculated as follows:

$$P'_s = 1.25 \gamma H [(13.9 - 36.4) \frac{d_1}{d_1} \frac{H}{d_1} - 0.67] + 1.03 (1 - 0.13) \frac{H}{d_1}$$

(6)

The wave pressure at the top of the embankment $P'_b$ is calculated as follows:

$$P'_b = 0.6 P'_s$$

(7)

The height of the center line of the wave above the still water surface is as follows:

$$h_0 = \frac{\pi H^2}{L} \text{cth} \frac{2 \pi d}{L}$$

(8)

where $H$ = wave height (m), $L$ = wave length (m), $d$ = water depth in front of the cofferdam (m), $\gamma$ = weight of the water (kN/m$^3$), $d_1 = $ water depth in front of the sheet pile (m), $P = $ total wave force (kN/m), and $B = $ width of the cofferdam.

The wave pressures of the standing wave and the near break wave in Tests 1–3 are calculated according to the Equation (1)–(8), as shown in Table 1. The results can be applied for numerical analysis as presented in Cai et al. (2018) [11] and Xiao et al. (2020) [12].

| Wave height (m) | Waveform            | Wave pressure (kPa) | Still surface water (m) |
|----------------|---------------------|---------------------|-------------------------|
| 0.04           | Standing wave crest | $P_d$ = 0.277       | $P_s$ = 0.407           | $P_b$ = 0.377           |
|                |                     | $h_0$ = 0.692       |                         |                         |
|                | Standing wave trough| $P'_d$ = 0.277      | $P'_s$ = 0.384          | $P'_b$ = 0.365          |
|                |                     | $h_0$ = 0.65       |                         |                         |
| 0.08           | Standing wave crest | $P_d$ = 0.555       | $P_s$ = 0.826           | $P_b$ = 0.763           |
|                |                     | $h_0$ = 0.736       |                         |                         |
|                | Standing wave trough| $P'_d$ = 0.555      | $P'_s$ = 0.826          | $P'_b$ = 0.763          |
|                |                     | $h_0$ = 0.736       |                         |                         |
3.3 Stress of the steel sheet

Figure 7 shows the stress curves on the outer row (sea side) and inner row (land side) steel sheet piles obtained from the fiber string test.

Under the action of a small standing wave (wave height of 4 cm in Stage 1), the seaside row of piles deforms toward seaside under the action of soil pressure. Due to the restriction of the tie rods (elevation of 30 cm), the top deformation is relatively small. The deformation increases along the pile downward until the foundation bed. After entering the foundation bed, the deformation gradually becomes smaller under the restriction of the seaside soil confinement. The landside row of piles deforms toward the landside as a whole under the action of the soils. Due to the constraints of the tie rods and the foundation bed, the central bending moment is larger, and the stress at the corresponding position is also larger, while the upper and lower stresses are smaller. In general, due to the greater effect of sand backfill between the two rows of piles, the outer wave force is smaller; the effect of the outer wave only affects the outer row of piles and has less influence on the inner row of piles.

Under the action of a larger standing wave (wave height of 8 cm in Stage 2), the hydrodynamic pressure at the foundation surface increases with the wave force, offsetting part of the backfill sand pressure. The stress appears as the S Type recurve shape. The deformation of the soil between the two rows of piles makes the stress of the inner row of steel sheet piles increase significantly with the maximum stress appearing at the bed surface.

Under the action of near break wave (wave height of 12 cm in Stage 3), the wave breaks during the first half cycle of the cofferdam, generating a hydrodynamic pressure much greater than that of the standing wave. The break wave makes the outer row of piles produce huge deformation with the maximum displacement occurring at the top of the pile (Figure 7). At the same time, the seaside row of steel sheet piles produced huge tensile stress. The maximum bending moment appears at a position 40 mm below the bed surface. According to its deformation and stress characteristics, the piles can be regarded as a cantilever plate and the fixing point is located below the bed surface.

| Wave Type | $P_d$ | $P_s$ | $P_b$ | $h_0^*$ |
|-----------|------|------|------|-------|
| 0.12 Near break wave | 0.555 | 0.738 | 0.714 | 0.65 |
| 0.832 | 2.345 | 1.407 | 0.762 |

Note: * $h_0$ notes the height (in mm) of the position where the wave pressure is 0.
Figure 7. Stress distribution in steel sheet piles: (a) seaside row; (b) landside row.

3.4 The deformation of the cofferdam

Figure 8 shows the final deformation of the three tests. In Stage 1, the piles did not deform for the relatively small wave pressure. The seaside base bed presents wave-like sand patterns. A small amount of over-wave scouring occurs on the top of the weir and the landside base bed remains intact. In Stage 2, the seaside steel sheet pile skirting was scoured and the insertion depth decreased, resulting in a large increase in the deformation of the steel sheet pile cofferdam. The deformation of the sheet pile causes local leakage and a small amount of erosion of the landside steel sheet pile skirting. In Stage 3, the deformation gradually accumulates with each wave of dynamic load, which makes the steel sheet pile bend more and more and the stress continues to increase. At the same time, larger waves generate deposition at the foundation bed, which increases the soil pressure and deformation on the outside of the steel sheet pile. The steel sheet pile breaks away from the glass wall of the sink, resulting in a large flow leakage. At the same time, the breaking wave crosses the top of the steel sheet pile on the seaside, continuously scouring the sand fill at the top of the weir and the landside bed (also see Peng et al., 2019; 2021 [8-9]), further causing the cofferdam to deform toward the landside.

Figure 8. The final deformation of the three stages under different wave heights
4. Conclusions

The paper investigated the effect of different wave forms on the DSSP cofferdam through a large-scale water flume tests using optical fiber testing technology. The following conclusions can be drawn:

(1) The DSSP cofferdam is similar to a vertical retaining wall under the condition of a high foundation bed. When water depth is shallow or wave height is large, breaking waves are generated. On the other hand, when the water depth is large or wave height is small, standing waves are generated.

(2) The standing wave produces a cycle action of crest pressure and trough suction to the DSSP cofferdam, forming a scour pit at the toe of the seaside steel sheet pile. The breaking wave does not produce obvious reflection and suction against the DSSP. The breaking wave convolvses the sediment upward and forward, and deposits in the area adjacent to the DSSP.

(3) Comparing the standing wave, the DSSP cofferdam undergoes obvious landside deformation under the breaking wave. The bending moment on the steel sheet pile is about 2 to 3 times that of the standing wave. The deformation of the steel sheet pile may cause leakage of the joint and soil erosion of the infilled sands, even resulting failure of the DSSP cofferdam. The calculation method only involving static water pressure, is insufficient to estimate the impact energy of breaking waves.

References

[1] Kang H.G., Sun W.Y. Study on mechanism of breaking wave loads on vertical walls. Port & Waterway Engineering, 2010, 3(439): 21-25.
[2] Hou Y.M., Wang J.H., Gu Q.Y. Deformation performance of double steel sheet piles cofferdam. Journal of Shanghai Jiaotong University, 2009, 43(10): 1577-1580.
[3] Jiang J., Gu Q. Y., Chen J., Zhu Y., Gao J.Y., Yu M.X. Redundancy analysis of the design parameters for the double-row steel sheet-pile cofferdam. Port & Waterway Engineering, 2017, 9(534): 174-180.
[4] Zhu Yan, Gu Qian-yan, Jiang Jie, Peng Ming. Reliability analysis for overall stability of large-span double-row sheet-pile dock cofferdam based on Bayesian method. Rock and Soil Mechanics, 2016, 37(S1): 609-615.
[5] Mitobe Y, Adityawan M B , Roh M , et al. Experimental Study on Embankment Reinforcement by Steel Sheet Pile Structure Against Tsunami Overflow. Coastal Engineering Journal, 2016 58(4): 1640018.
[6] Fujiwara K, Taenaka S, Otsushi K, Yashima A, Sawada K, Ogawa T, Takeda K. Study on levee reinforcement using double sheet-piles with partition walls. Japanese Geotechnical Society Special Publication, 2017, 5(2): 11-15.
[7] Xue R.Z., Bie SA, Guo LL, Zhang PL. Stability Analysis for Cofferdams of Pile Wall Frame Structures. KSCE Journal of Civil Engineering, 2019, 23(9):4010-4021
[8] Peng, M., Jiang, Q.L., Zhang, Q.Z., Hong, Y., Jiang, M.Z., Shi, Z.M., Zhang, L.M.. Stability analysis of landslide dams under surge action based on large-scale flume experiments. Engineering Geology, 2019, 259: 105191.
[9] Peng, M., Ma, C.Y., Chen, H.X., Zhang, P., Zhang, L.M., Jiang, M.Z., Zhang, Q.Z., Shi, Z.M. Experimental study on breaching mechanisms of landslide dams composed of different materials under surge waves, Engineering Geology, 2021, 291: 106242.
[10] Shen, D.Y., Shi, Z.M., Peng, M., Zhang, L.M., Jiang, M.Z. Longevity analysis of landslide dams. Landslides, 2020, 17(8): 1797-1821.
[11] Cai, Y.Q., Cao, Z.G., Wang, Y.L., Guo, Z., Chen, R., 2018. Experimental and numerical study of the tidal bore impact on a newly-developed sheet-pile groin in Qiantang river. Applied Ocean Research, 2018, 81: 106-115.

[12] Xiao, Z., Song, L., Li, J.H. Stability of the large cylindrical structures in Hong Kong-Zhuhai-Macao bridge: A case study. Applied Ocean Research, 2020, 97: 102092.

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