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Measuring Wave Force on a Rocky Intertidal Shore

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Abstract

Wave force, although a potent agent determining distribution and abundance of intertidal rocky communities, has seldom been measured in ecological studies. Here a simple dynamometer, which records the compression of a spring induced by the wave force, was employed to obtain a series of measurements at a number of sites on the rocky intertidal platform of Benten-jima, Usujiri, near Hakodate over a period of 12 months. These measurements were used to calculate the perpendicular component of the maximum dynamic pressure produced by the wave. When compared with several environmental variables, their agreement suggests that the dynamometer may be a useful device for measuring wave action on a rocky shore. In using this dynamometer, the intertidal stations in this study were divided into 4 groups, influenced by a gradient of wave force.

A wave breaking on a rocky shore is among the environmental factor which have been thought to play an important role in the distributional structure of rocky shore communities[1~6]. Most authors content themselves with describing rocky shore communities as "exposed" in contrast to "sheltered". No doubt this rough categorization is a consequence of the difficulties involved in providing accurate measurements of wave forces, due both to the complex water flow in breaking waves and to the large and often dangerous forces involved. Various types of apparatus have been devised for measurement of wave forces on a spatial scale appropriate to intertidal organisms. Some measurements, such as erosion of paris clods[7], paris balls[8], and cement blocks[9], have worked in specific circumstances, but, in general, they give unstandardized or uncertain results. Denny[10] designed a telemetory system by which the direction and magnitude of the forces imposed on intertidal organisms by individual breaking waves could be continuously monitored. Although this method provides data of wave direction, it requires substantial site preparation and is inappropriate for simultaneous wave monitoring over many sites. Jones and Demetropoulos[11] measured wave force by recording the maximum drag exerted on a drogue attached by a rope to a spring scale. In their device, the method used to record the wave force was a pivoted arm which remained in the extreme position to which it was pushed by the balance pointer. In the device of Palumbi[12], when a wave hits the device, the resulting force on a drogue causes to the sliding head of the cable tie to move forward until the opposite force exetred by the elastic equals the wave force on the drogue. The above mechanical dynamometers are simple to build, wieldy, inexpensive, and can be applied over various sites of a rocky shore. However, the force exerted in a direction perpendicular to the substratum cannot be induced from the records, because the drogue is free to move about.

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For many applications, a continuous record of individual wave force is unnecessary, and the maximum force in the perpendicular direction may prove of further importance in examining the foraging behavior and orientation of benthic intertidal organisms of the rocky shore.

In the present work, an attempt has been made to measure the perpendicular component of force exerted by breaking waves on a intertidal rocky shore, based on the compression induced in a spring by the wave force, at a number of sites on the intertidal platform over a period of 12 months.

Apparatus

The apparatus used in this study was devised to record the perpendicular component of the maximum wave force produced in the period during which the apparatus was exposed on the shore. Figure 1 shows the apparatus; it consists of a body and a sliding cup. The body is the dynamometer housing, cut from 26 mm-o.d. PVC tubing. The sliding cup is suspended from the housing by a steel spring, allowing it to move freely paralell along the outside of the body, and functions as a pressure disc on which the moving water acts, compressing the spring and producing a reading on the cable tie (T-30R, No. 04-5021). A sliding head of cable ties will move unidirectionally along the laterally grooved plastic ribbon. The force exerted on the sliding cup causes the sliding head of the cable tie to move forward until the opposite force exerted by the spring equals the force on the sliding cup. As backward movement of the sliding head is hindered, the head remains in place when the force recedes. The forward distance from the point where the sliding head just begans to move is an estimate of the perpendicular component of maximum wave force. Once readings are taken, the device can be reset by sliding the head back to its initial position at the base end of the cable. Results are derived from measurements using these devices and are indicated in units of g/cm^2 calcu-

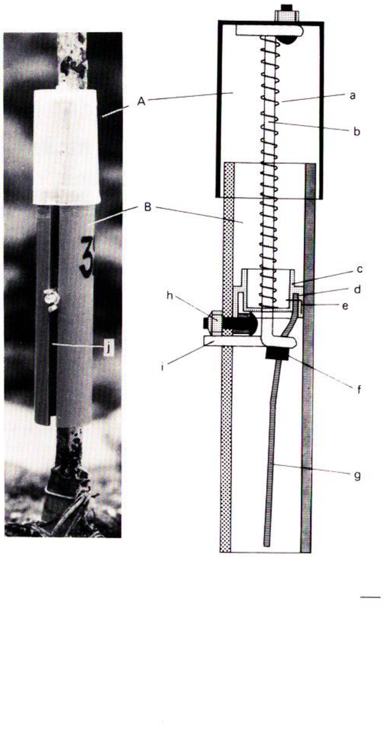

Fig. 1. Frame of simple spring dynamometer. A: sliding cup (40 mm in length, 30 mm in o.d.), B: body (110 mm in length, 26 mm in o.d.), a: spring, b: roading rod, c: removable septum, d: base end of cable tie, e: pin fixing cable tie, f: sliding head of cable tie, g: cable tie, h: stopper, i: guiding bar, j: guiding slit.

lated by dividing force measurements by the cross-sectional area of the sliding cup.

Methods

Study sites : Experiments were made on the rocky intertidal platform at Benten-jima, Usujiri, just northeast of Hakodate. This shore, as seen from the map (Fig. 2), faces southeast. The northern shore of this platform is protected on its eastern side by a large, detached mass of stack, creating an intertidal zone which is absent from the more wave-exposed parts of the platform. This zone has numerous large boulders. The southern part of this platform forms a roughly horizontal rocky shore, with small, shallow tide pools which may be less than 5 m across and usually only 10–20 cm deep. This southern, unprotected side is the most exposed to waves, and which seem much stronger than waves striking the exposed end of the northern part.

Application : Maximum wave force measurements were taken at various sites from October, 1986 through October, 1987 on Benten-jima platform. The device was attached to a steel post nailed into the rock, and wave measurements were taken bimonthly for 12–42 days running.

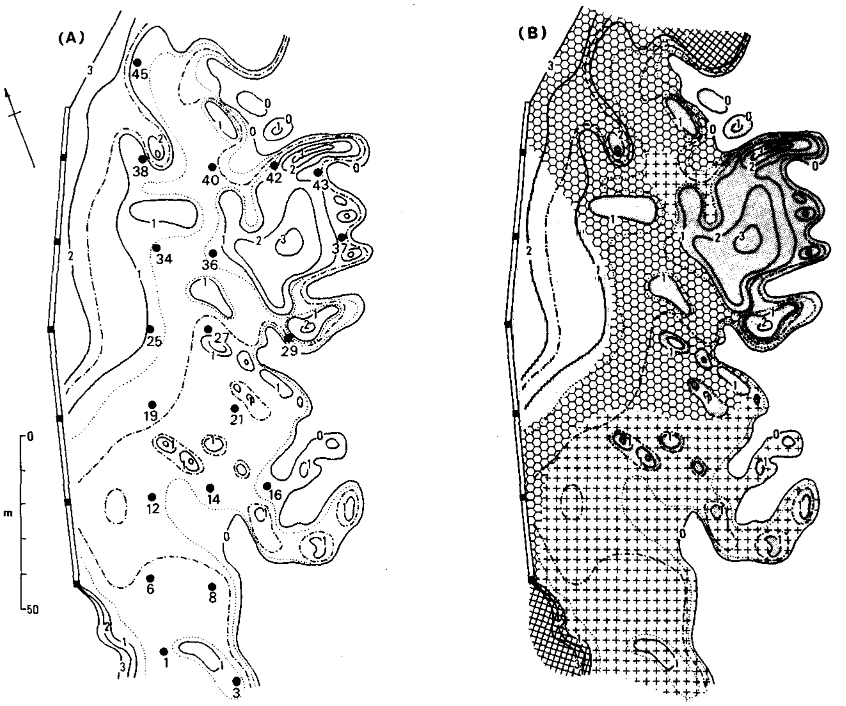

Fig. 2. Map of the Benten-jima intertidal platform. (A) : Station and height above datum (m). (B) : Substratum ; ⬡⬡ : boulder, ++ : rock slope, ▒ : stack, ▩ : cliff, |||||| : sand, ▬ : varrier.

Table 1. Wave forces measured at 20 stations. R : rock slope, St : stack, B : boulder, EE : extreme exposure, E : exposure, S : shelter, ES : extreme shelter.

	Environmental variable				Perpendicular component of maximum wave force (g•cm^{-2})					
Station	Height above datum (cm)	Substratum	Degree of exposure	Distance from shoreline (m)	Season 1 (Oct. 18 - Nov. 1)	Season 2 (Dec. 19 - Jan. 29)	Season 3 (Mar. 20 - Apr. 19)	Season 4 (May 13 - June 13)	Season 5 (July 14 - July 25)	Season 6 (Oct. 1 - Oct. 27)
1	70	R	E	22	27	52	22	32	27	30
3	84	R	EE	6	86	142	—	88	—	128
6	55	R	EE	27	61	67	45	26	19	51
8	59	R	EE	10	—	93	55	—	49	71
12	30	R	EE	26	37	30	41	26	26	44
14	38	R	EE	12	28	56	60	47	26	24
16	15	R	EE	4	72	84	71	80	46	84
19	54	B	E	40	75	52	41	47	35	60
21	36	B	S	20	10	27	15	22	25	27
25	100	B	S	33	19	50	41	22	17	49
27	25	B	S	18	20	40	27	30	26	37
29	34	St	ES	1	28	50	52	35	40	49
34	74	B	ES	40	32	41	34	13	22	23
36	76	B	ES	30	18	—	31	—	22	23
37	71	St	EE	2	99	120	90	90	60	97
38	83	B	ES	32	10	24	27	15	18	21
40	54	R	E	15	22	100	78	32	43	72
42	80	B	E	2	63	112	96	80	49	71
43	72	St	EE	2	96	107	84	93	99	95
45	95	B	E	22	10	11	7	22	15	16

Results and Discussion

The 20 intertidal stations observed here span the range of wave force regions from exposed to sheltered. Table 1 gives the results obtained in all seasons. Before accepting these results as valid indicators of degree of wave exposure, it was first necessary to verify that they actually reflect intensity of wave action and that the seasonal variations obtained were not due to chance.

Multiple regression analysis, applying nominal scale as predictive variables, was used to reveal any relationships between the environmental variables (distance from shoreline, degree of exposure, hegiht above datum and substratum) and the wave force measured. As can be seen in Table 2, the multiple correlation coefficient, R is 0.94, or $R^2=0.89$, indicating that 89% of the total variance may be predicted from the 4 environmental variables. Among the partial correlation coefficients, Item 1 (distance from shoreline) and Item 2 (degree of exposure) have the greatest value :

Table 2. Relationships between the environmental variables and the wave force measured.

Factor	Category	Score	Partial correlation coefficient
Item 1 : Distance from shore line (m)	0- 10	20.296	0.851
	10- 20	− 0.476	
	20- 30	−22.368	
	30- 40	− 7.082	
Item 2 : Degree of exposure	Extreme shelter	−16.607	0.712
	Shelter	− 9.186	
	Exposure	0.400	
	Extreme exposure	11.499	
Item 3 : Height above datum (cm)	0- 25	− 7.850	0.581
	25- 50	−15.143	
	50- 75	2.978	
	75-100	8.742	
Item 4 : Substratm	Boulder	− 4.847	0.367
	Rock slope	2.225	
	Stack	8.608	

Multiple correlation coefficient (R)=0.9438

0.851 and 0.712 respectively. These facts show that the perpendicular component of breaking wave force was most intense at the stations situated along the shoreline where wash first breaks, and that the greatest wave force was, in fact, obtained where subjective judgment suggested that degree of exposure would be most intense.

Comparison between the seasonal variation of wave focre and the magnitude of wash when measurements took place could not be made directly since the actual magnitude of wash had not been recorded. However, from the daily record of the sea conditions kept by the Usujiri Fisheries Experimental Station of our University, it was possible to estimate the probable maximum dimension of the waves during

Table 3. Sea conditions. Grade of wave is as follows ; aa : glassy sea, a : ripple, b : breaker, c : billow, d : angry billow, dd : fury billow. Number of season is the same as those shown in Table 1.

Grade of wave	Frequency (days)					
	Season 1	Season 2	Season 3	Season 4	Season 5	Season 6
aa	1	5	3	5	3	4
a	5	11	12	11	3	5
b	7	12	10	12	4	5
c	2	8	4	1	2	2
d	0	5	2	0	0	1
dd	0	1	0	0	0	0

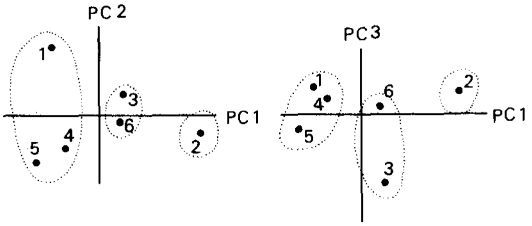

Fig. 3. Ordination (R-mode) of seasons on components 1 to 3. In this figure, seasons were given the same number as those used in Table 1.

each season. The sea conditions are summarized in Table 3. The most intense waves appeared in the wintertime during December to January, while the seasons of early summer and late autumn were exposed to calm conditions. Relationships between the above trends in the sea conditions and major trends in the seasonal variation of the measured wave force have been isolated by the multivariate statistical technique of principal component analysis. In this technique, if stations (columns) are chosen as "individuals", they are each represented by a number of "attributes" which are the records of the wave forces (rows) for those stations. Such a matrix is usually termed a Q-matrix, and the inverse of this matrix is a R-matrix[13]. Analysis is carried out to agglomerate and to analyse trends in the ordination of seasons (R-mode) or of stations (Q-mode). The first 3 components accounted for 82.6% of the total variance in the R-mode matrix; I: 55.3%, II: 21.1 %, III: 6.2%. Each eigenvector on Component I has a positive similar value. The first axis, therefore, seems to correlate with a gradient of the wave force. Component scores of the first 3 components are plotted in Figure 3. On the first axis, Season 2 has relatively high positive loadings, while Seasnos 1, 4 and 5 are given negative loadings. There are 3 season groupings: Group A represents winter (Dec. to Jan.), with the most intense waves; Group B includes spring and autumn of 1986, having moderate wave action; Group C includes 3 residual periods covering summer and autumn of 1987, when sea conditions were calm. This ordination corresponds with the results of Table 3 indicating the seasonal trend of sea conditions. It is infered from these results that the seasonal variation in the measurements is not a chance effect, but that the measured values are related to the exposure of the stations. Consequently this apparatus allows to be a reliable indicator of breaking wave force in a direction perpendicular to the substratum on rocky intertidal shores.

In order to investigate how wave impact depended on the intertidal platform on

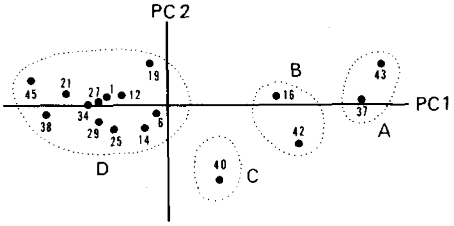

Fig. 4. Ordination (Q-mode) of stations on components 1 and 2. Number indicates the station.

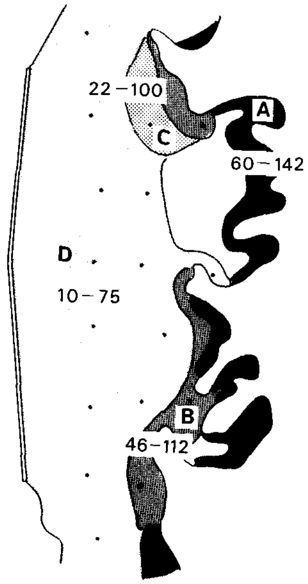

Fig. 5. Isodynamic area ; A,B,C, and D, agglomerated by the statistical analysis.

which devices were set, the values at each station were used for principal component analysis. This is done in order to group stations with similar wave forces. The ordination (Q-mode) obtained from the analysis of 17 stations is shown in Figure 4. The first 2 components explain 85.1% and 6.3% of the total variance of the system, respectively. There are 4 groups : Group A, consisting of stations 37 and 43 ; Group B, stations 16 and 42 ; Group C, station 40 ; Group D, stations 1, 6, 12, 14, 19, 21, 25, 27, 29, 34, 38 and 45. Group A and Group B, which consist of the stations with score over 2.0 to 1 of the 2 components, shows a distinct distribution. They are on the most outer area of this platform and are exposed directly to the first breaking point of wash. Station 29, at the outer end of the platform, is not included in these groups. This may be explained by its location just behind of the sheer stack. In fact, its degree of exposure is similar to the stations located in the inner area of the platform. Group D includes stations with scores ranging from −0.16 to −2.92 to Component I and with values from −0.53 to 0.56 to Component II. This group has the broadest distribution in the upper parts of the area studied. Since complete data could not be obtained due to damage and loss of the device, stations 3, 8 and 36 were excluded from the above analysis. However, the limited data obtained from these stations (Table 1) would allow them to be placed in any one of the groups categorized above. The map shown in Figure 5 summarizes the isodynamic area with the range of seasonal variations in the wave impact. Based on records of the maximum drag produced by a drogue free to swing in any direction, Jones and Demetropoulos[11)] reported that wave force on a rocky shore ranged from 100 g/cm^2 to 1000 g/cm^2, and Palumbi[12)] reported wave forces of $3.6\times10^3 \sim 7.1\times10^3$ N/m^2 measured in a similar manner from an exposed rock face. Both these results are some superior to the present observation which the wave force measured as the perpendicular component. This fact may be due to a difference of the manner employed to measuring wave force. Since wave impact may be a potent agent determining species presence, abundance, distribution, predation, and selection of habitat[14~18], in any way, further measurements are needed at various microhabitats of intertidal benthos.

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