LABORATORY EXPERIMENTS FOR WAVE RUN-UP ON THE TETRAPOD ARMOURD RUBBLE MOUND STRUCTURE WITH A STEEP FRONT SLOPE

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ABSTRACT

Two-dimensional laboratory experiments were conducted by changing the random wave conditions and structure configurations to develop a formula to predict run-up level on the tetrapod armourd rubble mound structure. The incident waves in the experiments included non-breaking, breaking, and broken wave conditions at the toe of the structure. In this study, a steep front slope (1:1.5) was set up to suggest the wave run-up formula while most of the previous studies focused on the milder sloped structures. The experimental results were compared to the previous research by van de Meer and Stam (1992). The results showed that the relative run-up height (the ratio of the run-up height to the significant wave height at the toe) converged as the incident wave steepness increased. On the other hand, the relative run-up height was highly dependent of the relative wave height (the ratio of the significant wave height to the water depth at the toe) as the incident wave steepness decreased. Then, the empirical formula for relative run-up height as a function of surf similarity parameter was suggested and the coefficients were determined. The formula and coefficients suggested by this study can be useful to design a rubble mound structure.

KEYWORDS: Wave run-up, Tetrapod, Rubble mound structure, Laboratory experiments, Steep front slope

1 INTRODUCTION

Wave run-up is one of the most important factors in the context of design for the coastal and harbour structures to determine the height of crown or parapet. The wave run-up heights are higher on rubble mound breakwaters than those on vertical breakwaters because the incident waves climb up on the front slope of the structure. Therefore, the wave run-up height is an important factor in determining the height of crown and parapet on the breakwater to prevent the wave overtopping induced by the wave run-up. Researchers (Ahren, 1979; Mase, 1989; van der Meer and Stam, 1992; Coastal Engineering Manual, 2005) conducted the experiments of wave run-up on the rubble mound structures and suggested empirical formulas of the wave run-up height as a function of the surf similarity parameter. However, most of the studies were performed in the case of the rubble mound structures covered with rocks. On the other hand, the present study focused on developing an empirical formula of the wave run-up on the structure armoured by tetrapods on a steeper front slope that is commonly used in the East Asia including Korea and Japan. Two-dimensional laboratory tests were conducted under the different random wave conditions and structure configurations to develop a formula to predict run-up level. Then, an empirical formula and equivalent coefficients according to the wave conditions and water depths were suggested through the experimental results. The results were also compared to the previous studies by van der Meer and Stam (1992).

2 LABORATORY EXPERIMENTS

The experiments were performed in the large wave flume in the Experimental Center for Coastal & Harbor Engineering, Chonnam National University, Korea. The flume size is 100m long, 2m wide and 3m deep and a piston-type wave generator for both regular and irregular waves is installed in the flume. As shown in Figure 1, a 1:25 scaled model structure was installed on the top of the 1:50 sloped bottom. Capacitance-type wave gages were installed along the flume to separate the incident
wave information from the measured water surface elevations. Three run-up gages were installed paralleled to the front slope at the center section of the flume and 50cm from the center section to both sides of the flume wall. The water surface elevations were collected by the wave gages with the sampling rate of 50 Hz. The rubble mound structure was covered with tetrapod armour blocks (nominal length, \( D_e = V^{1/3} \approx 9.28 \text{ cm} \)) on 1:1.5 front slope (\( \cot \beta \)) and two layers of tetrapods (thickness, \( A_T = 19.2 \text{ cm} \)) were armoured on the single layer of tripods. Tripods were used as an underlayer between the tetrapod layer and rubble-mound. 56 different irregular wave conditions were used in the experiments to consider the various wave shapes (non-breaking, breaking and broken waves) at the toe of the structure. The target incident wave periods \( (T_s, o) \) varied from 1.5s to 3.6s with the increment \( (\Delta T_s, o) \) of 0.3s and the significant wave heights \( (H_s, o) \) ranged from 12.0cm to 36cm with the increment \( (\Delta H_s, o) \) of 4cm. Series of random waves based on the Bretschneider-Mitsuyasu spectrum were generated under the different wave conditions. The 1/50 slope induced non-breaking, breaking, broken wave dominant conditions at the toe of the structure. Total 1000 waves were used to analyze the statistical characteristics of the wave run-up heights \( (R_u, max, R_u, 1\%, R_u, 2\%, R_u, 5\%, R_u, 10\%, R_u, 33\% \text{, and } R_u, \text{mean}) \). Four different water depths at the toe \( (d_t = 40, 55, 70, \text{ and } 85\text{cm}) \) were considered so that total 224 different cases were used in the experiments. The relative water depths at the toe (the ratio of the significant wave height to water depth at the toe, \( (H_s/d_t) \)) ranged from 0.17 to 0.53.

![Figure 1. A cross-sectional view of the experimental setup.](image)

### 3 RESULTS AND DISCUSSION

van der Meer and Stam (1992) suggested the empirical formulas of the wave run-up heights based on the porosity \( (P) \) of the rubble mound. Because there was no exact same condition as this study in the results from van der Meer and Stam (1992), we selected the formulas in the cases of \( P = 0.1 \) (nearly impermeable, Equation (1)) and \( P = 0.5 \) (armoured by rocks, Equation (2)) to compare the results in this study.

\[
\begin{align*}
R_{u,1\%}/H_s &= A\xi_{0m} \quad \text{for } \xi_{0m} \leq 1.5 \\
R_{u,5\%}/H_s &= B\xi_{0m}^c \quad \text{for } \xi_{0m} \geq 1.5 \\
\end{align*}
\]

\[\begin{align*}
R_{u,1\%}/H_s &= A\xi_{0m} \quad \text{for } 1.0 < \xi_{0m} \leq 1.5 \\
R_{u,5\%}/H_s &= B\xi_{0m}^c \quad \text{for } 1.5 < \xi_{0m} \leq (D/B)^{1/c} \\
&= D \quad \text{for } (D/B)^{1/c} \leq \xi_{0m} \leq 7.5
\end{align*}\]

\[
\xi_{0m} = \tan\beta / \sqrt{s_{0m}}
\]

\[s_{0m} = H_s / L_{0m}\]

where, \( R_{u,1\%} \) is the averaged value of the wave run-up that exceeds \( 1\% \), \( H_s \) is the significant wave height at the toe of the structure, and \( \xi_{0m} \) represents the surf similarity parameter. A, B, C, and D are equivalent coefficients that are determined by the experiments. In Equation (3), \( s_{0m} \) and \( L_{0m} \) represent the wave steepness and the wave length respectively. In this study, \( \xi_{0m} \) and \( s_{0m} \) were replaced with \( \xi_0 \) and \( s_0 \) respectively because we used the significant wave period to calculate the characteristic wave.
Figure 2 shows the relative wave run-up heights \((R_{u,i}/H_s)\) as a function of the surf similarity parameter. The solid lines and dotted lines represent the fitted lines by equations (1) and (2) respectively. In this figure, the relative wave run-up heights became widely distributed in all cases as the surf similarity parameter increased other than the results from van der Meer and Stam (1992). While van der Meer and Stam (1992) mostly conducted the experiments under the non-breaking wave dominant conditions on the constant water depth, this study considered non-breaking, breaking, and broken wave dominant wave cases over a sloping beach. Therefore, it is not relevant to suggest a single formula for the wave run-up height prediction even if the equation in the case of \(P=0.1\) from the study of van der Meer is relatively close to the results in this study. This result may be affected by the porosity of tripod (23\%) that covered rubble mound under the tetrapod layers.

Figure 2. Relative wave run-up heights as a function of surf similarity parameter. (open circles: experimental results; solid lines: fitted lines from the Equation (1); dotted lines: fitted lines from the Equation (2))
Figure 3. Relative wave run-up heights as a function of surf similarity parameter under the criteria divided by the relative wave he. (symbols: experimental results; lines: fitted lines from the Equation (4)).
Figure 3 shows the relative wave run-up heights as a function of the surf similarity parameter divided by different relative wave heights ($H/d$). Over all, with the same surf similarity parameter, the results showed that the relative wave run-up height increased as the wave steepness increased. This result is consistent with the result of Ahren (1979) in the mound slope of 1:1.5 and inconsistent with the result of Mase (1990). Since Mase (1990) conducted the experiments on the front slope of 1:5-1:30, the broken waves with the larger wave steepness on the milder slope might not induce the larger wave run-up height. However, because the front slope is steeper, the wave run-up heights were larger compared to the results of Mase (1990) under the similar conditions of the wave steepness. In this study, we suggest an empirical formula the relative wave run-up height on the tetrapod armoured rubble mound breakwater with the front slope of 1:1.5 and the underlayer porosity of 23% as shown in Equation (4). The lines in Figure 3 show the fitted lines of the relative run-up heights based on the Equation (4).

$$ R_{u,\%}/(H_s)_{toe} = A_{50s}^B $$

Figure 3 also shows that the correlations of the fitted lines are lowest in the case of the maximum wave run-up heights (Figure 3(a)) and the correlations seem to increase in other figures. Table 1 shows the coefficients of the fitted line for the relative wave heights in the range of the relative wave heights and the surf similarity parameters.

<table>
<thead>
<tr>
<th>$R_{u,%}/(H_s)_{toe}$</th>
<th>(H/d)$_1$ = 0.45-0.56</th>
<th>(H/d)$_1$ = 0.36-0.45</th>
<th>(H/d)$_1$ = 0.27-0.36</th>
<th>(H/d)$_1$ = 0.14-0.27</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.5 ≤ ξ$_{toe}$ ≤ 6.5</td>
<td>2.5 ≤ ξ$_{toe}$ ≤ 7.0</td>
<td>2.5 ≤ ξ$_{toe}$ ≤ 8.0</td>
<td>2.5 ≤ ξ$_{toe}$ ≤ 8.0</td>
</tr>
<tr>
<td>Max</td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>10.9</td>
<td>0.75</td>
<td>1.19</td>
<td>0.64</td>
<td>1.13</td>
</tr>
<tr>
<td>1%</td>
<td>0.99</td>
<td>0.75</td>
<td>1.07</td>
<td>0.64</td>
</tr>
<tr>
<td>2%</td>
<td>0.95</td>
<td>0.75</td>
<td>1.02</td>
<td>0.64</td>
</tr>
<tr>
<td>5%</td>
<td>0.89</td>
<td>0.75</td>
<td>1.02</td>
<td>0.64</td>
</tr>
<tr>
<td>10%</td>
<td>0.83</td>
<td>0.75</td>
<td>0.85</td>
<td>0.64</td>
</tr>
<tr>
<td>33%</td>
<td>0.73</td>
<td>0.71</td>
<td>0.74</td>
<td>0.58</td>
</tr>
<tr>
<td>mean</td>
<td>0.52</td>
<td>0.51</td>
<td>0.46</td>
<td>0.45</td>
</tr>
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</table>

CONCLUSIONS

In this study, two-dimensional laboratory experiments were conducted to investigate the wave run-up on the tetrapod armoured rubble mound structure with the steep front slope, which is commonly used as a breakwater in the East-Asian countries. Then, an empirical formula for the relative wave run-up heights as a function of surf similarity parameter by considering non-breaking, breaking, and broken wave dominant conditions. The results from this study can be summarized as following:

- The results in this study showed that relative wave run-up heights were widely distributed compared to the results from van der Meer and Stam (1992). This may be because the more various incident wave conditions were used in this study such as non-breaking, breaking, and broken wave dominant conditions on the steep front slope while the results from van der Meer and Stam (1992) were focused on the relatively smaller wave steepness and milder front slope.
- When the incident wave steepness’s were large, the relative wave run-up heights tended to converge, which is similar results to the previous studies. However, when the incident wave steepness’s were small, the relative wave run-up heights were affected by the relative wave heights. Therefore, we suggested an empirical formula and its equivalent coefficients of the relative wave run-up heights under the different relative wave heights.

The empirical formula and its coefficients obtained from this study is valid for the tetrapod armoured rubble mound breakwater with 1:1.5 slope and expected to be used for the breakwater design such as the heights of the crown and parapet. This formula proposed here may be applicable in the range of the surf similarity of 2 to 8. The experiments will be continued by changing the front slope to suggest robust formula for the wave run-up to contribute for the effective design of steeply sloped rubble mound breakwater including crown or parapet.
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REFERENCES


