CHAPTER 35

EXPERIMENTAL STUDIES OF SPECIALLY SHAPED CONCRETE BLOCKS FOR ABSORBING WAVE ENERGY

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ABSTRACT

Laboratory tests were performed to determine wave energy absorbing ability of and stability characteristics against breaking waves of various shaped pre-cast concrete armor units used for protective cover layers on the seaward slopes of rubble-mound breakwaters and for parallel dykes placed the offshore sides of seawalls. A new shape of armor units, a hollow tetrahedron concrete block with a porosity of 25 percentages in the body was proved to have better characteristics for wave energy absorbing ability and attenuation of wave run-up, as well as for stability against breaking waves also than tetrapod or other armor units used up-to-date.

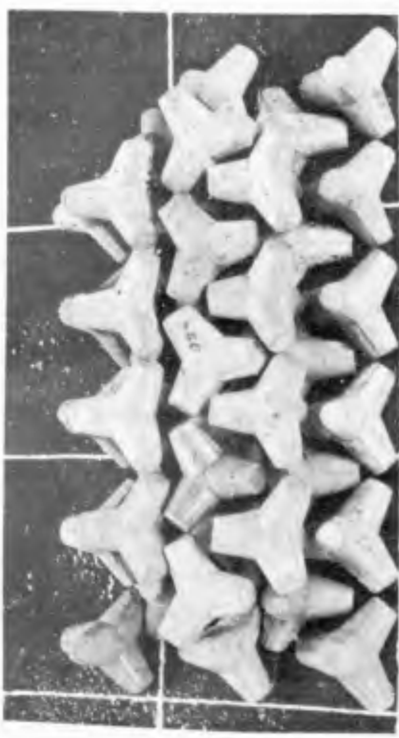
EXPERIMENTAL EQUIPMENT AND PROCEDURE

TESTS FOR PROTECTIVE COVER LAYERS OF RUBBLE-MOUND BREAKWATERS

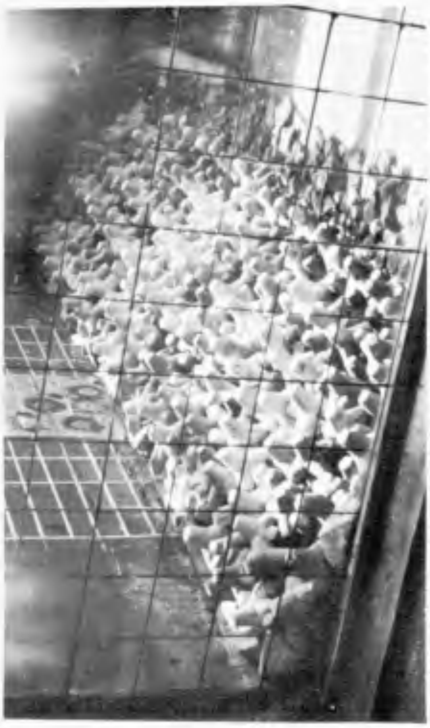
An open wave channel, which is 25 m. long, 2 m. wide, and 1 m. deep, was used for the experiments of the protective cover layers of rubble-mound breakwaters. Waves were generated by a flutter type wave generating machine, ranging the period $T = 1.2$ to 1.9 sec., the height $H = 10$ to 24 cm., and the steepness $H/L = 0.040$ to 0.085. Since the scale ratio between the model and prototype is approximately 1/20, the heights and periods of the model waves are scaled up approximately to $H = 2$ to 4.8 m. and $T = 5.4$ to 8.5 sec. in sea by the use of Froude's law.

A number of laboratory tests were performed of concrete armor units such as tetrahedrons, hexabars, tetrapods and hollow tetrahedrons made in 1/20 scale ratio to prototype, comparing with quarry-stone armor units placed pell-mell and with mounds made of wooden plates. The energy absorbing ability of armor units in these experiments was determined by use of the resultant forces of maximum simultaneous shock pressures(1) exerted by breaking waves on the vertical walls of composite-type breakwaters, which were measured by pressure-gauges of strain-gauge type, and also by use of wave run-up along the vertical walls as well as reflection ratio from the walls, both of which were measured by visual observation.

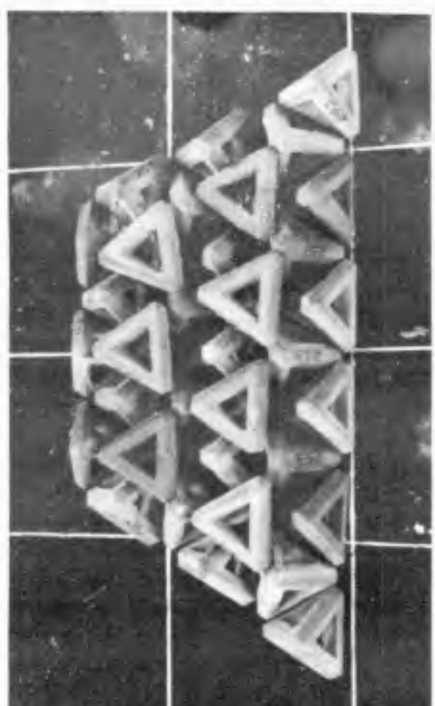
The shapes and characteristics of the specially shaped armor blocks used in the tests are shown in Figure 1 and Table 1. The armor units were in all tests constructed with the two layers of the specially shaped concrete blocks on a $1 : 1\frac{1}{2}$ slope, because it was proved by the tests that the two-layer placing and the $1 : 1\frac{1}{2}$ slope were the optimum condition for the stability of these



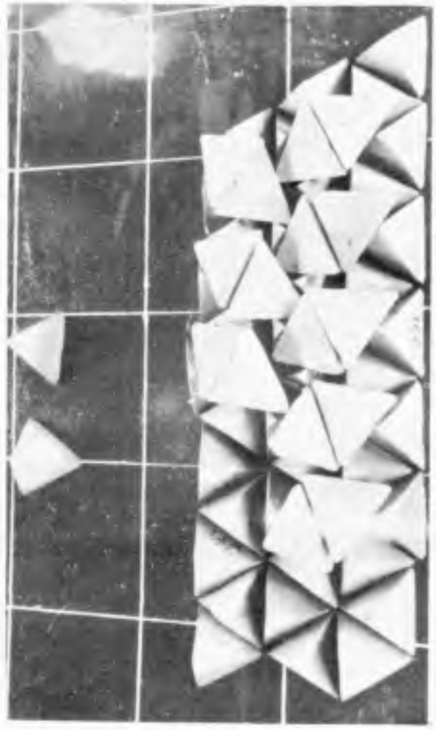
(a) Concrete tetrapods (upper blocks reversed).



(b) Concrete tetrapods (upper blocks normal).



(c) Concrete hollow tetrahedrons.



(d) Concrete tetrahedrons.

Fig. 1. Types of concrete armor units and manner of placing.

Table 1. Characteristics of concrete armor units tested.

Type of Blocks	Vol. of a block (cm^3)		Weight of a Block		Porosity (%)			Height (cm)	No. of Blocks in 2-layer Placing			Slope at Sliding		Slope at Overturning	
	Net Vol.	Apparent Vol.	Model (g)	Prototype (t)	One Block	Two Layers	Pell-mell		Lower Layer	Upper Layer	Total	One Layer	Two Layers	One Layer	Two Layers
Tetrapod	110	110	227 ~ 275 aver.251	aver. 2.0	0	r.66	50	7.3	r 267 n 267	230 132	497 399	36° ~ 42°	r35° ~ 42° n37° ~ 41°	57° ~ 63°	r 59° n 70
Tetrahedron	150	150	298 ~ 374 aver.337	2.7	0	50	57	9.3	229	145	374	32° ~ 38°	31° ~ 36°	61°	65°
Hollow Tetrahedron No. 1	116	155	246 ~ 288 aver.267	2.1	25	66	60	7.6	222	112	334	28° ~ 34°	32° ~ 36°	67°	67° ~ 74°
Hollow Tetrahedron No. 2	90	123	173 ~ 226 aver.201	1.6	27	59	58	7.0	363	138	501	33° ~ 34°	33° ~ 34°	65° ~ 69°	70° ~ 71°
Hollow Tetrahedron No. 3	108	166	224 ~ 271 aver.248	2.0	35	70	68	8.0	213	114	327	33° ~ 35°	34° ~ 37°	67° ~ 69°	69° ~ 85°

r : reversed, n : normal

Table 2. Test results in Figures 7 and 8.

Wave Period Tm = 1.5 sec (Tp = 6.7 sec.)

Construction of a Base-mound	h_1 (cm)	H (cm)	H/L	Max. Press Intensity P_{max} (g/cm^2)	Ratio (%)	Result. of Max. Simult. Wave Press P (g/cm)	Ratio (%)	Stability of Blocks	Impulse (g cm /sec.)	Impulse Momentum α (%)	Ratio of Wave Energy α^2 (%)	Run-up Ru (cm)	Reflect. Ratio (%)
Wooden Pl.	7.0 13.0	13 15	0.049 0.053	70 102	100 100	452 510	100 100		355x10^3	61.7	38.0	23 ~ 26 27 ~ 32	45 28
Quarry-stone	7.0 13.0	12 15	0.059 0.052	80 30	114 30	331 405	74 79					16 ~ 18 25 ~ 30	29 21
Tetrapod (reversed)	7.0 13.0	14 17	0.054 0.062	80 23	114 23	376 291	83 57	overturn.				21 ~ 26 22 ~ 25	54 28
Tetrapod (normal)	7.0 13.0	15 16	0.054 0.056	60 85	86 83	292 441	66 87	rocking	314x10^3	54.6	29.8	21 ~ 23 22 ~ 25	36 27
Tetrahedron (reversed)	7.0 13.0	13 15	0.053 0.060	60 60	86 59	302 588	67 115	several bls. rock. unstable	189x10^3	34.4	11.8	21 ~ 26 25	24 33
Hollow Tetrahedron No. 1	7.0 13.0	12 16	0.042 0.059	60 15	86 15	242 216	54 42	stable "	127x10^3	21.3	4.5	16 ~ 18 20	37 20
Hollow Tetrahedron No. 2	7.0 13.0	13 15	0.051 0.057	70 26	100 26	314 400	70 78	severe rock stable				20 ~ 23 28 ~ 33	36 10
Hollow Tetrahedron No. 3	7.0 13.0	12 15	0.046 0.055	40 35	57 34	248 476	55 93	rocking rocking & roll. down				26 20 ~ 24	30 33

Table 3. Test results in Figures 9 and 10.

Wave Period Tm = 1.3 sec. (Tp = 5.8 sec.)

Construction of a Base-mound	h_1 (cm)	H (cm)	H/L	Max. Press Intensity P_{max} (g/cm^2)	Ratio (%)	Result. of Max. Simult. Wave Press. P (g/cm)	Ratio (%)	Stability of Blocks	Impulse (g.cm /sec.)	Impulse Momentum α (%)	Ratio of Wave Energy α^2 (%)	Run-up Ru (cm)	Reflect. Ratio (%)
Wooden Pl.	7.0 13.0	14 18	0.063 0.073	65 58	100 100	452 725	100 100		262x10^3	44.4	19.7	26 ~ 31 35 ~ 37	32 22
Quarry-stone	7.0 13.0	15 18	0.072 0.082	75 55	115 95	375 329	83 45					28 ~ 31 35 ~ 40	36 33
Tetrapod (reversed)	7.0 13.0	15 18	0.063 0.078	65 37	100 64	481 513	106 71	several bls. roll. down				31 ~ 36 35 ~ 40	40 31
Tetrapod (normal)	7.0 13.0	15 19	0.068 0.079	80 29	123 50	400 417	89 58	stable stable	129x10^3	24.0	5.8	31 ~ 36 30 ~ 40	29 20
Tetrahedron (reversed)	7.0 13.0	15 18	0.058 0.069	60 40	92 69	366 548	81 76	unstable unstable	189x10^3	30.6	9.4	26 ~ 31 35 ~ 37	24 33
Hollow Tetrahedron No. 1	7.0 13.0	14 18	0.058 0.077	75 16	115 28	343 192	76 27	stable stable	87x10^3	13.9	1.9	26 30 ~ 32	33 33
Hollow Tetrahedron No. 2	7.0 13.0	14 18	0.055 0.072	65 24	100 41	274 365	61 50	several bls. rock. unstable				26 ~ 31 36 ~ 41	24 17
Hollow Tetrahedron No. 3	7.0 13.0	15 17	0.064 0.073	30 32	46 55	105 432	23 60	several bls. rock. several bls. roll. down				21 30	31 36

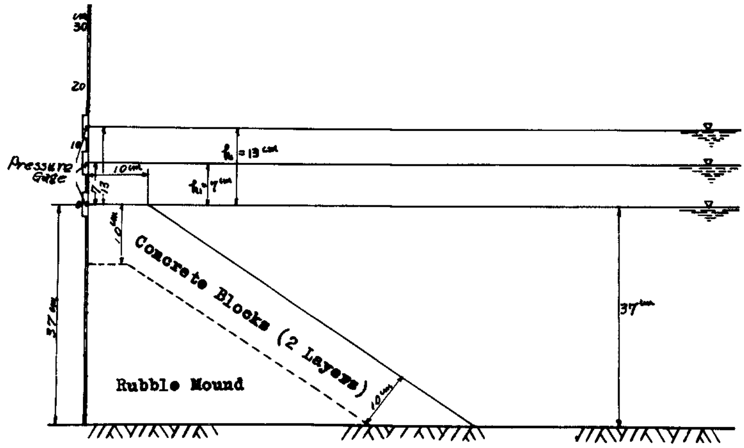


Fig. 2. Composite breakwater with high vertical wall (top width of rubble mound B = 10 cm).

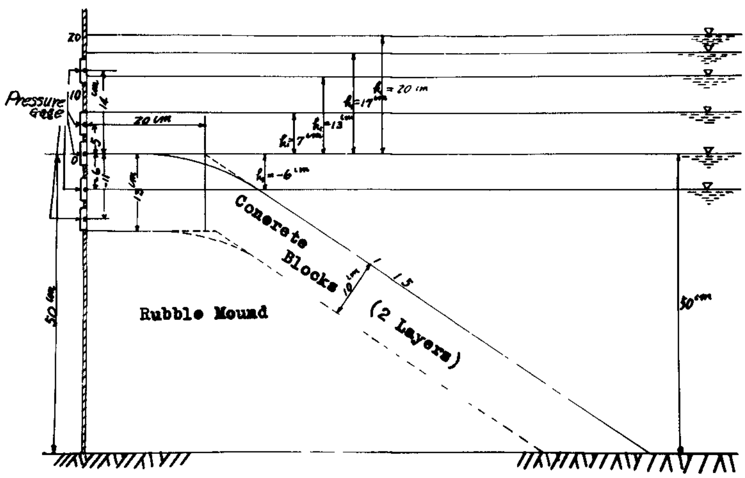


Fig. 3. Composite breakwater with high vertical wall (B = 20 cm).

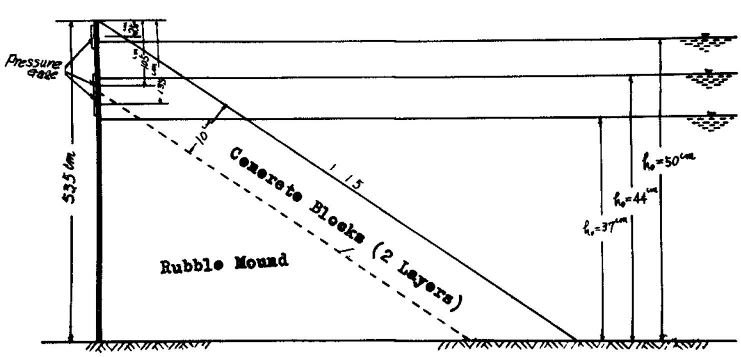


Fig. 4. Composite breakwater with low vertical wall (B = 0).

concrete armor units.

The types of composite breakwaters and rubble-mound breakwaters used in the tests are shown in Figures 2, 3 and 4. The protective cover layers composed of the two layers of cast concrete specially shaped armor units were placed in some orderly manner or pell-mell over a core of quarry-stones, the diameters of which d ≒ 2.8 to 7.3 cm..

Figs. 2 and 3 are types of composite breakwaters with vertical walls sufficiently high to prevent overtopping by the test waves, and Fig. 4 is a type of composite breakwaters with low vertical walls subjected to overtopping at high water levels. In these low breakwaters cast concrete blocks are placed up to the crown of the vertical walls.

TESTS OF PARALLEL DYKES FOR THE PROTECTION OF RUN-UP ON SEAWALLS

A lot of experiments was performed to determine the effect of parallel dykes, which were constructed with the two layers of concrete tetrapods and hollow tetrahedrons and placed in front of seawalls, on the attenuation of wave run-up and of wave pressures on the seawalls. A wave channel used in these experiments was 23 m. long, 1 m. wide, and 1 m. deep, as shown in Fig. 5, and the nearly overall length of the channel was covered on the top with semicircular duralmin plates for generating winds of various speeds parallel with the direction of propagation of waves which were generated by a flutter type wave generator. The speed of revolution of a wind blower was varied by the use of a vari-pitch connected with a 15-horse power electric motor so as to generate winds of speed up to 20 m./sec.. One typical type of the seawalls tested is shown in Fig. 6.

The characteristics of waves generated by the flutter type wave generator were T = 1.2 to 1.9 sec., H = 8 ~ 14 cm., H/L = 0.020 ~ 0.070. The wave run-up as well as the behaviors of spray and overtopping were measured by the use of a 16 millimeter movie taken at 100 frames per second.

EXPERIMENTAL RESULTS

TESTS FOR THE PROTECTIVE COVER LAYERS OF RUBBLE-MOUND BREAKWATERS[2]

(a) Test results in composite breakwaters shown in Figs. 2 and 3

Figs. 7, 8, 9 and 10 show maximum simultaneous shock pressures exerted by breaking waves of periods T = 1.3 and 1.5 sec. on the vertical walls of the composite breakwaters shown in Fig. 2.

The states of run-up in breaking waves with T ≒ 1.5 sec., H ≒ 16 cm., H/L ≒ 0.060 impinged against the vertical walls placed on the various kinds of base-mounds are shown in Figs. 11, 12, 13 and 14.

The test results are summarized in Tables 2 and 3, concerning

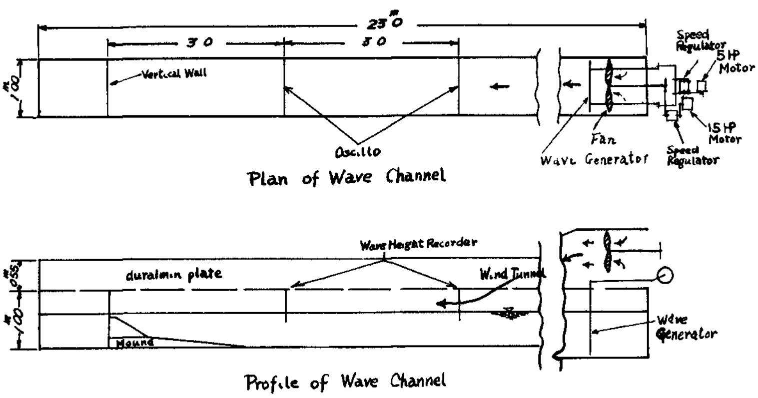


Fig. 5. Closed wave channel with a wind blower.

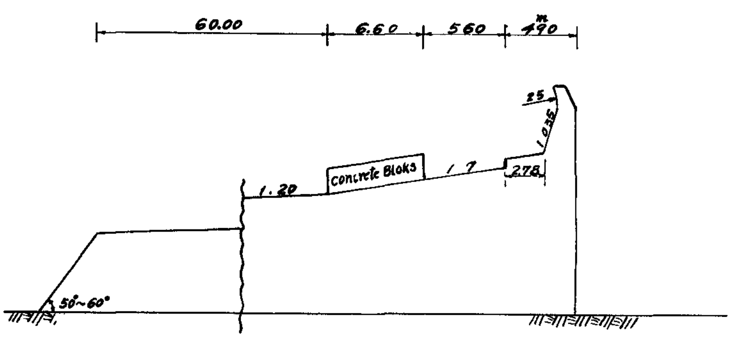


Fig. 6. A Type of sea walls tested, section of a sea wall and shore at Suma, at Kobe, Japan.

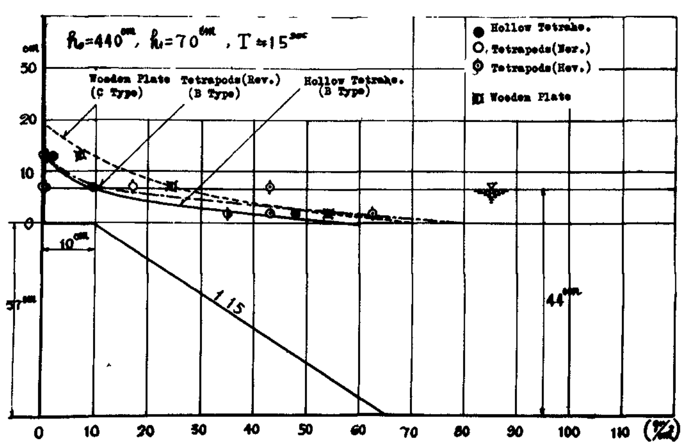


Fig. 7, Maximum simultaneous shock pressures by breaking waves of T = 1.5 sec (water depth above the top of the mounds h_1 is constantly 7 cm).

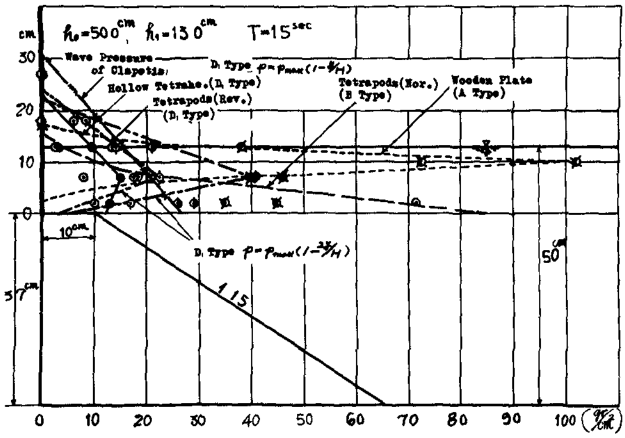


Fig. 8. Maximum simultaneous shock pressures by breaking waves of T = 1.5 sec (h_1 = 13 cm).

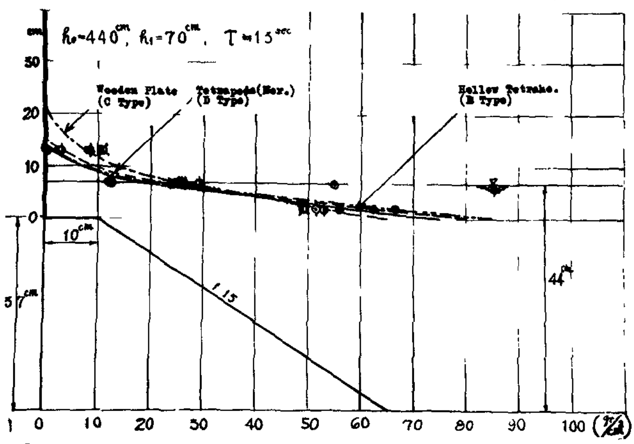


Fig. 9. Maximum simultaneous shock pressures by breaking waves of T = 1.3 sec (H_1 = 7 cm).

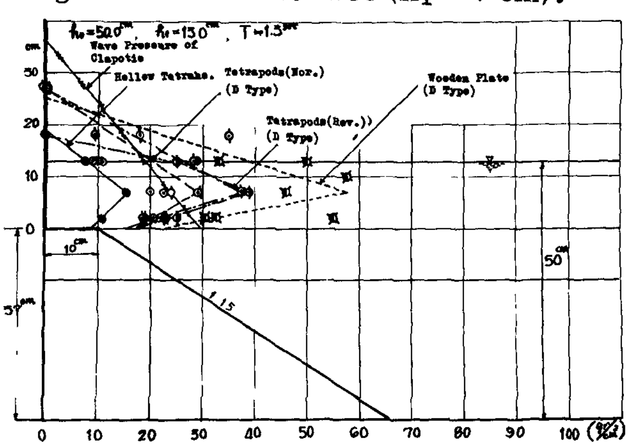


Fig. 10. Maximum simultaneous shock pressures by breaking waves of T = 1.3 sec (h_1 = 13 cm).

with the maximum intensities of shock pressures and the resultants of maximum simultaneous shock pressures exerted on the vertical walls of the composite breakwaters by the breaking waves, the heights of wave run-up, the ratioes of wave energy attenuation, and the stability of the armor units on the seaward slopes of the base-mounds.

The effect of the specially shaped concrete armor units on absorbing wave energy was also determined by use of the ratio of wave energy attenuation, α^2, defined as follows.

The momentum per the unit width of the channel transported by a breaking wave for a period is obtained by $\rho Q \omega$, where ρ is the density of water, ω , the horizontal velocity of a water particle in a breaking wave, may equal to the celerity of the breaking wave with sufficient accuracy, and Q is the water mass per unit width of the channel transported for a period by the breaking wave. If the breaking wave is assumed that of a solitary wave, ω and Q are given by

$$\omega = \sqrt{2.28 g H} \tag{1}$$

in which g is the acceleration of gravity, and H the height of the breaking wave, and

$$Q = 4 h_o^2 \sqrt{\frac{H}{3 h_o}} \tag{2}$$

in which h_o is a depth below the still water level at the horizontal bottom of the channel.

The resultant of the impulse exerted by the breaking wave on unit width of the vertical wall for a period is denoted by $\int_0^h \int_0^\tau p dt \cdot dh$ where τ is smaller than the period T of the breaking wave, and h the height from the top of the base-mound up to the highest point of the wave pressure exerted by the breaking wave. If the ratio of the resultant of the impulse on the vertical wall to the momentum transported is denoted by α,

$$\frac{\int_0^h \int_0^\tau p dh \cdot dh}{\rho Q \omega} = \alpha \text{ , } \quad 0 < \alpha \leqq 1$$

$$\int_0^h \int_0^\tau p dh \cdot dh = \alpha \cdot \rho Q \omega \tag{3}$$

Substituting Eqs. (1) and (2), into Eq. (3), we obtain

$$\int_0^h \int_0^\tau p dt \cdot dh = \rho \cdot 4 h_o^2 \sqrt{\frac{\alpha H}{3 h_o}} \cdot \sqrt{2.28 g \cdot \alpha H} \tag{4}$$

The right-hand side of Eq. (4) may be considered the momentum transported by a breaking wave with a height of αH. Since the net wave energy E_{net} acted on the vertical wall by this breaking wave will be

$$E_{net} = \frac{1}{8} \rho g (\alpha H)^2$$

the ratio of the net breaking wave energy acting on the vertical wall to the total breaking wave energy before impinging against the breakwater should be obtained by the equation

$$\frac{E_{net}}{E} = \frac{\frac{1}{8}\rho g(\alpha H)}{\frac{1}{8}\rho g H^2} = \alpha^2 \qquad (5)$$

By the use of the experimental data the values of α^2 were calculated from Eqs. (3) and (5).

From Tables 2 and 3 it is seen that the hollow tetrahedron armor units constructed with the two layers of cast concrete hollow tetrahedrons with a porosity of 25 percentages have the optimum characteristics of wave energy absorbing ability as well as of stability on the 1 on 1.5 slope, showingespecially 30 to 50 percentages greater attenuation of the maximum simultaneous shock pressures than that due to the tetrapod armor units. It is considered that when the depth h_1 above the top of a base-mound covered with specially shaped concrete armor layers is small, the roughness on the surface of concrete block layers plays a greater role than the permeability of concrete block layers, on the contrary, the latter plays a greater role than the former when h_1 is large. Wave run-up on the vertical walls of composite breakwaters is also smaller in the hollow tetrahedron armor layers than in the tetrapod armor layers.

From experiments in the composite breakwaters of such shapes as shown in Fig. 3, nearly the same trend as shown in Tables 2 and 3 was proved.

(b) Test results in composite breakwaters with low vertical walls shown in Fig. 4 Maximum simultaneous shock pressures exerted by breaking waves on the low vertical walls, up to the top of which the seaward slopes of the rubble-mound were covered with concrete tetrapod or hollow tetrahedron armor units, and the stability of those armor units on the slopes were measured by making breaking waves with the periods of T = 1.3 and 1.5 sec. on the slopes in the three different water levels. These experimental results are shown in Figs. 15, 16, 17, 18, 19 and 20.

As it is known from the Figures, when waves break on the slopes in the cases of low water level, the magnitudes of shock pressures exerted by the breaking waves on the vertical walls are nearly the same in the two different armor units, indicating small values, but in the cases of high water level the effect of the hollow tetrahedron armor units on the attenuation of wave pressures is distinguished, comparing with that of the tetrapod armor units. The quantity of overtopping in the hollow tetrahedron armor units is also smaller than that in the tetrapod armor units. The stability on the slopes was nearly the same in the two armor units.

(c) Test results of parallel dykes for the protection of wave run-up on sea-wall It was proved from a lot of experiments that if parallel dykes covered with the two layers of concrete hollow tetrahedron or tetrapod armor units were placed in front of seawalls, wave run-up on the slopes of the seawalls could be reduced to a

Fig. 11. Run-up in composite breakwater with base-mound of wooden plates.

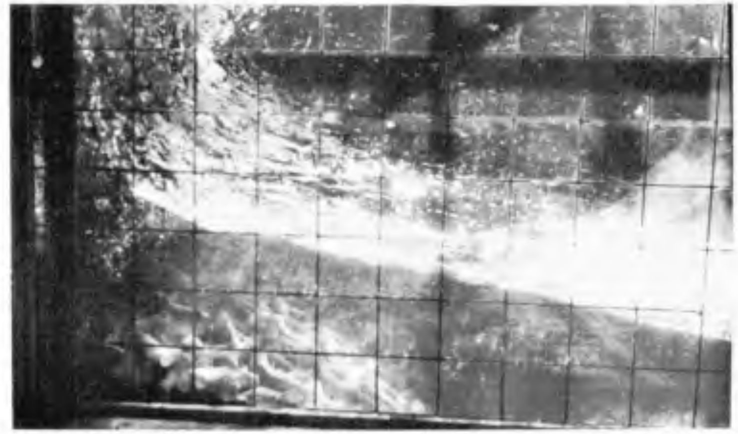


Fig. 12. Run-up in composite breakwater with base-mound covered with the 2 layers of tetrapods.

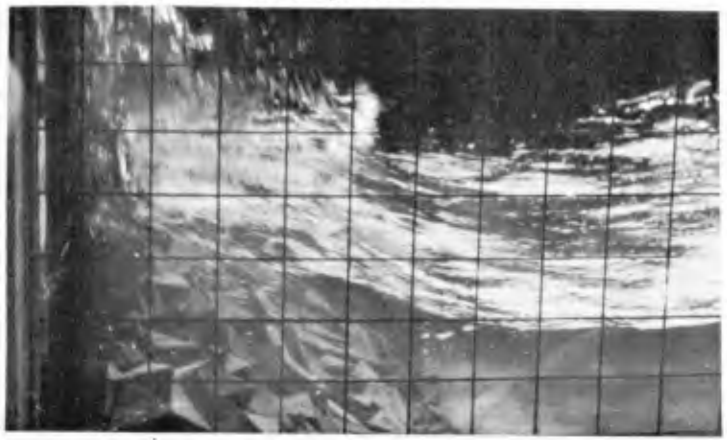


Fig. 13. Run-up in composite breakwater with base-mound covered with the two layers of tetrahedrons.

Fig. 14. Run-up in composite breakwater with base-mound covered with the 2 layers of hollow tetrahedron with a void ratio of 25%.

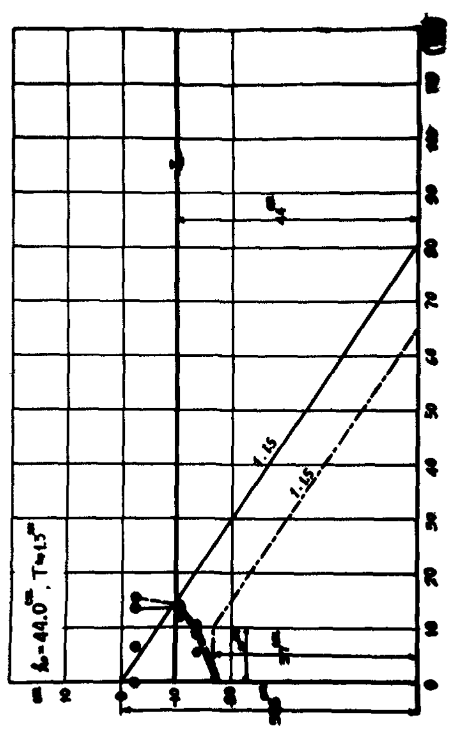


Fig. 15. Maximum simultaneous shock pressures on the vertical wall, H = 14 cm, H/L = 0.048.

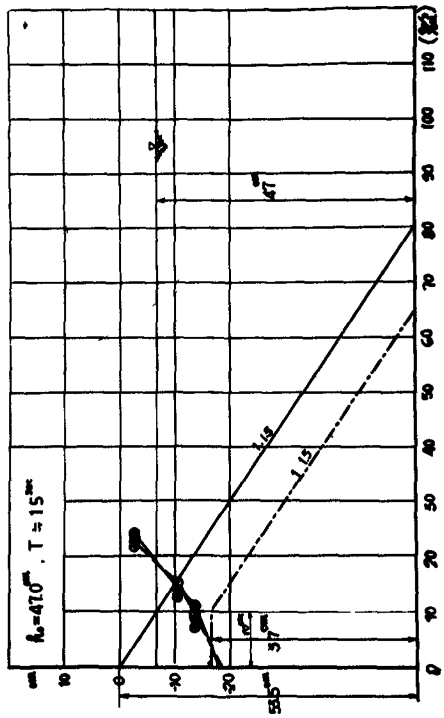


Fig. 16. Maximum simultaneous shock pressures on the vertical wall, H = 16 cm. H/L = 0.054.

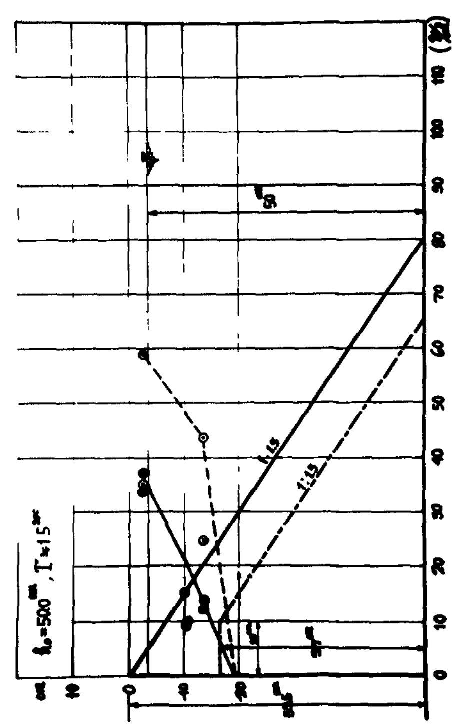


Fig. 17. Maximum simultaneous shock pressures on the vertical wall, H = 17 cm, H/L = 0.057.

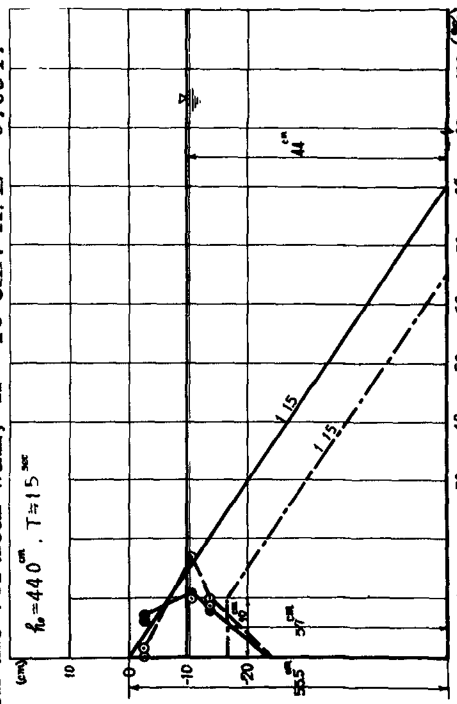


Fig. 18. Maximum simultaneous shock pressures on the vertical wall, H = 16 cm, H/L = 0.066.

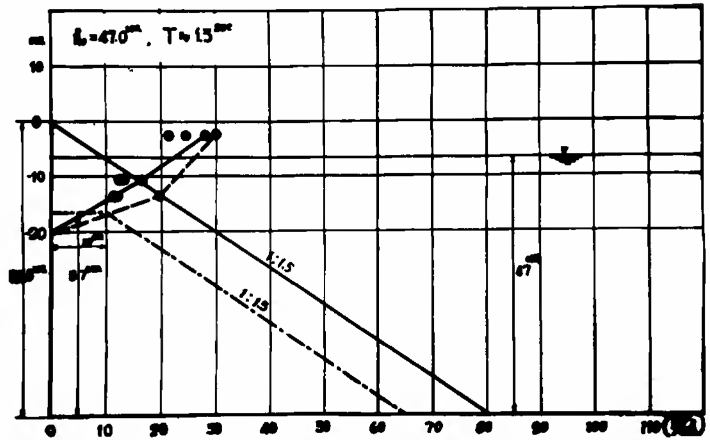


Fig. 19. Maximum simultaneous shock pressures on the vertical wall, H = 18 cm, H/L = 0.073.

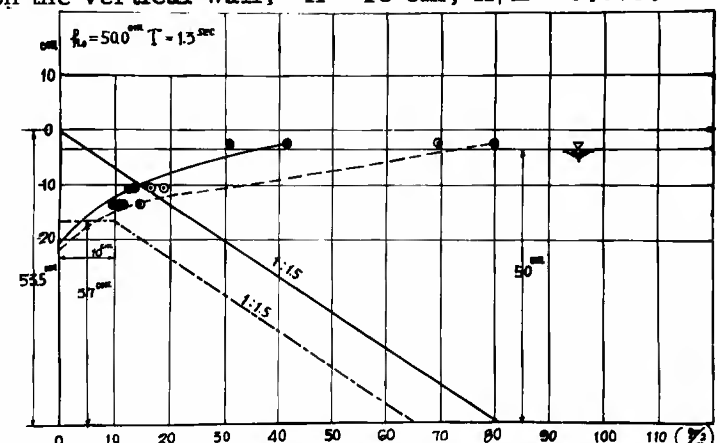


Fig. 20. Maximum simultaneous shock pressures on the vertical wall, H = 19 cm, H/L = 0.078.

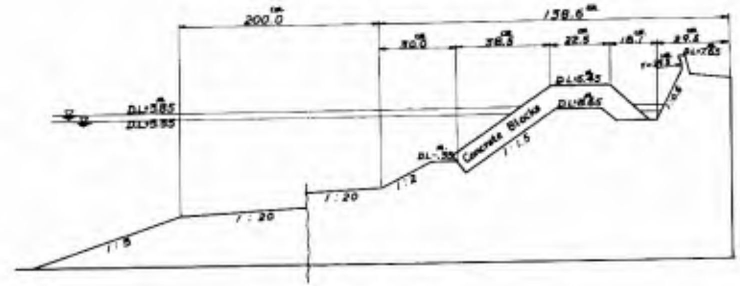


Fig. 21(a). Section of a sea-wall at Amagasaki City, Japan.

Fig. 21(b). Behavior of wave run-up in the case of wind speed V = 20 m/sec in prototype at the sea wall with a parallel dyke constructed with hollow tetrahedron armor units.

Fig. 22a. Behavior of spray and wave run-up at the sea wall without a parallel dyke shown in Fig. 6. Wind speed V = 25 m/sec in prototype.

Fig. 22b. Behavior of wave run-up at the sea wall with a parallel dyke covered with 2 layers of hollow tetrahedron armor units, V = 25 m/sec.

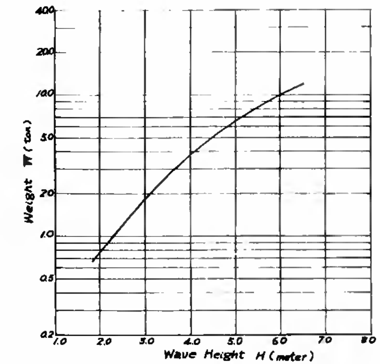


Fig. 23a. When $h_1 \leqq 0$, i.e. waves break on the slopes of mounds.

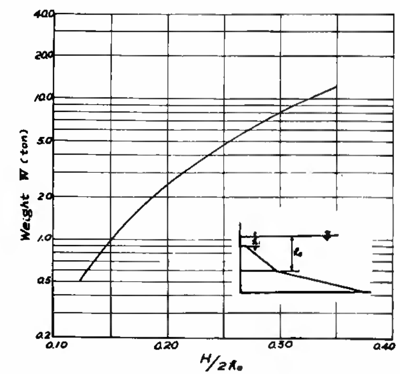


Fig. 23b. When $h_1 > 0$, i.e. sea levels are higher than the tops of mounds.

Fig. 23. Curves of stability for the concrete hollow tetrahedron armor units on $1 : 1\frac{1}{2}$ slopes.

great extent. The tops of the parallel dykes should be high suffi cient to prevent a large amount of overtopping by the test waves at the design height of sea level, probably being 0.50 m. or more above the design sea level.

The effect of the hollow tetrahedron armor units on the attenuation of wave run-up on the seawall slopes was proved more prominent than that due to the tetrapod armor units. Only the two examples are shown in Figs. 21 and 22 to show the effect of the attenuation of wave run-up due to the parallel dykes with the cover layers composed of the hollow tetrahedron armor units. Fig. 21 is a case where a depth in front of a seawall at the design sea level is so large that the design waves do not break before arriving the sea-wall, on the contrary Fig. 22 is a case where the design waves break at or in front of a sea-wall at the design sea level.

(d) Stability of the hollow tetrahedron armor units on the slope of rubble-mounds[3] As mentioned above, the hollow tetrahedron armor units on the slopes of rubble-mounds were proved to be in general more stable against the attack of waves than tetrapod armor units, because of wedge action caused by the upper layer blocks inversely set into among the lower layer blocks, as well as of the small up-lift pressures of receding waves reduced due to the hollowness of the blocks. The curves of stability of the concrete hollow tetrahedron armor units were determined from a number of experiments on the 1 : $1\frac{1}{2}$ slopes of rubble-mounds as shown in Fig. 23.

(e) Tests of the strength of the concrete hollow tetrahedron blocks Several field tests of prototype two-ton condrete hollow tetrahedron blocks with the porosity of 25 percentages (with no reinforcement) was performed to know strength against very roughly dumping in seas by the measures of falling down on gravel layers and on hollow tetrahedron blocks from some 3-meter height.

From the tests the concrete hollow tetrahedron blocks were confirmed very tough against rough piling up or hard mutual colliding by storm waves because of resisting as Rahmen structures.

CONCLUSIONS

It is concluded from the results of tests completed up to date that:

(a) Two layers composed of the concrete hollow tetrahedron armor units have better characteristics for absorbing wave energy or wave pressure and for stability against breaking waves than the other specially shaped concrete armor units which have been used up to date.

(b) When the two layers of hollow tetrahedron armor units are used for protective cover layers on the seaward slopes of the rubble-mound of composite-type breakwaters, it will be expected to obtain approximately 30 to 50 percentages greater attenuation of shock pressures exerted by breaking waves on the vertical walls than that due to tetrapod armor units. When the two layers of hollow tetrahedron armor units are used for the protective cover layers of parallel dykes located in front of sea-walls, the attenuation of wave run-up on the slopes of the sea-walls will be obtained to a great extent and be materially effective to prevent overtopping from the sea-walls.

(c) The hollowness of a hollow tetrahedron block was proved optimum in the case of a porosity of 25 percentages, from the view points of wave energy absorbing ability as well as of the strength of a block.

(d) The two layers of concrete hollow tetrahedron armor units have favorable characteristics for stability on 1 on $1\frac{1}{2}$ slopes, because of wedge action caused between the two layers and of reduction of up-lift pressures caused by receding waves.

(e) The number of concrete hollow tetrahedron blocks necessary for two-layer placing on a given area is on an average 15 percentages fewer than that of tetrapod blocks with the same dead weight.

PRACTICAL USES OF HOLLOW TETRAHEDRON ARMOR UNITS

Interim report on the tests of the hollow tetrahedron armor units was first done at the 6th Conference of Coastal Engineering in Japan held at the beginning of November, 1959. One to two ton concrete hollow tetrahedron armor units have been in use or partly under construction for protective cover layers of rubble-mound breakwaters and for wave energy absorbing parallel dykes located in front of sea-walls at several harbors and coasts in Japan. The effect of absorbing wave energy of the hollow tetrahedron armor units will be checked when subjected to attack by heavy storm waves generated by typhoon at August and September this year.

REFERENCE

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3. "Laboratory Tests on Stability of Hollow Tetrahedron Armor Units on 1 : $1\frac{1}{2}$ Slopes," by S. Nagai and S. Ueda, Annual Meeting of Japan Soc. of Civil Eng., May 1960.