Proceedings of the 6th International Conference on the Application of Physical Modelling in Coastal and Port Engineering and Science (Coastlab16)

Ottawa, Canada, May 10-13, 2016

HYDRAULIC EXPERIMENT FOR STABILITY OF CHI BLOCKS

TAEK SANG KIM[1], YOUNG HYUN PARK[2], KYUNG-DUCK SUH[3]

1 Seoul National University, Republic of Korea, stozy@snu.ac.kr

2 Korea Institute of Ocean Science and Technology, Republic of Korea, yhpark@kiost.ac.kr

3 Seoul National University, Republic of Korea, kdsuh@snu.ac.kr

ABSTRACT

The Chi blocks (Chi block 1, 2, and 3) are new armor units developed by KIOST to reduce the intensity of wave energy. In this study, uniform placement in single layer is proposed for Chi blocks and the corresponding stability coefficients are determined. 3-point separation technique is used to separate incident significant wave height and reflected significant wave height. Hudson formula is used to calculate the stability coefficient with the incident signnificant wave height. In order to determine the most economical block between Chi blocks, the void ratio is calculated. Chi block 2 is the most stable block because its stability coefficient is the highest value and Chi block 1 is the most economical block because its void raio is the highest void ratiovalue. The stability coefficient of Chi block for uniformly x-shape placement method is compared with Because the stability coefficients of all Chi blocks are bigger than stability coefficient of Tetrapod, which is used frequently in Korea, Chi blocks are suitable blocks to withstand the abnormally high waves in Korea.that of Chi block for other placement method. In addition, the stability coefficient of Chi block is compared with those of other armor units such as Accropode, Core-loc, and X-bloc (single-layer), and Tetrapod and Dolos (two-layer).

KEYWORDS: new armor unit, Chi block, stability coefficient, Hudson formula, x-shape placement method

1 INTRODUCTION

A rubble mound breakwater is constructed by placing armor units on a sloping rubble mound structure such that waves are broken to lose their energy on the structure slope. Numerous armor units of different shapes have been developed, but effort is still made to develop a new armor unit that is more stable and economical. Especially, the appearance of abnormally high waves probably due to the recent climate change necessitates more stable armor units. For example, about 2,000 Tetrapods were damaged at the east breakwater of the Seogwipo Port in Korea due to the high waves during the typhoon "Bolaven" in 2012, and the Korea Institute of Ocean Science and Technology (KIOST) performed a study to develop new armor units which can withstand abnormally high waves.

This paper describes the hydraulic experiment to compare the stability of three different types of Chi block, which was developed during the study. In order to generate the irregular wave in the laboratory, 100 regular waves with different periods are superimposed. The spectrum amendment are made until the measured spectrum became very close to the target spectrum and final amended spectrum is obtained. To separate incident and reflected significant wave height, 3-point separation technique (Suh *et al*., 2001) is used. The incident significant wave height is increased gradually until the damage of Chi blocks is observed. The stability coefficient is calculated by using the Hudson formula with significant wave height that initiates damage.void ratio

2 NEW ARMOR UNIT: CHI BLOCK

The new armor units, named Chi blocks, are based on interlocking between blocks. The characteristics of the three Chi blocks are given in Table 1. The blocks were manufactured to the scale of 1:65.The thickness of model Chi blocks is 45 mm. To account for the density difference between sea water and fresh water, the specific gravity of the block of 2.23 was used in the experiment. The shape of the blocks is similar to the alphabet X. Chi block 1 is the basic shape and Chi block 2 has shorter legs than Chi block 1, whereas Chi block 3 has thinner legs than Chi block 1. The shapes of the three Chi blocks are shown in Figure 1. Single layer placement is required for economic reasons.

Park *et al*. (2016) suggested the uniformly + shape placement method in a single layer, as shown in Figure 2. However, there is a problem with the + shape placement method; the tip of the chi blocks sticks out in the toe and upper part of the breakwater. In order to solve this problem, the uniformly x-shape placement method was used in this study, as shown in Figure 3. However, because there is no interlocking effect in the vertical direction of the x-shape placement method, a sliding failure, which is the biggest problem in the single layer placement method, could occur. The placement methods shown in Figures 2 and 3 look quite academic, but they could be achieved in nature if the blocks are placed one by one from the lowest row.

Table 1. The characteristics of three Chi blocks

	Specific gravity	Weight	Volume
Chi block 1	2.23	247.2 g	107.49 cm^3
Chi block 2	2.23	230.6 g	100.26 cm^3
Chi block 3	2.23	230.2 g	100.09 cm^3

Figure 1. The shape of Chi blocks (Chi block 1(Left) to Chi block 3(Right))

Figure 2. The method of placement for Chi blocks (uniformly + shape placement in single layer)

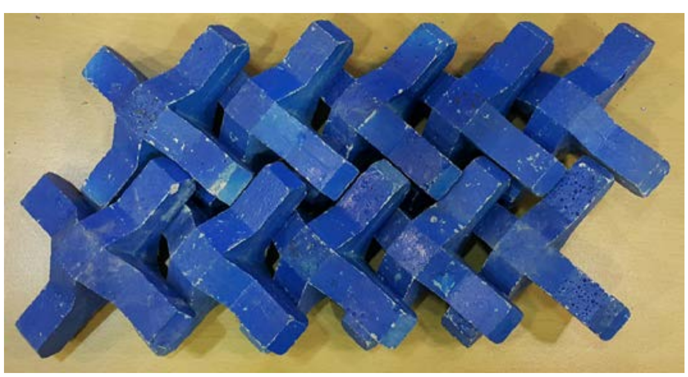

Figure 3. The method of placement for Chi blocks (uniformly x-shape placement in single layer)

3 HYDRAULIC EXPERIMENTS

Hydraulic experiments were carried in the wave flume at the Hydraulic and Coastal Engineering Laboratory of Seoul National University. Figure 4 shows the schematic wave flume and experimental setup. The flume was 36 m long, 1.0 m wide, and 1.2 m high, and wave absorbers were installed at both ends to reduce wave reflection. A piston type wave generator was installed at one end of the wave flume. From the point 13 m away from the wave generator, the wave flume was divided into two channels of 0.6 m and 0.4 m widths. From the point 20 m away from the wave generator, a plane slope was installed for 5 m up to the elevation of 0.2 m to simulate a foreshore slope of 1:25. From the point 25 m away from the wave generator, the model breakwater was built and the horizontal bed began with a few centimeters of breakwater toe. The breakwater was installed in the 0.6 m channel, whereas three wave gauges were installed in the 0.4 m channel but at the same location as the breakwater. The three wave gauges were used to separate the incident and reflected waves using the 3-point separation technique. The time series of the surface elevation of the incident and reflected waves was estimated by the 3-point separation technique. The significant wave height was calculated by zero-upcrossing method of the time series of the incident wave profile. The distance between the wave gauges should be within one wavelength. Therefore, the distance between the first and second wave gauges was 0.3 m and the distance between the second and third gauges was 0.5 m. The wave maker is equipped with an active wave absorption control system to minimize the effect of wave re-reflection from the wave paddle. However, the wave absorption system is not completely satisfactory, so the flume division method was used along with the wave absorption system.

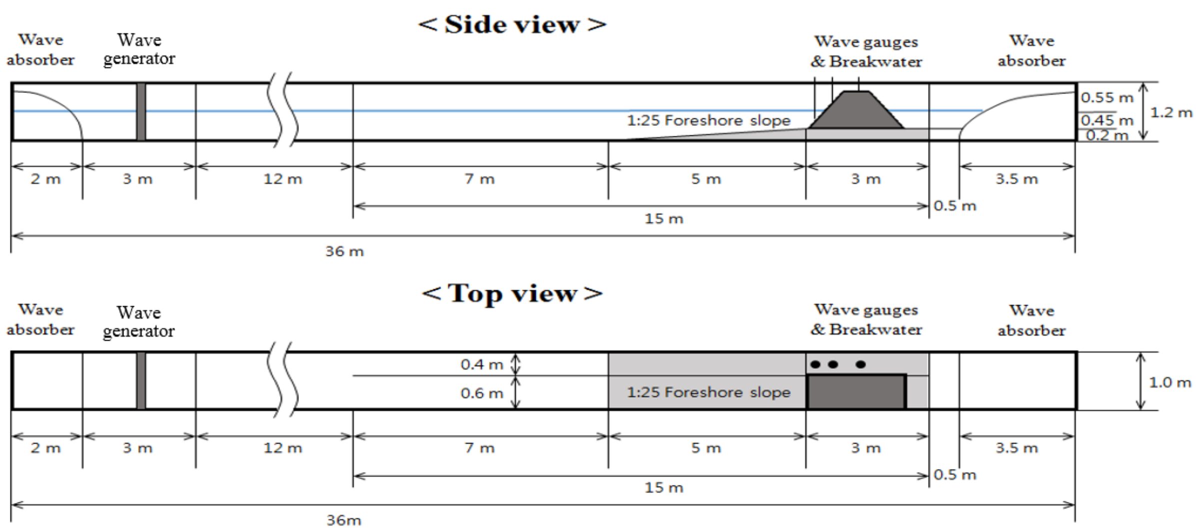

Figure 4. The schematic wave flume and experimental setup

The cross-section of the breakwater is shown in Figure 5. The slope of the breakwater was fixed at $\cot\theta = 1.5$, which is the most frequently used slope in Korea. The breakwater consisted of core, filter layer, and toe. The core consisted of stones of nominal size $D_n = 0.5 \sim 1.5$ cm, and the filter layer and toe consisted of stones with nominal size $D_n = 1.6 \sim 1.8$ cm. As shown in Figure 6, the Chi blocks were placed in a uniformly x-shape on the filter layer of breakwater and they were painted in diferent colors in order to easily visualize where the damage occured. 10 pieces of Chi blocks 1 and 2 and 14 pieces of Chi block 3 fit in a single row. The Chi blocks placed on the side walls had relatively weaker interlocking effects, and thus they were fixed with wires; and the damage occured on these blocks were not regarded as an actual damage on the experiments. It is recommended to use about $W/10$ to $W/15$ for the filter layer and about $W/200$ for the core, where W is the armor weight (Sorensen, 2006). In comparison with the recommended value, somewhat coarse core material was used in the experiment to reproduce a correct degree of permeability of the core, which may result in a favorable armor stability. To compensate for this effect, for the filter layer, somewhat smaller stones were used than the recommended value.

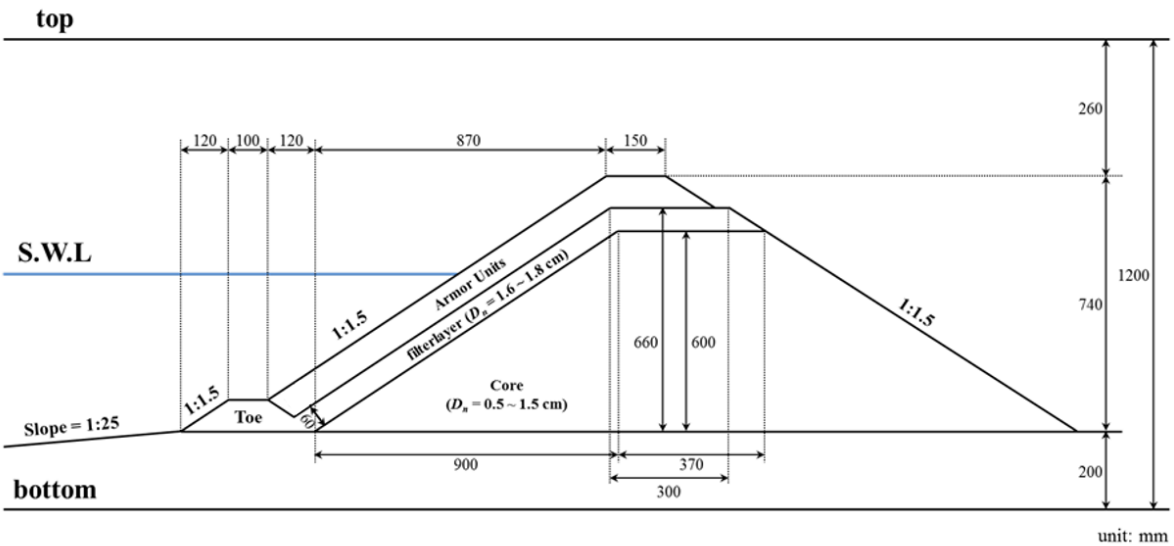

Figure 5. The cross-section of the model breakwater

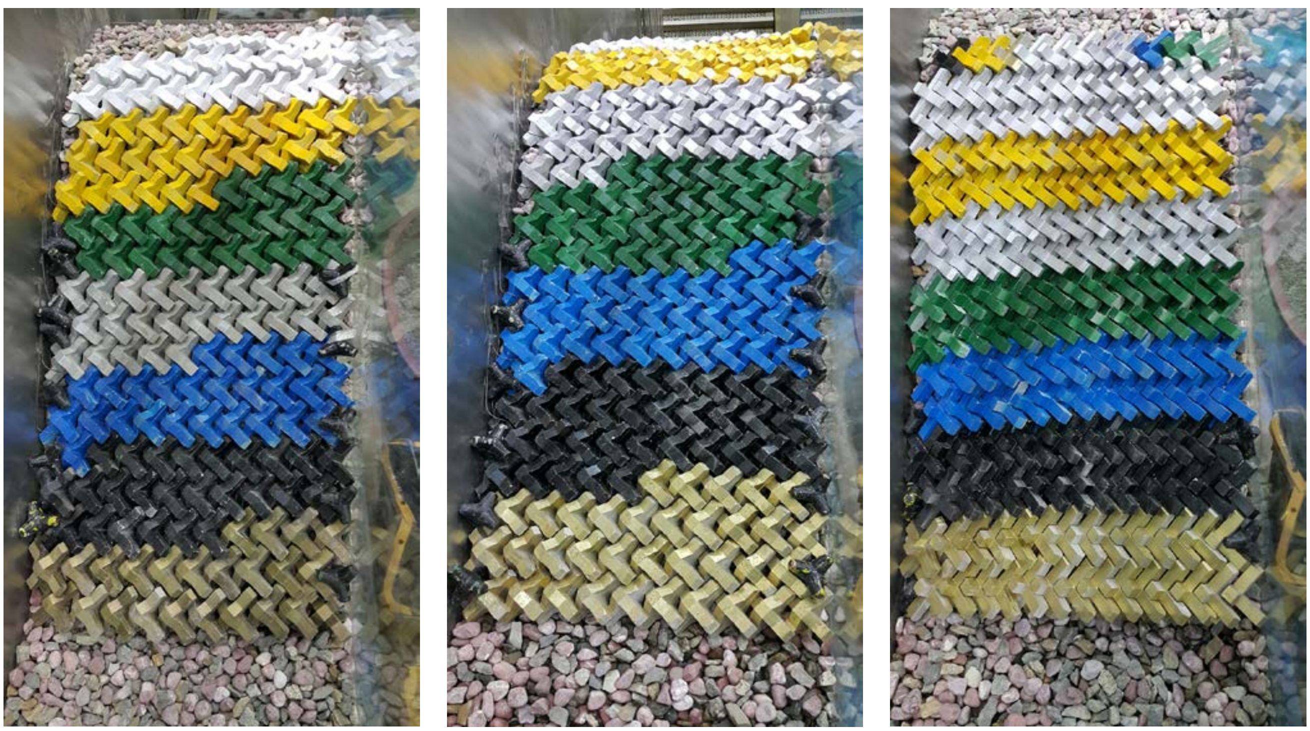

Figure 6. Chi blocks in a uniformly x-shape on the filter layer (Chi block 1(Left) to Chi block 3(Right))

The significant wave period(T_s) was 13 s in the prototype, which is a typical storm wave period. According to the Froude similarity, it was converted to 1.61 s in the experiments with 1:65 scale. The significant wave height (H_s) was 6.6 ~ 7.8 m in the prototype, which was 10.2 ~ 12.0 cm in the experiments. The detailed wave conditions are given in Table 2. Waves were generated at a water depth of 0.56 m, and the water depth at the breakwater was 0.36 m.

Table 2. The wave conditions of experiment

Case	Prototype		Experiment	
	T_s (s)	H_s (m)	T_s (s)	H_s (cm)
1	13	6.6	1.61	10.2
2	13	6.8	1.61	10.5
3	13	7.0	1.61	10.8
4	13	7.2	1.61	11.1
5	13	7.4	1.61	11.4
6	13	7.6	1.61	11.7
7	13	7.7	1.61	12.0

The ISSC spectrum given by Equation (1) was used in the experiments, which is identical to the modified Pierson-Moskowitz spectrum.

$$S(f) = 0.11 H_s^2 T_m (f T_m)^{-5} \exp\left[-0.44 (f T_m)^{-4}\right] \quad (1)$$

where $S(f)$ is the wave spectral density function, f is frequency, H_s is significant wave height, and T_m is the mean wave period. Because it was not possible to completely simulate the real waves in the laboratory, 100 regular waves with different periods were superimposed to generate irregular waves. However, the spectrum of such generated waves showed a difference from the target spectrum. In order to reduce the difference, the spectrum amendment was made until the measured spectrum became very close to the target spectrum. The spectrum amendment was carried out for each wave condition, and the final amended spectrum was used in the experiments. Figure 7 shows an example of target spectrum and the estimated spectrum using 500 waves before the installation of the breakwater.

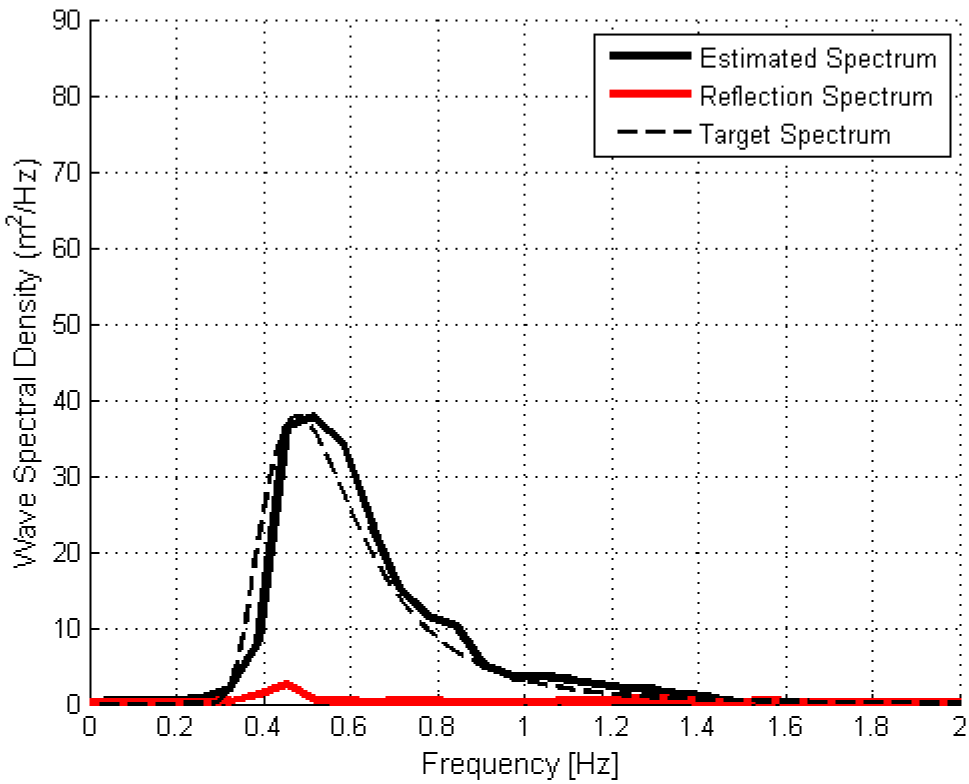

Figure 7. The example of spectrum amendment

Each test began with a generation of small waves of $H_s = 7.7$ cm and $T_s = 1.61$ s for 1000 s for stabilizing the Chi blocks. By using the final amended spectrum, waves were generated for 1000 s while visually observing the displacement of Chi blocks in naked eye. The duration of 1000 s corresponds to about 2.2 hours in prototype, which is a typical storm duration due to a typhoon in Korea. In the hydraulic experiments, Chi blocks can be displaced because the size of the Chi blocks is reduced following the Froude similitude but its strength remains the same. Therefore, there is a possibility of the damage to be underestimated in the hydraulic experiments. In order to compensate this underestimation, each of the Chi blocks was regarded as damaged when it moved more than one diameter, when it came back to its position after short displacement, or when it rotated more than $180°$. The damage due to breakage of Chi blocks were not taken into account in the laboratory experiments. The test was repeated while continuously increasing the significant wave height from 10.2 cm to 12.0 cm by 0.3 cm until any damage of the Chi block occurred. If a damage of the Chi block occurred at a certain wave height, the next higher waves were generated to check whether more damage of Chi block was to occur. The stability coefficient was calculated by using the Hudson formula given in Equation (2).

$$K_D = \frac{\gamma_a H_{si}^3}{W(S-1)^3 \cot\theta} \tag{2}$$

where γ_a = specific weight of Chi blocks, W = weight of the Chi blocks, S = specific gravity of Chi blocks. According to the Shore Protection Manual, when the stability coefficient was estimated based on 0 to 5 percent damage, it was generally referred to as no-damage condition for two-layer armors. However, because the damage of single-layer armors may trigger the brittle failure of the entire structure and there is greater uncertainty in the prototype than in the laboratory, the experiments were conducted conservatively. Therefore, the wave height H_{si} corresponding to the initiation of damage was used in the calculation of the stability coefficient.

4 EXPERIMENTAL RESULTS

The results for each Chi blocks for uniformly x-shape placement in single layer were given in Table 3 and Figure 8 showed each Chi blocks for uniform placement after the experiments. Because the uniform placement of Chi blocks was so strong, it was difficult to find any damage even at 7.8 ~ 8.0 m wave significant wave height, which was the maximum wave height can be generated in laboratory.

The maximum incident significant wave heights of Chi block 1, 2, and 3 were 7.79 m, 7.94 m, and 7.75 m, resepectively. The corresponding stability coefficients of Chi block 1, 2, and 3 were greater than 12.24, 13.88 and 12.93, respectively. Although any damage of Chi blocks was not occurred during the experiments, the damage of filter layer was occured because of gap between the Chi blocks. The void ratios of Chi block 1, 2, and 3 were 47.0 %, 44.6 %, and 40.5 %, respectively. The void ratio is one of the important factors in the design of armor units because it is closely related to economic efficiency. If the void ratio is high, the required number of blocks becomes smaller and thus it is more economical. Summarizing the results, Chi block 2 was the most stable block among Chi blocks because its stability coefficient was the highest, whereas Chi block 1 is the most economicalvoid ratio block among Chi blocks because the void ratio was the highest.

Table 3. The results for Chi blockss for uniformly x-shape placement

	Incident significant wave height	Stability coefficient(K_D)	Void ratio	Packing density
Chi block 1	7.79 m	Greater than 12.24	47.0 %	0.53
Chi block 2	7.94 m	Greater than 13.88	44.6 %	0.55
Chi block 3	7.75 m	Greater than 12.93	40.5 %	0.60

Figure 8. Chi blocks for uniform placement after experiments (Chi block 1(Left) to Chi block 3(Right))

The results of this study were compared with different placement methods of Chi blocks. The stability coefficient of the Chi block for uniformly + shape placement method and random placement method were provided by Park (2016). The stability coefficients are 13.7 for both uniformly + shape placement method and random placement method. The stability coefficient of uniformly x-shape placement method in this study was greater than 12. Because the only difference between x-shape placement method and + shape placement method was the angle of placed Chi blocks, the stability coefficients of Chi blocks for both methods had quite similar values. In other words, the stability coefficients of Chi blocks had a similar value regardless of the angle of the blocks for uniform placement methods.

In order to check whether the Chi blocks are adequate for abnormally high waves, the results were compared with other armor units such as Accropode, Core-loc, X-bloc, Tetrapod, and Dolos, which are widely used throughout the world. Min et al. (2015) suggested the stability coefficient of Tetrapod is about 7.5 for uniform placement in double layer and the Shore Protection Manual of U.S Army Corps of Engineers (USACE, 1984) suggested that the stability coefficient of Dolos for random placement in double layer is 15.8.

Medina et al. (2014) proposed a formula to calculate the void ratio as

where ϕ is the packing density, and n is the number of layers. USACE (1984) recommended $\phi = 0.83,\ n = 2$ for Dolos and Van der Meer (2000) recommended $\phi = 1.04,\ n = 2$. Therefore, the void ratios are 0.58 and 0.48, respectively, for Dolos and Tetrapod. The void ratio of Chi block in this study is about 0.45, which is slightly smaller than Dolos and Tetrapod.

The stability coefficient, void ratio, and packing density of armor units are given in Table 4. Because the stability coefficients of Chi blocks are greater than 12, Chi blocks are more stable than Tetrapod but probably less stable than other single-layer blocks and Dolos. However, considering that all types of Chi blocks did not exhibit any damage at the maximum wave height in this study because of the limitation of the wave generator, additional experiment is required in a wave flume in which larger waves can be generated. The void ratio and packing density indicate that the Chi block is comparable to other single-layer blocks in terms of economical efficiency and it is more economical than two-layer blocks.

Table 4. Stability coefficient, void ratio, and packing density of different armor units

Armor unit	Stability coefficient	Void ratio	Packing density
Chi blocks	Greater than 12	0.45	0.55
Accropode	15	0.35	0.65
Core-loc	16	0.42	0.58
X-bloc	16	0.59	0.41
Dolos	15.8	0.58	0.83
Tetrapod	7.5	0.48	1.04

5 CONCLUSIONS

In this study, new armor units named Chi blocks were introduced and a uniform placement method in single layer for Chi blocks was proposed armoring a rubble mound breakwater. In order to compare the stability and economic feasibility among different types of Chi blocks, the stability coefficient provided by Hudson and the void ratio were used. The stability coefficients were calculated by conducting hydraulic experiments. The stability coefficients of Chi block 1, 2, and 3 were greater than 12.24, 13.88 and 12.93, respectively. The void ratio of Chi block 1, 2, and 3 were 47.0 %, 44.6 %, and 40.5 %, respectively. However, tbe the most economical since it has void ratio

Comparison with other frequently used armor units showed that the Chi blocks are more stable than Tetrapod but probably less stable than other single-layer blocks and Dolos. It was also shown that the Chi block is comparable to other single-layer blocks in terms of economical efficiency and it is more economical than two-layer blocks (because of the smaller packing density of Chi blocks). Finally, additional experiment in a wave flume in which larger waves can be generated is required to determine the final stability coefficient of Chi blocks.

ACKNOWLEDGEMENT

This research was supported by Development of technology for armor blocks and crown structure against high waves through the Korea Institute of Marine Science and Technology Promotion (KIMST) funded by the Ministry of Oceans and Fisheries (KIMST-20120178). The research was conducted at the Engineering Research Institute of Seoul National University.

REFERENCES

Hudson, R.Y., 1959. Laboratory investigation of rubble-mound breakwaters, *Journal of Waterways and Harbors Division*, 85(3), 93-121.

Medina, J.R., Molines, J., Gómez-Martín, M.E., 2014. Influence of armour porosity on the hydraulic stability of cube armour layers, *Ocean Engineering*, 88, 289-297

Min, E.J., Cheon, S.H., Suh, K.D., Matsushita, H., 2015. Stability coefficients of Tetrapod, Rakuna-IV, and Dimple depending on placement methods, *Proceedings of the Twenty-fifth (2015) International Ocean and Polar Engineering Conference*, Hawaii, USA, 1394-1399.

Park, Y.H., Won, D., Han, T.H, Kim, Y-T., 2016. Development of a New Concrete Armor Unit for High Wave: Chi Block, *Submitted to Coastal Engineering, (in review)*.Sorensen, R.M., 2006. *Basic Coastal Engineering*, 3rd ed., Springer.

Suh, K.D., Park, W.S., Park, B.S., 2001. Separation of incident and reflected waves in wave-current flumes, *Coastal Engineering*, 43, 149-159.

U.S Army Corps of Engineers, 1984. *Shore Protection Manual*, U.S. Government Printing Office, Washington, DC.

Van der Meer, J.W., 2000. Design of concrete armor layers, Proceedings of Coastal Structures ,99, A.A. Balkema, 213-221.