

Article

# Experimental Study on Local Scour Depth around Monopile Foundation in Combined Waves and Current

Junhan Li <sup>1,†</sup>, Bin Zhang <sup>1,†</sup>, Chao Shen <sup>1</sup>, Xiaoli Fu <sup>1,\*</sup> and Weichao Li <sup>2,\*</sup>

<sup>1</sup> Department of Hydraulic Engineering, College of Civil Engineering, Tongji University, Shanghai 200092, China; muzi199607@126.com (J.L.); zhangb@tongji.edu.cn (B.Z.); shenc@tongji.edu.cn (C.S.)

<sup>2</sup> Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, Shanghai 200092, China

\* Correspondence: xlfu@tongji.edu.cn (X.F.); WeichaoLi@tongji.edu.cn (W.L.)

† These authors contributed equally to this work and should be considered co-first authors.

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**Abstract:** Local scour is one of the key factors that cause the collapse of structures. To avoid structure failures and economic losses in water, it is usually essential to predict the equilibrium scour depth of the foundation. In this study, several design models which were presented to predict the equilibrium scour depth either under steady clear water conditions and combined waves and current conditions were recommended. These models from China, the United States and Norway were analyzed and compared through experiments. Moreover, flume tests for monopile foundation embedded in sand under different flow conditions were carried out to observe the process and gauge the maximum depth around the pile. Based on this study, for predicting the equilibrium scour depth around bridge piers, the computational results of three design methods are all conservative, as expected. For the foundation of offshore structures in marine environment, most of the predicted scour depths by design methods are different from field data; in particular, the mean relative error with these design methods proposed may reach up to 966.5%, which may lead to underestimation of the problem, overdesign and consequently high construction cost. To further improve the ability of the scour prediction in a marine environment, data from flume tests and some field data from a previous study were used to derive the major factors of scour. Based on the dimensional analysis method, a new model to estimate the equilibrium scour depth induced by either current or waves is proposed. The mean relative error of the new formula is 49.1%, and it gives more accurate scour depth predictions than the existing methods.

**Keywords:** local scour depth; flume tests; prediction equation; combined waves and current

## 1. Introduction

Scour is recognized as one of the key factors that causes structure failures, which in turn leads to economic and life loss. After investigation into the causes of damage to 143 bridges in the world, Smith [1] found that nearly 50% bridges were damaged due to water scour. For instance, in July 2013, the Panjiang Bridge in Jiangyou City of Sichuan Province collapsed due to undermined pier foundation caused by flood scour (Figure 1). Furthermore, structures in a marine environment also suffer scour to different extents, which may endanger the stability of the structures. For instance, in September 2010, the ShengLi Well Workover Platform III of Chengdao Oil Field at Yellow River Estuary in Bohai Sea collapsed due to the interaction of various factors, including scour (Figure 2).

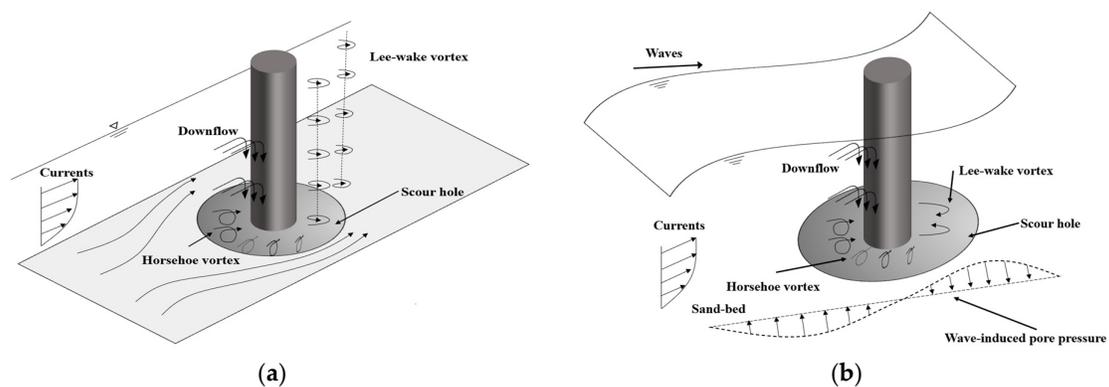


**Figure 1.** Collapsed Sichuan Panjiang Bridge [2].



**Figure 2.** ShengLi Well Workover Platform III overturning accident [3].

Generally, scour can be classified as general scour or local scour. General scour refers to the scouring of the riverbed under the whole bridge section after the construction of the bridge. Local scour refers to the silty sand surrounding the piles being taken away as the flow field surrounding structures is changed to create a complex three-dimensional flow that causes formation of downward flow and horseshoe vortex in front of the base, linear contraction in the water flow direction on the side of piles and surging wake vortex behind piles (Figure 3). Based on the current research results [4], local scour is one order of magnitude greater than general scour (over 10 times). We believe that local scour is the key factor that results in structural failures.



**Figure 3.** Vortex around a monopile foundation. (a) Scour at pile foundation in current-alone (modified from [5]). (b) Scour at pile foundation under combined waves and current [6].

Local scour is primarily influenced by the following three effects [7–19]: (1) water flow; (2) sediments of seabed or riverbed; and (3) the type and characteristics of pier. The most common conditions of water flow are mainly as follows: steady current, tidal current, and combined waves and current. According to current research [18,20] at the current stage, under steady currents, the main influencing factors of local scour depth ( $h_b$ ) are: flow velocity ( $v$ ), water depth ( $h$ ) and median particle size ( $d_{50}$ ) of soil on seabed or riverbed. Furthermore, the dimensionless depth  $h_b/D$  ( $D$  is the diameter of column) may be expressed as the function of three dimensionless quantities of  $v/v_0$ ,  $h/D$  and  $D/d_{50}$ ; see Equation (1):

$$\frac{h_b}{D} = f\left(\frac{v}{v_0}, \frac{h}{D}, \frac{d_{50}}{D}\right) \quad (1)$$

where  $v_0$  is the critical initial velocity of silty sand. In case of combined waves and currents, the relative flow velocity  $U_{cw}$  and KC number (Keulegan–Carpenter) [15] are the two important factors that influence the scour depth surrounding the piles. The  $U_{cw}$  value may be obtained through Equation (2):

$$U_{cw} = U_c / (U_c + U_w) \quad (2)$$

where  $U_c$  means the flow velocity at the point 1.0  $D$  below the bed surface under single action of water flow and  $U_w$  is the maximum horizontal velocity of wave water particles near the bottom. When  $U_{cw}$  is close to 1, it can be deemed that there is pure action of currents; when  $U_{cw}$  is close to 0, it can be deemed that there is pure action of waves; where  $U_{cw}$  is greater than 0.5, the scour is mainly dominated by currents; when  $U_{cw}$  is greater than 0.7, the maximum scour depth is closer to the pure action of currents. KC number is a main parameter that controls the scour process of movable bed in case of pure action of wave. It is defined as the three main factors that influence the local scour depth surrounding the columns under single action of waves; the relationship among the maximum horizontal velocity  $U_{wm}$  of wave water particles near the bottom, the wave period  $T_w$  and the column diameter  $D$  is shown in Equation (3):

$$KC = U_{wm} T_w / D \quad (3)$$

It can be seen that the process of local scour is complex and changeable. Over the last few decades, various methods have been conducted by scholars to reduce losses which are caused by local scour. These endeavors can be classified into two major categories: (a) appropriate protective measures may be taken against scour, thus reducing the scour depth surrounding the foundation and improving the safety and stability of structure [21,22]; (b) accurate prediction of the local scour depth in the stage of design and construction to prevent problems. In recent years, many scholars have created corresponding formulas for predicting local scour depth through theoretical analysis, model tests and analysis of onsite measured data, etc. For instance, Melville and Sutherland [20] established a design method for the estimation of equilibrium depths of local scour at bridge piers which was based upon envelope curves drawn to experimental data derived mostly from laboratory experiments. The Lacey formula [23] was established by the field data of rivers in India and the Jain formula was derived from model test data. Pandey et al. [24] described the phenomenon of temporal scour depth variation at bridge piers and investigated six temporal scour depth equations. Moreover, many scholars [4,5,25] have studied the prediction formula for local scour depth, and some of these equations have been adopted in countries specifications due to their accuracy and convenience.

In this paper, an analysis on six design codes for the equilibrium scour depth from China, the United States and Norway is firstly presented. Furthermore, a new prediction model under combined waves and currents is proposed based on the local scour test results and dimensional analysis method. The statistical evaluation criteria are used to

verify the reasonability and validity of the new formula. This study attempts to deepen the understanding of the parameters that are important to the equilibrium local scour depth under wave-current action and provide references for designing estuarine, coastal and offshore structures in practice.

### 2. Existing Design Methods for Local Scour Depth

In this paper, a total of six recommended prediction models for local scour depth are selected: Formula 65-2 and Formula 65-1 (modified formula) [26], HEC-18 formula [27], Han Haiqian Formula, Wang Rukai Formula and Sumer method [28]. The first three formulas are usually applied for the prediction of the maximum scour depth around bridge piers, and the last three formulas mainly target the prediction of local scour depth of the subsea and offshore structures. The detailed information is shown in Table 1.

**Table 1.** The design methods used for comparison in this study.

| Codes                      | Equations  | Design Specifications  | Notes  |
|----------------------------|--|--|--|
| 65-2                       | $h_b = \begin{cases} K_\xi K_{\eta 2} D^{0.6} h^{0.15} \left( \frac{v - v_0'}{v_0} \right) & v \leq v_0 \\ K_\xi K_{\eta 2} D^{0.6} h^{0.15} \left( \frac{v - v_0'}{v_0} \right)^{n_2} & v > v_0 \end{cases}$ <p>where <math>K_{\eta 2}</math>, <math>v_0</math>, <math>v_0'</math> and <math>n_2</math> is given by</p> $K_{\eta 2} = 0.0023\bar{d}^{-2.2} + 0.375\bar{d}^{-0.24}; v_0 = 0.28(\bar{d} + 0.7)^{0.5};$ $v_0' = 0.12(\bar{d} + 0.5)^{0.55}; n_2 = \left( \frac{v_0}{v} \right)^{0.23 + 0.19 \log \bar{d}}$   | Hydrological Specifications for Survey and Design of Highway Engineering (JTG C30-2015) [26] | <ol style="list-style-type: none"> <li>1. Based on field and experiment data collected in China [29]</li> <li>2. Performed well in the following decades</li> <li>3. Dimensional disharmony</li> <li>4. The expression is valid for both live-bed and clear water</li> </ol>   |
| 65-1<br>(modified formula) | $h_b = \begin{cases} K_\xi K_{\eta 1} D^{0.6} (v - v_0') & v \leq v_0 \\ K_\xi K_{\eta 1} D^{0.6} (v - v_0') \left( \frac{v - v_0'}{v_0 - v_0'} \right)^{n_1} & v > v_0 \end{cases}$ <p>where <math>K_{\eta 1}</math>, <math>v_0</math>, <math>v_0'</math> and <math>n_1</math> is given by</p> $K_{\eta 1} = 0.8 \left( \frac{1}{\bar{d}^{0.45}} + \frac{1}{\bar{d}^{0.15}} \right);$ $v_0 = 0.0246 \left( \frac{h_p}{\bar{d}} \right)^{0.14} \sqrt{332\bar{d} + \frac{10 + h}{\bar{d}^{0.72}}};$ $v_0' = 0.462 \left( \frac{\bar{d}}{D} \right)^{0.06} v_0; n_1 = \left( \frac{v_0}{v} \right)^{0.25\bar{d}^{0.19}}$ | Hydrological Specifications for Survey and Design of Highway Engineering (JTG C30-2015) [26] | <ol style="list-style-type: none"> <li>1. Based on field and experiment data collected in China</li> <li>2. Performed well in the following decades</li> <li>3. Dimensional disharmony [29]</li> <li>4. The expression is valid for both live-bed and clear water</li> <li>5. Makes up for the insufficiency of the large calculation value of the 65-2 type pair in predicting the local scour depth around the pier and the river bed in the foundations such as large boulders and pebbles</li> </ol> |
| HEC-18                     | $\frac{h_b}{h} = 2.0 K_1 K_2 K_3 K_4 \left( \frac{D}{h} \right)^{0.65} F_r^{0.43}$ <p>where <math>F_r</math> is given by</p> $F_r = \frac{v}{\sqrt{gh}}$   | American Association of State Highway and Transportation Officials (AASHTO LRFD) [27]        | <ol style="list-style-type: none"> <li>1. Based on field and experiment data collected in USA</li> <li>2. Include the coefficients for the effect of bed forms, size of bed materials, and wide piers</li> <li>3. Dimensionally consistent</li> <li>4. The expression is valid for both live-bed and clear water</li> </ol>  |

|                     |  |  |   |
|---------------------|--|--|---|
| Han Haiqian Formula | $\frac{h_b}{h} = 17.4k_1k_2 \left(\frac{D}{h}\right)^{0.326} \left(\frac{d_{50}}{h}\right)^{0.167} F_r^{0.628}$ <p>where <math>F_r</math> is given by</p> $F_r = \frac{v}{\sqrt{gh}}$  | Chinese Code for Design of Wind Turbine Foundations for Offshore Wind Power Projects (NB/T 10105-2018) [28]  | <ol style="list-style-type: none"> <li>1. Based on field and experiment data collected in China under tidal current</li> <li>2. Include the coefficients for the effect of arrangement form</li> </ol>  |
| Wang Rukai Formula  | $\lg\left(\frac{h_b}{h}\right) = -1.2935 + 0.1917 \lg \beta$ <p>where <math>\beta</math> is given by</p> $\beta = \frac{H_w^2 v^3 L_w D \left[ v + \left( \frac{1}{T_w} - \frac{v}{L_w} \right) \frac{H_w L_w}{2h} \right]^2}{\left( \frac{\rho_s - \rho}{\rho} \right) \nu g^2 h^4 d_{50}}$ | Chinese Code for Design of Wind Turbine Foundations for Offshore Wind Power Projects (NB/T 10105-2018) [28]  | <ol style="list-style-type: none"> <li>1. Comprehensive considerations</li> <li>2. Complicated calculation</li> </ol>   |
| Sumer method        | $\frac{S}{D} = \begin{cases} 1.3 & KC < 6 \\ 1.3 \{1 - \exp[-0.03(KC - 6)]\} & KC > 6 \end{cases}$   | Chinese Code for Design of Wind Turbine Foundations for Offshore Wind Power Projects (NB/T 10105-2018) [28] & The DVN GL standard for Support structures for wind turbines (DNVGL-ST-0126-2018) [30] | <ol style="list-style-type: none"> <li>1. The expression is valid for live-bed conditions</li> <li>2. For steady current, which implies <math>KC \rightarrow \infty</math>, it appears from this expression that <math>S/D \rightarrow 1.3</math></li> <li>3. For waves it appears that for <math>KC &lt; 6</math>, no scour hole is formed. The physical explanation for this is that no horseshoe vortex develops for <math>KC &lt; 6</math></li> </ol> |

$h_b$  = the local scour depth (m);  $K\epsilon$  = type factor for piers;  $D$  = the diameter of column (m);  $h$  = the water depth (m);  $v_0$  = sediment-moving incipient velocity (m/s);  $v_0'$  = critical mean approach flow velocity for entrainment of sediment upstream of the pier (m/s);  $\bar{d}$  = the average particle size of sediment bed (m);  $d_{50}$  = median particle size of sediment bed (m);  $v$  = the flow velocity (m/s);  $\rho_s$  = dry sand density (kg/m<sup>3</sup>);  $\rho$  = the water density (kg/m<sup>3</sup>);  $H_w$  = the wave height (m);  $L_w$  = the wave length (m);  $T_w$  = the wave period (s);  $\nu$  = the kinematic viscosity of water (m<sup>2</sup>/s).

### 3. Experimental Verification

#### 3.1. Experiments Arrangement

The experiments were carried out in a flow–structure–soil interaction flume, which were capable of synchronously generating waves and current. The arrangement of the experiment model is shown in Figure 4; the flume is 50 m in length, 0.8 m in width and 1.2 m in depth. A soil box, which is 1.0 m in depth, 0.65 m in width and 2.2 m in length, is located in the middle section of the flume. During experiment, the soil box was filled with saturated sand whose height was equal to the elevation of flume bottom, and the cylindrical model piles with diameters  $D = 0.04$  m was buried in the center of the soil box. At the front edge of soil box, there was an Acoustic Doppler Velocimetry (ADV) and a wave height gauge.

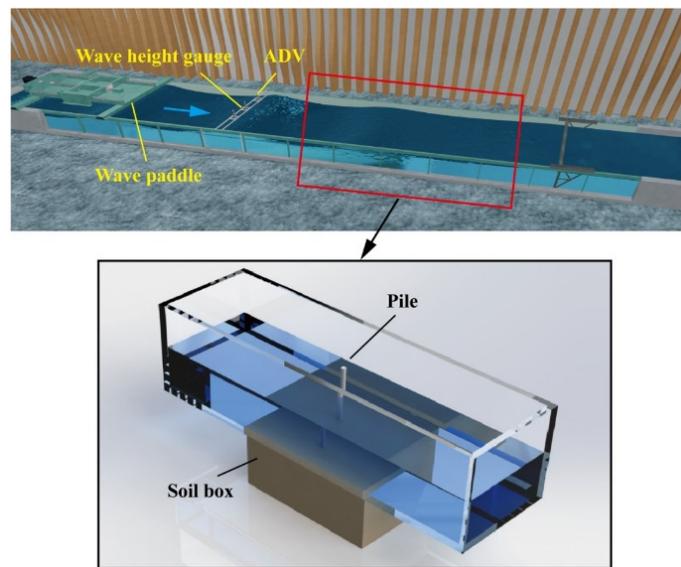


Figure 4. Schematic diagram of the experiment arrangement.

In order to facilitate comparative analysis of different groups of experiments, the same silty sand was used for all experiments. With sieving method, it was measured that the mean particle size of sandy soil,  $d_{50}$  was 0.22 mm; unevenness coefficient  $C_u = d_{60}/d_{10} = 1.67$ ; the soil saturation density  $\rho = 1370 \text{ kg/m}^3$ ; and dry density  $\rho_0 = 1096 \text{ kg/m}^3$ . The grain distribution curve of the soil samples is shown in Figure 5.

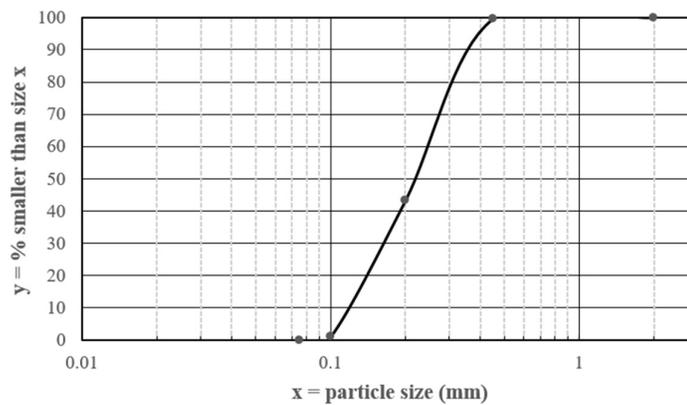


Figure 5. Grain distribution curve of soil samples.

Based on calculating the critical velocity of sand and the available wave height of wave flume, the experiment groups and working conditions are shown in Table 2.

Table 2. Test Conditions for Experiments.

| Group | Hydraulic Condition | Model  | Pile Diameter (m) | Water Depth (m) | Flow Velocity (m/s) | Wave Height (m) | Wave Period (s) |
|-------|---------------------|--------|-------------------|-----------------|---------------------|-----------------|-----------------|
| A1    | Steady current      | Column | 0.04              | 0.3             | 0.25                |                 |                 |
| A2    | Steady current      | Column | 0.04              | 0.4             | 0.225               |                 |                 |
| A3    | Steady current      | Column | 0.04              | 0.4             | 0.25                |                 |                 |

|    |                 |        |      |     |       |      |   |
|----|-----------------|--------|------|-----|-------|------|---|
| C1 | Waves & current | Column | 0.04 | 0.4 | 0.225 | 0.06 | 1 |
| C2 | Waves & current | Column | 0.04 | 0.4 | 0.225 | 0.08 | 1 |
| C3 | Waves & current | Column | 0.04 | 0.3 | 0.225 | 0.06 | 1 |

### 3.2. Experimental Results and Analysis

#### 3.2.1. Verification of Main Influencing Factors

During the experiment, the local scour depth on the model side was recorded with the help of scale pasted on the side of monopile model. Based on the observations in the experiment (Figures 6 and 7), it was found that the scour depth changed fast in the first 30 min during the process. With passage of time, the scour depth tended to be stable. After 2 h, there were no obvious changes of scour depth, which could be deemed as the equilibrium state. Under the six groups of test conditions, the equilibrium local scour depth was 4.1 cm, 3.5 cm, 3.7 cm, 4.0 cm and 3.5 cm. Therefore, it was found that when the water depth was the same (comparison between A2 and A3), the scour depth was increased with increased flow velocity; when the flow velocity was the same (comparison between A1 and A3), the scour depth was reduced with increased water depth but such influence was minor; when flow velocity was different (comparison between A1 and A2), the scour depth was increased with increased flow velocity and such influence was significant. Furthermore, waves may increase scour depth. When water depth and flow velocity were the same (comparison between C1 and C2), the scour formation also changed in addition to increased scour depth with increased wave height.



(a)



(b)



(c)



(d)

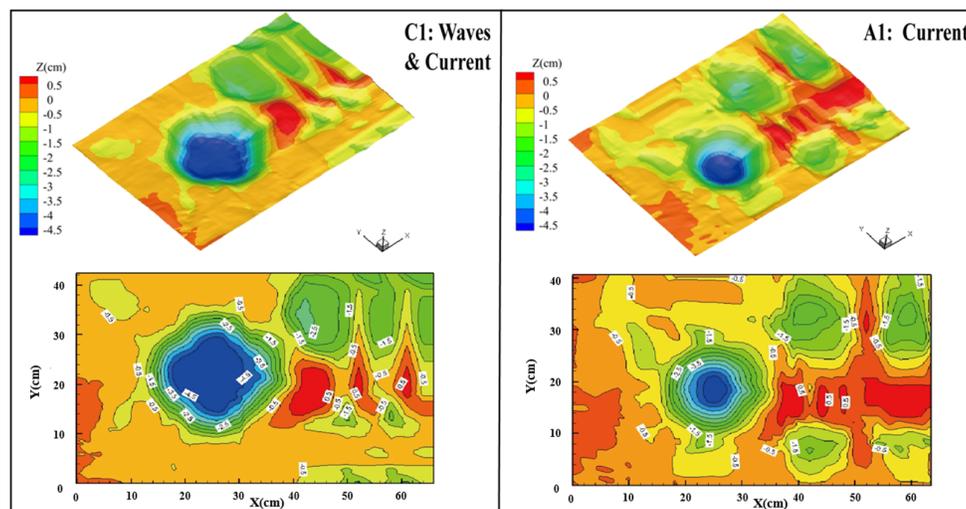


(e) (f)  
**Figure 6.** Pictures of scour holes and scour forms under steady current with flow velocity  $v = 0.25$  m/s (Run A1). (a) 0 s, (b) After 15 s, (c) After 1 min, (d) After 15 min, (e) After 1 h, (f) After 2 h.



**Figure 7.** Pictures of scour holes and scour forms under combined waves and current (Run C1). (a) After 15 min, (b) After 3 h.

Figure 8 gives 3D maps and contour maps of scour forms under different flow conditions. It shows that the differences near the scour hole between flow conditions, and the shape and trend of wake vortex scour area are obviously different. When the waves and current coexist, the sediment is normally picked up by the waves due to its higher capacity of lifting sands and transported by the current due to its higher capacity of carrying sands. Nevertheless, the effect of waves and current's coexistence is more than just a superimposition of their capacities of initiating and carrying sediment. When the combined current–wave flow encounters a monopile, the characteristics of the horseshoe vortex and lee-wake vortex around the pile can be very different. The foregoing experiments verify that flow velocity, water depth and wave height are the main factors that affect the local scour depth of monopile.



**Figure 8.** 3D maps and contour maps of scour forms under different flow conditions (after 3 h).

### 3.2.2. Verification of Local Scour Depth

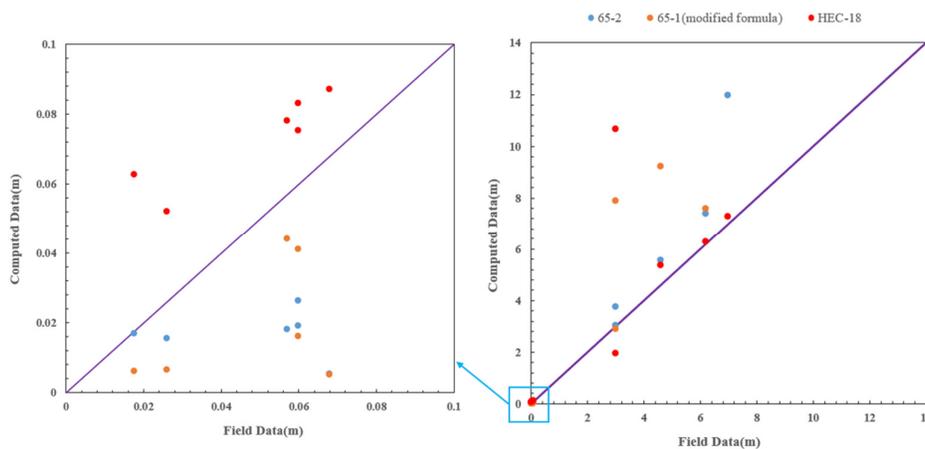
In order to evaluate the accuracy of local scour depth calculated with scour equation that proposed from the previous findings, the experimental conditions were substituted into the calculation formula and the results are shown in Table 3. Compared with the experimental measured data under steady current, the calculation results of HEC-18 formula are much higher than the field data, indicating excessively conservative calculation of local scour; the predicted values with Formula 65-2 and 65-1 (modified

formula) are generally smaller. For working conditions combined waves and current, the Sumer method is relatively reasonable; the calculation results of HEC-18 and Han Haiqian Formula are greater than the field data; the values with 65-2 formula, 65-1 modified formula and Wan Rukai Formula are relatively smaller.

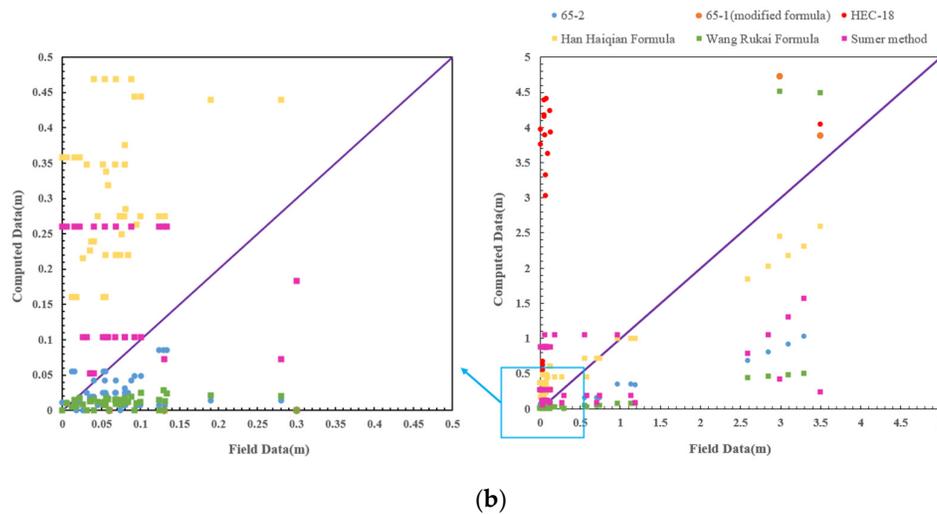
**Table 3.** Calculation results with different scour depth calculation formulas (cm).

| Group | Measured Depth | 65-2 Formula | 65-1 Modified Formula | HEC-18 | Han Haiqian Formula | Wang Rukai Formula | Sumer Method |
|-------|----------------|--------------|-----------------------|--------|---------------------|--------------------|--------------|
| A1    | 4.1            | 2.29         | 3.42                  | 56     | -                   | -                  | -            |
| A2    | 3.5            | 1.80         | 2.02                  | 62     | -                   | -                  | -            |
| A3    | 3.7            | 2.19         | 3.95                  | 70     | -                   | -                  | -            |
| C1    | 3.7            | 1.90         | 2.02                  | 54     | 24                  | 1.34               | 5.20         |
| C2    | 4.0            | 1.80         | 2.02                  | 62     | 24                  | 1.54               | 5.20         |
| C3    | 3.5            | 1.90         | 2.41                  | 67     | 23                  | 1.29               | 5.20         |

Since the experimental working conditions are relatively few, in order to further analyze and evaluate the accuracy of local scour depth predicted with each equation, another 35 laboratory and 20 field data [6,18,31–35] were selected for verification. Then, a scatter diagram was drawn with the computed data as the vertical coordinate and the field data as the horizontal ordinate (Figure 9). The diagonal lines indicate perfect agreement. Points that plot above these lines represent conservative estimates of scour depth. It can be learned from Figure 9 that for prediction of local scour depth at bridge piers, the prediction values of local scour with the 65-2 formula, 65-1 modified formula and HEC-18 formula were generally higher than the field data with satisfactory accuracy and adaptability. They can be well applied in engineering practice. Moreover, as to the calculation results in the experiments, there was also a phenomenon that the prediction results with HEC-18 formula were greater and that with Formula 65-2 and 65-1 (modified formula) were smaller. The reason may be that existing prediction models in specifications are mostly established based on observation data of actual cases and model experiments. Therefore, the formulas are strongly empirical and pertinent. When they are applied in predicting equilibrium scour depth of monopile in flume, large error may occur due to scale effect and ununified dimensions, etc.



(a)



**Figure 9.** Comparison between computed and observed scour depth. (a) Steady current, (b) Combined waves and current.

As to predication of local scour depth under combined waves with current, the mechanism of local scour is more complex with more influencing factors, resulting in great differences among the prediction formulas for equilibrium scour depth as recommended in specifications. Compared with the calculations in the experiments, the predication values with Wang Rukai formula and 65-2 formula were obviously smaller; and that with the HEC-18 formula, Han Haiqian formula and Sumer method were greater. As to actual calculation in engineering, the prediction results with all methods were smaller than the measured value.

#### 4. Prediction Equation in Combined Waves and Current

The equations above have made great contribution to the practice in their country, respectively; however, there are great differences among the calculated local scour depth under combined waves and current. In this section, based on the local scour experimental data and relevant field data, dimensional analysis was adopted to deduce a new combined waves and current-based equation. Furthermore, the statistical method was used to verify the reasonability and validity of the new prediction formula.

##### 4.1. Dimensional Analyses

In each specific water flow movement, there is certain relationship among the corresponding physical quantities which can be expressed with a physical equation. Dimensional analysis is a method that explores the relationship among physical quantities by the theory of dimensional homogeneity. Based on the experimental result, it can be believed that the local scour depth of monopile of offshore structures is mainly decided by pier width  $D$ , sediment size  $d_{50}$ , flow velocity  $v$ , water depth  $h$ , wave height  $H_w$  and wave length  $L_w$ . The relationship can be stated as following (Equation (4)):

$$h_b = f(D, d_{50}, v, h, H_w, L_w) \quad (4)$$

According to theorem,  $h$ ,  $D$  and  $v$  are selected as the base quantity to indicate other variables. Furthermore, based on the theory of dimensional homogeneity, the above formula can be re-written into Equation (5):

$$\frac{h_b}{h} = f\left(\frac{v^2}{gh}, \frac{d_{50}}{h}, \frac{H_w}{D}, \frac{L_w}{D}\right) \quad (5)$$

When only the main influencing factors of local scour depth under wave-current action are taken into account, the maximum pier scour depth can be expressed in product form as Equation (6):

$$\frac{h_b}{h} = a_0 \left( \frac{v^2}{gh} \right)^{a_1} \left( \frac{d_{50}}{h} \right)^{a_2} \left( \frac{H_w}{D} \right)^{a_3} \left( \frac{L_w}{D} \right)^{a_4} \quad (6)$$

where  $a_0$ ,  $a_1$ ,  $a_2$ ,  $a_3$  and  $a_4$  are undetermined parameters. Through fitting of experimental data, the parameters with scour depth predication formula are 1.318, 0.624,  $-0.282$ ,  $-0.288$  and  $-0.757$ , respectively. Therefore, the formula for local scour depth under combined waves and current is finally organized as:

$$\frac{h_b}{h} = 1.318 \left( \frac{v^2}{gh} \right)^{0.624} \left( \frac{d_{50}}{h} \right)^{-0.282} \left( \frac{H_w}{D} \right)^{-0.288} \left( \frac{L_w}{D} \right)^{-0.757} \quad (7)$$

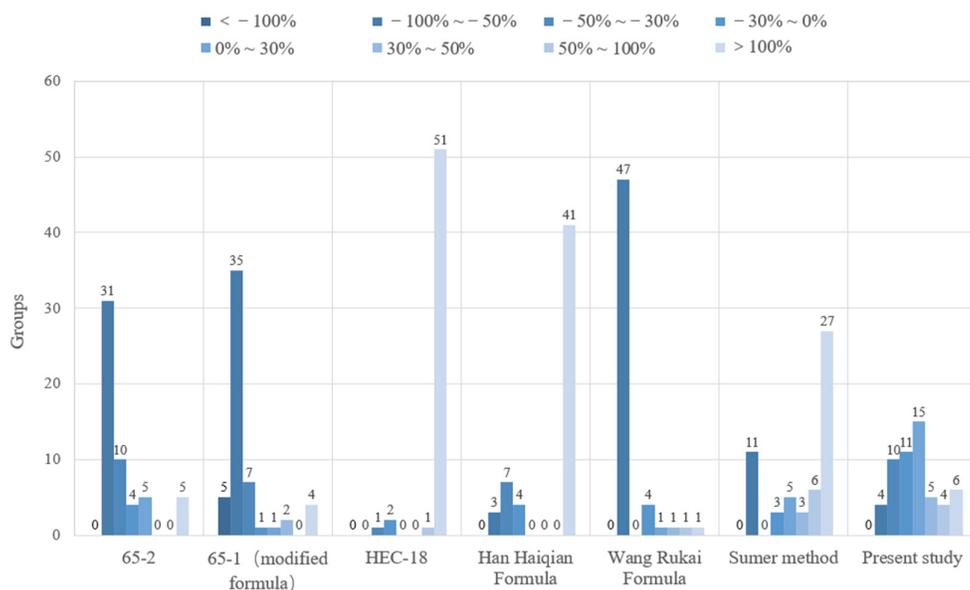
#### 4.2. Verification of New Predication Formula

In this part, in order to give a quantitative description of applicability of local scour prediction formula, the relative error  $\varepsilon_r$  (Equation (8)) and average absolute relative error  $\varepsilon_a$  (Equation (9)) are selected as two indexes to measure the accuracy. The equations for the statistical analysis are shown below:

$$\varepsilon_r = \frac{h_{\text{computed}} - h_{\text{measured}}}{h_{\text{measured}}} \times 100\% \quad (8)$$

$$\varepsilon_a = \frac{1}{n} \sum_{i=1}^n \left| \frac{h_{\text{computed}} - h_{\text{measured}}}{h_{\text{measured}}} \right| \times 100\% \quad (9)$$

The calculated relative error of different local scour depth prediction equations is shown in Figure 10. It is found that the calculation results are divided into eight regions: less than  $-100\%$ ,  $-100\sim-50\%$ ,  $-50\sim-30\%$ ,  $-30\sim0\%$ ,  $0\sim30\%$ ,  $30\sim50\%$ ,  $50\sim100\%$  and more than  $100\%$ . The relative error with Formula 65-2, 65-1 (modified formula) and Wang Rukai formula is mainly concentrated between  $-50\sim-30\%$ . This indicates that the predicted values of these models are relatively smaller but also with less deviation from actual results. When this formula is adopted in engineering practice, the predicted local scour depth of pier base may be increased appropriately. The relative error with HEC-18, Han Haiqian Formula and Sumer method is generally greater than  $100\%$ , which may result in excessive estimation of scour depth and cause unnecessary waste in terms of base construction costs. The mean absolute relative error is based on the 55 working conditions. Upon calculation, the mean relative error with Formula 65-2, 65-1 (modified formula), HEC-18, Han Haiqian Formula, Wang Rukai Formula, Sumer method and the new prediction method proposed herein are  $74.7\%$ ,  $82.5\%$ ,  $966.5\%$ ,  $490.1\%$ ,  $76.8\%$ ,  $425.9\%$  and  $49.1\%$ , respectively, which means the present prediction formula will be apparently better than other formulas.



**Figure 10.** Comparison between equations with the relative error.

#### 4.3. Discussions

A series of experiments and field data have been analyzed in the present paper to quantify the accuracy of different equations about the equilibrium scour depth around the monopile. It has been shown that as to predication of local scour depth under combined waves with current, the existing design methods all cannot perform perfectly. Formula 65-2 and Formula 65-1 (modified formula) which are usually used in bridge piers evidently underestimate the scour depth That is probably because they were based on field and experiment data of bridge piers and the influence of waves was not taken into account with these two methods. Moreover, Equation HEC-18 frequently overestimates, and previous studies have shown that HEC-18 sometimes cannot predict the equilibrium scour depths well, and overestimations relatively frequently [4,36]. This may be due to little consideration about sediment size and modified roughly by parameter coefficient. The Han Haiqian formula was developed to estimate the maximum scour depth at sea/bay-crossing bridges under the condition of tidal currents. It also ignored the influence of waves on the local scour depth. The Wang Rukai formula significantly underestimates the scour depth in some instances, while the Sumer method frequently overestimates. Although wave elements are taken into account with Wang Rukai formula, it requires more parameters than other methods, which means it may be not convenient when used at the design stage. The calculation process of Sumer method is simple but the important parameter of KC number is hard to measure accurately in actual engineering. This method purposed that no horseshoe vortex develops for  $KC < 6$  in waves alone, however, previous studies [6] and a lot of experiments have shown that the scour depth due to waves combined with strong currents varies significantly [37]. Therefore, it also cannot effectively predict the maximum equilibrium scour depths in engineering design.

It should be noted that there are some new formulas have been proposed for estimating the equilibrium scour depth at the condition of tidal currents and combined waves and current. For example, Han et al. [38] developed a new formula to estimate the maximum scour depth at sea/bay-crossing bridges with multiple piles under the action of tidal currents, and Dai et al. [39] proposed a calculation model of the equilibrium scour depth under combined waves and currents which is based on the energy balance concept and considering the changing flow field around the monopile. However, few formulas have been developed to assess the maximum scour depth accurately in all instances at the

condition of combined waves and current. Compared with the above design models, our proposed formula generally predicted more reasonable scour depths. Note that our proposed formula takes the characteristics of wave flow, riverbed sediment grain size and pile dimension into account. In particular, for  $2 < KC < 10$  and scour depths due to waves combined with strong currents, the new formula may predict more reasonable than the proposed methods. Moreover, we carried out a more in-depth analysis of some instances that the new method significantly underestimates or overestimates. We found that when the sediment particle size was smaller than 0.05 mm, the calculated relative error was large.

## 5. Conclusions

In this study, a series of flume tests under current condition and wave–current combined condition were carried out. Based on these laboratory and field equilibrium local scour data, several design models from China, the United States and Norway were selected to verify the accuracy either under steady clear water conditions and combined waves and current conditions. The following conclusions can be drawn based on this study:

- (1) For the prediction of the local scour depth of bridge piers, Formula 65-2, 65-1 (modified formula) and HEC-18 equation have similar computed results, and the Formula 65-2 is the most stable and reliable.
- (2) The local scour depth around monopile foundation in combined waves and current is important in the field of coastal and offshore engineering, but it has not been sufficiently studied. The design methods above cannot assess the maximum scour depth accurately in all instances. The Han Haiqian formula focuses on estimating the maximum local scour depth at foundation of sea/bay-crossing bridges in tidal currents. The Wang Rukai formula takes waves into account, but this equation requires more parameters than other methods, which means it may be not convenient when used at the design stage. The Sumer method has a simple calculation process, but it may underestimate the scour depth due to waves combined with strong currents. The mean relative errors of Formula 65-2, 65-1 (modified formula), HEC-18, Han Haiqian Formula, Wang Rukai Formula and Sumer method proposed herein are 74.7%, 82.5%, 966.5%, 490.1%, 76.8% and 425.9%, respectively.
- (3) Considering to the principle of dimensional analysis, experimental phenomena, and the main influencing factors of the local scour depth of a monopile, a new equation for predicting the equilibrium scour depth of a monopile under the action of combined waves and current is proposed. The mean relative error between the predicted value of the formula and the measured value in this paper is 49.1%, which is significantly smaller than other formulas.

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