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DISPERSION OF WAVE FORCES ON CAISSON BREAKWATERS USING INTERLOCKING SYSTEMS

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Interlocking caisson-type breakwaters have recently gained attention for enhancing the stability of the conventional breakwaters. In this study, the dispersion characteristics of wave forces using interlocking systems connecting the upper part of caissons with cables in the normal direction of breakwaters were investigated. Based upon numerical experiments, the higher wave forces are transmitted through the cable as the angle of incident wave increases, while the maximum allowable wave force was capable of being increased by sharing the wave forces with the adjacent caissons. It was also found that the larger the stiffness of the interlocking cable, the larger the wave-dispersion effect.

Keywords: Breakwater, Interlocking, Unusual wave, Force dispersion, Numerical analysis.

1 INTRODUCTION

As climates continue to warm, it important to respond effectively to unusual extreme waves generated by strong typhoons, because the waves can destroy breakwaters and cause severe coastal erosion (Allan and Komar, 2002). In August 2012, Typhoon Bolaven generated waves 11.3 m high in deep water off the Korean Peninsula (KHOA 2012). In shallower water near Jeju Island, the maximum wave height was 11.8 m, and the duration of waves exceeding 50-year return-period wave of 9.3 m was estimated at 14 hours (KHOA 2012). Due to the unusual waves, the breakwater of Seogwipo Harbor in Jeju Island was severely damaged, bringing forth proposals for the reinforcement of existing breakwaters in Korea.

From decades ago, it was reported that the maximum wave force acting on a breakwater caisson can be reduced by adopting a long caisson structure (Battjes, 1982; Takahashi and Shimosako, 1990; Burcharth and Liu, 1998). The reason for the decrease is the phase difference among wave pressures acting on the caisson surface caused by the directionality of the incident wave. This study investigated the possibility for increasing stability through by simply combining adjacent caissons. Using a caisson breakwater composed of 10 caissons, numerical experiments were carried out for major design parameters, i.e., stiffness of connecting cables and wave attack angle. The caisson was assumed to be a rigid body, the foundation replaced by springs attached to the caisson in the horizontal and vertical directions, and the connecting cables modelled as springs. The wave force acting on the caisson was calculated by using Goda's pressure formula and standing wave solution to consider phase differences.

2 MATHEMATICAL MODEL

A regular wave train of amplitude, A, and angular frequency, ω, propagating over the constant seabed of water depth, h, and toward a caisson breakwater with angle of attack, ψ, was considered. A Cartesian coordinate system (x, y, z) was adopted, with x measured in the direction of wave propagation, y in the longitudinal direction of the breakwater, and z vertically upwards from the still-water level. A caisson breakwater consists of n caissons with height H_C, width B_C in x-direction and W_C in y-direction, which are interlocked each other by cables as shown in Figure 1.

2.1 Static Equilibrium Equation

Assuming rigid caissons, elastic behaviors of the foundation and connecting cables, and small displacements of the caisson, the static equilibrium equation of the i-th caisson in Figure 2 can be expressed as:

$$2k_H^I k_H^S \xi_i - 2k_H^I H_C \theta_i - k_H^I (\xi_{i-1} + \xi_{i+1} - H_C \theta_{i-1} - H_C \theta_{i+1}) = F_H^W \tag{1}$$

$$k_V^S B_C \zeta_i + k_V^S \frac{B_C^{\ 2}}{2} \theta_i = -W + F_V^W \tag{2}$$

$$2k_H^I H_C \xi_i - k_V^S \frac{B_C^{\ 2}}{2} \zeta_i - \left(2k_H^I H_C^{\ 2} + k_V^S \frac{B_C^{\ 3}}{3} \right) \theta_i - k_H^I H_C (\xi_{i-1} + \xi_{i+1} - H_C \theta_{i-1} - H_C \theta_{i+1}) = -F_H^W d + Wb - F_V^W l \tag{3}$$

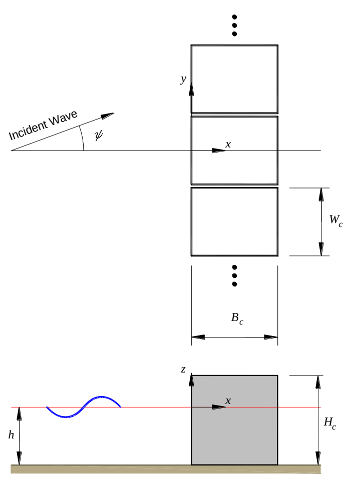


Figure 1. Definition sketch.

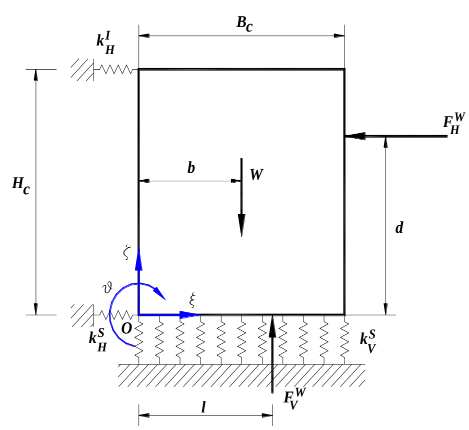


Figure 2. Definition sketch.

in which ξ_i, ζ_i = displacements of the i-th caisson in x and z-direction, respectively; θ_i = rotational angle of the i-th caisson along y-axis; k_H^S, k_V^S = stiffness coefficients of foundation springs in the horizontal and vertical directions, respectively; k_H^I = stiffness coefficient of the spring representing connecting cable; F_H^W, F_V^W = wave forces acting on the caisson in the horizontal and vertical directions, respectively; W = effective weight of the caisson. For the convenience of formulation, the spring constants for each caisson are assumed to be same as each other. Using linear half-space theory, the stiffness coefficients of foundation springs can be obtained as (Newmark and Rosenblueth, 1971):

$$k_H^S = \frac{E_s\sqrt{B_C W_C}}{1-\nu^2} k_T\,;\; k_V^S = \frac{E_s\sqrt{W_C / B_C}}{1-\nu^2} c_s \tag{4}$$

in which, E_s = Young's modulus of the foundation; ν = Poisson's ratio of the foundation; k_T and c_s are tabulated in Table 1.

Table 1. Coefficient, k_T and c_s .

Aspect ratio	c_s	k_T				
		ν =0.1	0.2	0.3	0.4	0.5
1.0	1.06	1.00	0.938	0.868	0.792	0.704
1.5	1.07	1.01	0.942	0.864	0.770	0.692
2.0	1.09	1.02	0.945	0.870	0.784	0.686
3.0	1.13	1.05	0.975	0.906	0.806	0.700
5.0	1.22	1.15	1.050	0.950	0.850	0.732
10.0	1.41	1.25	1.160	1.040	0.940	0.940

The stiffness coefficient of the connecting cable can be expressed as:

$$k_H^I = E_c A_c / L_c \tag{5}$$

in which E_c, A_c, L_c = Young's modulus, cross-sectional area, and length of the cable, respectively.

2.2 Wave Forces Acting on the Caisson

The wave forces acting on the caisson, F_H^W, F_V^W , may be evaluated by integration of hydrodynamic pressure on the caisson surface, which as given by Goda's pressure formula (Goda 2010) considers the phase lag as:

$$F_H^W = F_H^G \times \delta;\; F_V^W = F_V^G \times \delta \tag{6}$$

$$\delta = \frac{2\sin\left(k_y W_C / 2\right)}{k_y} \cos(\omega t + k_y y_0 - \pi) \tag{7}$$

in which, F_H^G, F_V^G = wave forces per unit width in horizontal and vertical directions when the incident wave attack normal to the breakwater, i.e., $\psi = 0^\circ$; $k_y = k\sin\psi$; $y_0 = y$ coordinate of the caisson center.

3 NUMERICAL ANALYSIS AND DISCUSSION

3.1 Caisson Breakwater for Experiments

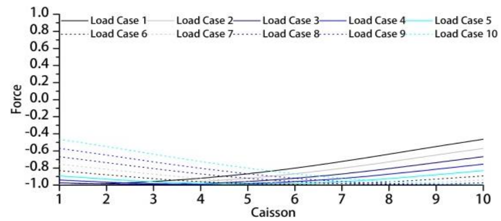
To investigate the possibility for increasing the stability through combining adjacent caissons, a caisson breakwater was designed, consisting of 10 caissons with $20\,\mathrm{m}(B_C)\times 20\,\mathrm{m}(W_C)\times 20\mathrm{m}(H_C)$. The depth of water was assumed to be 15 m, and the design significant waves of 50-year return period was set at 15s and 9 m. Effective weight of caisson W was determined by using the safety factor of 1.2 for sliding.

3.2 Results and Discussion

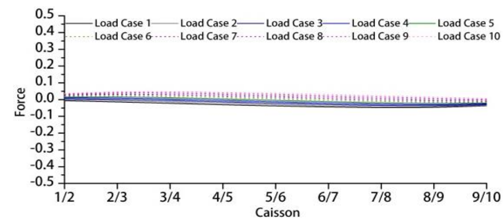
For numerical experiments, 3 angles of incident wave attack, 3 stiffness coefficients of connecting cable, and 10 load cases were considered. The i -th load case denotes that the maximum load is applied to the i -th caisson. Using these various experimental cases, numerical experiments were carried out, and the results were analyzed, especially for transmitting forces to the foundation and tensile forces in cables In Figure 3 and 4, both forces scaled by maximum wave force acing on each caisson were presented with respect to 10 load cases. The results indicate that the dispersion effect increases as the angle of incidence increases ((a)~(c)), and as the stiffness of the connecting cable increases ((c)~(e)). Dispersion degrees are 0.6~2.0% of maximum wave force for $\psi = 10^\circ$, 2.3~6.9% for $\psi = 20^\circ$, and 4.6~12.8% for $\psi = 30^\circ$. If the applied load increases up to design load (for example 100 years and 200 years return period loads), the effect should increase, because the transmitting forces for certain caissons will be limited as the capacity of frictional resistance. Figure 4 shows the variations of tensile forces in connecting cables. The results indicate that tensile force increases as the angle of incidence increases ((a)~(c)), and as the stiffness of the connecting cable increases ((c)~(e)). It is interested that the maximum tensile force occurs near not maximum but minimum wave forces acting on the caisson (see Figure 3.). In other word, as the gradient of the load distribution increases, the tensile force in the cable increases. Theoretically, the tensile force is proportional to the difference horizontal displacements between adjacent two caissons. So, it is expected that the bigger differences of the foundation stiffness and frictional resistance capacity between adjacent two caissons, the tensile forces will become large.

4 CONCLUSION

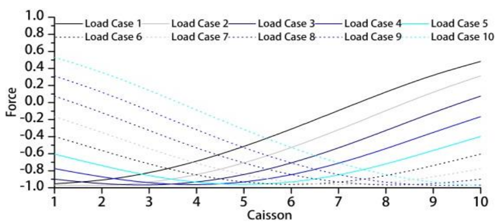
In this study, it was investigated the possibility for increasing the stability through combining adjacent caissons simply. Using a caisson breakwater composed of 10 interlocked caissons by cables, numerical experiments were carried out for major design parameters, i.e., stiffness of connecting cables and wave attack angle. The results indicate that the dispersion effect increases as the angle of incidence increases, and as the stiffness of the connecting cable increases. The tensile force in the connecting cable increases also with increase of dispersion effect. To conclude, it is reasonable to enhance the stability of the caisson breakwater stability through connecting adjacent caissons by cables. To use the method *in situ*, nonlinear dynamic analysis is required for unusual extreme wave conditions exceeding design wave conditions. In future research, the analysis will be performed with hydraulic model tests. It is expected that the dispersion effect will increase significantly, because the load exceeding limit capacity of frictional resistance will be transmitted to adjacent caissons.



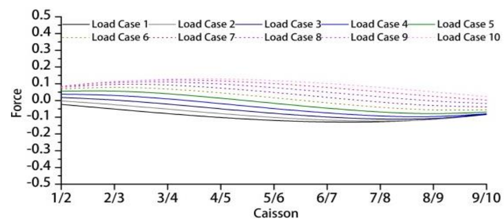
(a) $\psi = 10^{\circ}$, $k_H^I / k_H^S = 0.1$



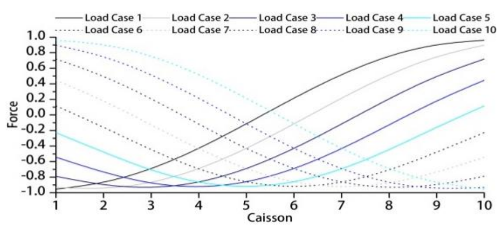
(a) $\psi = 10^{\circ}$, $k_H^I / k_H^S = 0.1$



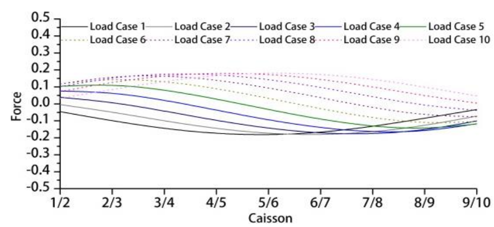
(b) $\psi = 20^{\circ}$, $k_H^I / k_H^S = 0.1$



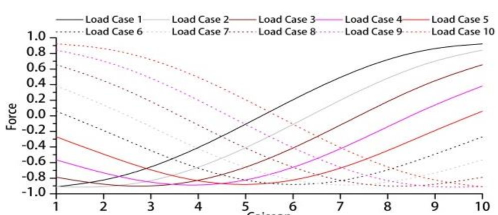
(b) $\psi = 20^{\circ}$, $k_H^I / k_H^S = 0.1$



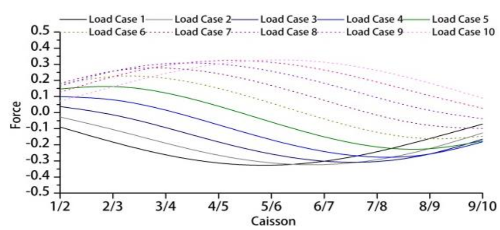
(c) $\psi = 30^{\circ}$, $k_H^I / k_H^S = 0.1$



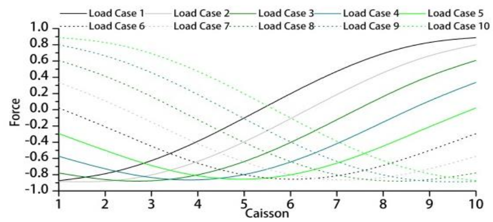
(c) $\psi = 30^{\circ}$, $k_H^I / k_H^S = 0.1$



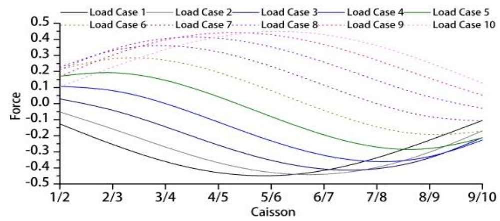
(d) $\psi = 30^{\circ}$, $k_H^I / k_H^S = 0.2$



(d) $\psi = 30^{\circ}$, $k_H^I / k_H^S = 0.2$



(e) $\psi = 30^{\circ}$, $k_H^I / k_H^S = 0.3$



(e) $\psi = 30^{\circ}$, $k_H^I / k_H^S = 0.3$

Figure 3. Variations of transmitting forces.

Figure 4. Variations of cable tensions.

Acknowledgments

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