Research on the characteristics and physical model test method of penetration depth for ship emergency anchoring

Liu Lei¹, Li Baoyu¹, Ma Qianwen¹

¹China Waterborne Transport Research Institute, Beijing, 100088, China

¹Corresponding author’s e-mail: liulei@wti.ac.cn

Abstract: Based on the whole process theory, the characteristics of penetration depth for ship emergency anchoring are summarized. Combined with the actual project, the physical model test was carried out, and the scale ratio was set for the soil and anchor. Different working conditions are designed for water flow, vertical height and horizontal velocity Angle, and the model test of anchor penetration depth was carried out. The experimental results show that whether there is water flow or not and the variation of water flow conditions have certain effects on the penetration depth of anchor; when the anchor only has vertical velocity, the faster the anchor hits the bottom, the deeper the anchor penetrates into the soil; when the anchors have horizontal velocity synchronously, the penetration depth of the anchors increases slightly. Compared with the traditional model, the results obtained by this method are closer to reality and provide ideas and references for penetration depth for ship emergency anchoring.

1. Introduction

In recent years, more and more pipelines or tunnels have been constructed to cross the waterway. Emergency anchoring happens occasionally due to accidents, and the penetration depth is closely related to the operation safety of underwater structures [1-2]. Ship emergency anchoring is a complex process, involving ship navigation, fluid mechanics, geotechnical mechanics and other disciplines. Under different environmental conditions, the penetration depth for ship emergency anchoring is different. Therefore, the penetration depth for emergency anchoring needs to be determined through thematic research.

Recently, many scholars have studied the penetration depth. Wang weiwei [3] established a simple physical model of ship emergency anchoring, proposed an effective calculation method of penetration depth, and compared the accuracy of the calculation results. Yan shuwang et al. [4] proposed the penetration depth calculation method of anchor dragging in sand based on the limit equilibrium theory of soil mass. The method is in good agreement with the experimental results, and then he proposed a fitting formula between the grasping force coefficient and the sand strength parameter. Du ying et al. [5] designed the theoretical algorithm of anchor penetration depth based on the taisha ultimate bearing capacity formula and the energy method. She used the least square method to fit the experimental data, and calculated the penetration depth of the anchor in the sand. Traditionally, the model of anchor penetration depth is usually configured with soil sample and anchor in accordance with a certain scale ratio, and then the anchor falls vertically and directly into the soil. However, the influence of water flow and other factors was ignored, and there are some deviations between the test results and the practice.

In this paper, based on the characteristics of penetration depth for ship emergency anchoring, a certain scale model is proposed based on the whole process theory. Considering the combination of
water flow and different speeds, the maximum penetration depth of hall anchor under different working conditions was simulated. The research results have important reference value for the penetration depth research of emergency anchoring.

2. Characteristics of penetration depth for emergency anchoring

According to the relevant literature, a large number of tests and the captain's experience of emergency anchoring, there are three characteristics for ship emergency anchoring.

(1) The anchor has a certain horizontal velocity at the moment of falling. Ship emergency anchoring refers to that ship in voyage is forced to anchor due to accidents. Therefore, the anchor has the same horizontal speed as the ship at the moment of landing.

(2) There are great differences in water depth, flow velocity and riverbed geology at different emergency anchorage location. Emergency anchoring is different from anchoring in anchorage. The ship accidents and emergency anchoring location are unpredictable. As long as there are appropriate conditions for anchoring, the captain will slow down the ship by anchoring.

(3) Emergency response of ship out of control may change the attitude of anchor into soil. Most scholars believe that the anchor is vertical at the moment of contacting the soil. However, in the actual situation, due to the different emergency anchoring accidents, under the combined action of the current and the braking measures adopted by the ship, the attitude of the anchor may change when it is inserted into the riverbed, and it may be inclined to penetration at a certain Angle.

3. Test preparation

3.1 Configured soil sample

Taking W city tunnel project as an example, according to the geological survey results, the riverbed composition is mainly silty sand and slightly coarse sand. The soil samples similar to in-situ silty sand are obtained by adjusting the particle size distribution of quartz sand (the results of particle sieving are listed in Table 1). The soil samples with relative compaction of 0.45 are prepared by stratified compaction method for testing.

| Soil sample | 0.5-0.25mm (%) | 0.25-0.075mm (%) | <0.075mm (%) | Friction angle (°) |
|-------------|----------------|------------------|-------------|-------------------|
| test        | 10.5           | 57               | 32.5        | 32                |
| in situ     | 8.3            | 58.4             | 33.2        | 31                |

Static cone penetration test (CPT) was carried out on soil samples. The diameter, height and angle of the conical probe are 14.4 mm, 16.5 mm and 60 degrees respectively. The curve of resistance of CPT end with penetration depth is shown in Figure 1. The test results show that the CPT curves obtained by the two measurements are close to each other, which indicates that the uniformity of the soil sample is better.
3.2 Scale of Model Anchor and Test

In the small scale model test, in order to ensure that the physical quantities obtained from the model test can truly reflect the situation under the prototype conditions, it is necessary to satisfy certain scale conditions:

\[
\lambda = \frac{l_p}{l_m} \quad \lambda_v = \lambda^{1/2} \quad \lambda_H = \lambda^3 \quad \lambda_p = \lambda^3 \quad \lambda_k = \lambda^4
\]

Formula: \( \lambda \) - model length scale; \( l_p \) - prototype length; \( l_m \) - model length; \( \lambda_v \) - velocity scale; \( \lambda_H \) - depth scale; \( \lambda_p \) - potential energy scale; \( \lambda_k \) - gravity scale; \( \lambda_k \) - kinetic energy scale.

| Anchor weight (kg) | Size (mm) |
|-------------------|-----------|
| 1.74              | 193 105 23 149 105 58 69 |

In this model test, the scale of Hall anchor model is \( \lambda = 15 \), and the converted model size data are listed in Table 2. The model anchor is made of iron and treated with anti-rust. Hall anchor model as shown in Figure 2, the quality of the processed Hall anchor model is 1.74 kg, which is slightly larger than the ideal model quality (1.68 kg) obtained by the scale of the prototype weight (5.61 tons), and
can meet the test requirements.

3.3 Velocity Measurement Technology
Two measurement techniques are used in this experiment: (1) A MEMS acceleration sensor is installed on the anchor to capture the acceleration of the anchor when it falls. As shown in Figure 4, the specific model of the sensor is ADXL326, the measurement range is (+16g), the size (long × width × height ) is (18mm×18mm×3.2 mm), and the mass is 3 g. There will be no big deviation from the experimental results. (2) A high-speed camera is installed at the front of the test box to capture the anchor’s falling position at different times. The anchor’s speed is calculated by identifying the change of anchor’s position in two pictures with known time intervals [6]. At the same time, the vertical velocity of anchor calculated by using the MEMS accelerometer is checked.

3.4 Combination of test conditions
According to the characteristics of penetration depth for ships emergency anchoring, different working conditions are designed from three aspects of water flow, vertical height and horizontal velocity by using the method of comparison with or without. As shown in Table 3, different vertical height can be set for each working condition, and the penetration depth for ships emergency anchoring can be further refined.

| Combination of Working Conditions | Vertical Height yes or no | Horizontal velocity yes or no | Water yes or no |
|----------------------------------|--------------------------|-------------------------------|----------------|
| Working Conditions 1             | yes                      | no                            | no             |
| Working Conditions 2             | yes                      | yes                           | no             |
| Working Conditions 3             | yes                      | no                            | yes            |
| Working Conditions 4             | yes                      | yes                           | yes            |

3.5 Test process
The main test steps are as follows: first, the dry density of the soil sample is calculated according to the relative compactness of the target soil sample, and the required sand quality of the 5 cm soil sample is calculated, which is scattered into the model box and compacted to the target thickness; repeat this step until the preparation of the soil sample is completed. The second step is to saturate the soil sample with water. The third step is to test the saturated soil samples by CPT. The fourth step is that the anchor model is suspended at a certain height above the soil sample by fishing line. The position is calculated by the design vertical velocity of the anchor and the free fall formula of the object in the air. The fifth step is to put the high-speed camera in front of the model box and adjust the light brightness and shooting range. The sixth step is to debug the data acquisition system, confirm that the output signal of the acceleration sensor is stable, and then burn the fishing line[7]. The seventh step is to measure the depth of the anchor penetrating the soil. Repeat the process according to the design conditions.

4. Test results and analysis
4.1 Test result
According to the working conditions designed in Table 3, a number of tests were carried out. There were 6 groups of tests with only vertical velocity, including 4 groups with different heights in anhydrous state and 2 groups with water state. One group of horizontal velocity anchoring test. The model test conditions are listed in Table 4. Taking H1 as an example, the measured acceleration curve with time is shown in Fig. 3.
Table 4. Tests conditions and results

| Test Number | Anchor weight (kg) | Vertical velocity (m/s) | Horizontal velocity (m/s) | Penetration depth (m) | Water yes or no |
|-------------|--------------------|-------------------------|---------------------------|-----------------------|-----------------|
| H1          | 1.74               | 1.64                    | 0                         | 0.08                  | No              |
| H2          |                    | 2.01                    | 0                         | 0.11                  | No              |
| H3          | 1.74               | 2.56                    | 0                         | 0.14                  | No              |
| H4          |                    | 3.02                    | 0                         | 0.23                  | No              |
| H5          |                    | 2.56                    | 0                         | 0.15                  | Yes             |
| H6          |                    | 3.02                    | 0                         | 0.26                  | Yes             |
| H7          |                    | 2.25                    | 0.46                      | 0.13                  | Yes             |

Figure 3. Curve of anchor’s acceleration vs. time (case H1)

4.2 Result analysis
According to the test data in Table 4, compared with the test data of the same type of anchor, it can be seen that the anchor depth increases with the increase of the anchor's bottom-touching velocity, which is because the greater the anchor's bottom-touching velocity is, the greater the kinetic energy it has, the greater the penetration depth is. According to the formula put forward by Li Xiaosong et al. [8] the ultimate velocity of anchor falling in water can be calculated to be 5.33-9.74 m/s and 1.38-2.51 m/s under the corresponding model conditions. According to the data in Table 4, when the model velocity is 2.33 m/s (corresponding to the prototype velocity is 9.02 m/s), the penetration depth of Hall anchor is 0.12 m and the corresponding prototype depth is 1.8 m, which is about 52.2% of the anchor length.

When the vertical velocity of Hall anchor is 2.25 m/s (prototype 8.71 m/s) and the horizontal velocity is 0.46 m/s (prototype 1.78 m/s), the penetration depth of corresponding prototype is 1.95 m, which is 12.1% higher than that of only vertical velocity (1.74 m). When the anchor has horizontal velocity, the penetration depth of Hall anchor is slightly larger than that of the same vertical velocity. Due to the effect of horizontal velocity, increased initial kinetic energy, and the anchor inclined penetration occurs after contacting silt and fine sand foundation. If the anchor penetrates the bottom of the soil, the maximum penetration depth increases relative to the vertical penetration, but the increase is not more than 20%.

5. Conclusion
The penetration depth of emergency anchoring is related to many factors, such as ship speed, ship type, water depth, current velocity, riverbed geological conditions, anchor type and anchor weight. Based on the whole process theory and theoretical analysis method, this paper summarizes the characteristics of
penetration depth of emergency anchoring. According to the characteristics, the working conditions and processes of physical model test are designed from different point of view, and the penetration depth of anchor under different working conditions is compared and analyzed. The research results can provide some reference for the study of physical model of penetration depth of emergency anchoring. In the next step, the physical model test under the condition of simulating a certain flow velocity can be considered.

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