CHAPTER 156

ON STRESS IN TETRAPODS UNDER WAVE ACTION

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ABSTRACT

Recently, as well as hydraulic stability, structural strength of armor blocks has emerged as a major problem in breakwaters. This problem is studied by research organizations in many countries. In Nippon Tetrapod Co., Ltd., a series of hydraulic model tests was conducted to measure the surface strain on Tetrapods under wave action.

In this paper, the results of the hydraulic model test are described. Prior to the hydraulic test, a similitude relation on impact stress and strain between the prototype and model was derived and a drop test was performed to investigate the scale effect on impact strain on Tetrapods. The hydraulic test was conducted to measure the surface strain on 50kg model Tetrapods using strain gages. In addition, impact strain on 50t Tetrapods under wave action was estimated applying the similitude relation.

The strain on Tetrapods under wave action was clarified through this study.

1. INTRODUCTION

In recent years very large armor blocks have been used for many coastal structures especially in rubble mound breakwaters in deep areas. Wave forces hitting structures in these areas are very large. Blocks in an armor layer receive extreme wave forces and some of them are subject to breakage. In one such incident, the breakwater in Sines, Portugal received serious damage.

Armor layers are usually designed by means of Hudson's formula or hydraulic experiments on their stability. Structural damage to individual blocks is not considered, so there is a possibility that the armor blocks are hydraulically stable but structurally unstable

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as a result of such design methods. Structural damage to individual blocks can escalate into hydraulic damage to the whole armor layer. It is necessary to design coastal structures that take into consideration not only block hydraulic stability but also block structural strength.

In order to study stress occurring in blocks, Terao et al (1982) and Burcharth (1981) carried out drop tests using prototype Dolosse while Delft Hydraulics Laboratory (1983) and Hall et al (1984) measured bending moment in model Tetrapods and stress in model Dolosse respectively, both made of new materials, under wave action using new measuring techniques.

Stress in blocks is not well known under wave action. If the stress in blocks could be monitored and clarified, the results could contribute to the design of better armor layers.

From this view point, a hydraulic model test was conducted to measure the surface strain on blocks under wave action. The block utilized was Tetrapod because it is commonly used for coastal structures in Japan. In the test section, 50kg Tetrapods were placed in two standard layers and surface strain on two instrumented Tetrapods in the vicinity of each other just above the still water level was measured using strain gages.

The behavior of Tetrapods under wave action can be distinguished as follows, (1) Tetrapods rocking slightly, (2) Tetrapods rocking easily and repeatedly and (3) Tetrapods falling down. The test was conducted to examine the strain on Tetrapods for each category of behavior due to waves.

2.LAW OF SIMILITUDE

In the case of block collisions, the impulse induced by the impact force is assumed to be equal to the change in momentum, so the following equation is validated.

$$\int_{0}^{T} P d dt = m \left(v' - v \right) \tag{1}$$

where Pd; impact force

v,v'; velocity of the block just before and after collision respectively

- m; mass
- τ ; duration of impulse

From eq. (1),

$$Pd \propto \frac{m v (1+e)}{\tau}$$
(2)

where e; coefficient of restitution

is derived. The time it takes for a longitudinal shock wave to travel from the point of impact to a free edge and back again equals the duration of an impulse, as shown by Burcharth (1981) and Aoyagi (1972). As concrete was used for the model material, the modulus of elasticity, density, coefficient of restitution and the speed of a longitudinal wave in concrete are the same as those of the proto-type. Therefore, the impact force is proportional to the speed of collision, and inversely proportional to the distance between the impact point and a free edge of the block.

In this test, the armor blocks are assumed to be moving according to Froude's law,

$$vm / vp = \lambda^{1/2}$$
(3)

where λ is a linear scale of a model Tetrapod and the subscripts m and p refer to the model and prototype respectively.

From the consideration above, the similitude ratios of the impact and elastic forces are obtained as follows.

$$Pdm / Pdp = \lambda^{5/2}$$

$$Pem / Pep = (\sigma m / \sigma p) \lambda^{2} = (\varepsilon m / \varepsilon p) \lambda^{2}$$
(4)
(5)

where Pe; elastic force σ ; stress ϵ ; strain

The similitude relations of the stress and strain between the model and prototype under wave action are represented by eq. (6), as eq. (4) is equal to eq. (5).

$$\sigma \mathbf{m} / \sigma \mathbf{p} = \varepsilon \mathbf{m} / \varepsilon \mathbf{p} = \lambda^{1/2} \tag{6}$$

3. TEST EQUIPMENT AND TEST METHOD

3.1.Model of Tetrapod

The following equation should be valid in order for the similitude relation to hold true.

 $\varepsilon = \alpha v$

(7)

where ε; impact strain
 v; collision speed
 α; a constant factor

The value of α in the model is the same as that in the prototype. A drop test was performed beforehand to confirm the validity of eq. (7) using from 736g to 4t Tetrapods. Fig. 1 shows α values calculated by eq. (7) utilizing measured values of maximum impact compressive strain generated at the top of a leg (on the compressive side) with a linear scale factor based on 40kg Tetrapods. This figure indicates that α became constant when Tetrapods heavier than 40kg were utilized. So if 50kg Tetrapods were used in the test,



Fig. 1 Scale Effect Concerning Impact Strain on Tetrapod



Fig. 2 Locations for Strain Measurement

eq. (6) could be applied. Therefore in the hydraulic experiment, 50kg Tetrapods were used.

Four instrumented Tetrapods of 50kg were made of concrete using gravel of size 25mm. Strain was measured at three locations 120 degrees to each other on the top center of each leg. Totally 12 points per one Tetrapod were examined as shown in Fig. 2. Strain gages (length=10mm) on the surface of the instrumented Tetrapods were covered with waterproofing cement. Photos 1 and 2 show a Tetrapod model completed. Characteristics of the test Tetrapods were measured and tabulated in Table 1. These values were close to standard concrete.



Photo 1 Strain Gages on the Surface of the Test Tetrapod



Photo 2 50kg Tetrapod Model

Characteristics of the test Tetrapods	Moist condition	Air-dried condition
Unit weight (kgf)	50.6	49.7
Specific weight (gf cm ⁻³)	2.36	2.31
Static modulus of elasticity $(kgf cm^{-2})$	3.08×10 ⁵	2.45x10 ⁵
Dynamic modulus of elasticity (kgf cm ⁻²)	3.60x10 ⁵	3.68x10 ⁵

Table 1 Characteristics of the Test Tetrapods

3.2.Test Equipment

A large wave channel, 205m long, 3.4m wide and 6.0m deep, at the Central Research Institute of Electric Power Industry was used in order to generate large waves for the 50kg Tetrapods utilized. Fig. 3 shows the diagram of the test section.



Fig. 3 Sketch of Test Section (unit; m)

The apparatus for measurement used in the experiment is listed below.

*Dynamic strain amplifier; This was used for amplifying electric current from strain gages. *Data recorder; This was used in order to record analog data through the dynamic strain amplifiers. *Multi-channel oscillograph; Strain was reproduced on a multichannel oscillograph chart. *Video system; This was used to record Tetrapod motion.

3.3.Test Method

A test section was constructed at a distance of 130m from the wave paddle in the flume. In the test section, 50kg Tetrapods were set up in two standard layers. The two instrumented Tetrapods were placed in the vicinity of each other just above the still water level so that they received the maximum impact wave force. Photo 3 shows the condition during placement.

Strain was recorded by the data recorder and reproduced on a strip chart at a speed ratio of 1:32 that of the recording speed for the duration of the impact strain itself, which was in the order of one millisecond to obtain a clearer result. Strain on the chart was measured by a scale.



Photo 3 The Condition during Placement

3.4.Test Cases

Test cases are summarized in Table 2. In the table, *h (m) ; water depth at a toe of the Tetrapod slope *T (sec) ; wave period *Lo (m) ; wave length in deep water *Ho' (m) ; equivalent deep water wave height *H (m) ; wave height at the toe of the Tetrapod slope with the structure not in place *Ns ; stability number *Tetrapod Number; T.P.No.1-4 are the instrumented Tetrapod number.

Experiments were conducted to study the strain on Tetrapods for each category of behavior of Tetrapods due to waves (as mentioned in the introduction).

Case No.	h (m)	T (sec)	Lo (m)	Ho' (m)	H (m)	Ns ³	Tetrapod Number
1-1 1 1-11	1.7	4.0	24.96	0.96 1 1.51	1.04 ι 1.51	23.6 1 72.1	T.P. No.1,4
2-1 1 2-9	1.4	6.0	56.1 5	0.87 ι 1.17	1.55	78.0	T.P. No.2,3
3-1 1 3-8	1.5	6.0	56.15	1.09 1 1.31	1.60	85.8	T.P. No.2,3
4-1 1 4-4	1.5	4.0	24.96	0.90 1 1.33	0.97 1.35	19.1 1 51.5	T.P. No.3,4
5			Drop	Test			T.P.No.3

Table 2 Test Cases

In cases 1-3, tests were carried out after standard placement to measure the impact strain for Tetrapods rocking slightly. In case 4, one of the two instrumented Tetrapods was placed so that it rocked easily and repeatedly, while the other was placed so that it would fail down easily. Waves were generated for 100sec in cases 1 and 4, and 60sec in cases 2 and 3. This was decided after taking effect of re-reflected waves from the wave paddle in the wave tank into consideration. In case 5, one instrumented Tetrapod was pushed down manually from the crown of the dike in the still water condition. Photo 4 shows waves hitting Tetrapods in case 1.



Photo 4 Waves Hitting Tetrapods

4.TEST RESULTS

Test results are classified into three categories according to the behavior of Tetrapods due to waves.

4.1. Category No.1 ; Tetrapods Rocking Slightly

In this category, Tetrapods were placed with sufficient interlocking. Actual motion of test Tetrapods was not visible under wave action in the flume, but was observed by a comparison of the position of Tetrapods just before and after waves hit.

Measured impact strain is tabulated in Table 3. ε tmax and ε cmax are used for the maximum values measured on tensile and compressive side respectively when collisions occurred. Behavior of Tetrapods due to wave attack is shown in Fig. 4.

In case 1, Tetrapods moved gradually according to wave action and Tetrapod No.1 fell down in case 1-11. The impact strain was not measured on Tetrapod No.4, but was measured in case 1-10-3 (during the third wave generation) on Tetrapod No.1. In cases 1-1-1-9, impact strain was not measured.

In case 2, a number of waves, of which the wave heights measured 1.55m, hit the Tetrapods. Because both instrumented Tetrapods moved only slightly, the impact strain on them was not measured.

In case 3, impact strain was not measured in cases 3-1-3-4, but was measured and found to be $3-26\times10^{-6}$ on Tetrapod No.2 in cases 3-5-3-7-1. Tetrapod No.2 fell down in case 3-7-2, because a number of large waves, of which Ns³ = 85.8 hit them continuously. In this case, impact strain on Tetrapod No.3 was measured after the fall of Tetrapod No.2. When impact tensile strain had just exceeded 25×10^{-6} , it decreased gradually even though waves were continuously generated.

4.2. Category No.2 ; Tetrapods Rocking Easily and Repeatedly

In this category, the movements of the instrumented Tetrapod are noted in Fig. 5. Its reactions to waves were as follows ; leg 1 crashed into Tetrapod A due to the waves and returned to its previous location due to gravity. Leg 2 collided with Tetrapod B. The distance which leg 1 moved was approximately 20cm. The measured impact strain is summarized in Table 4.

4.3. Category No.3 ; Tetrapods Falling Down

In this category, the measured values of impact strain are summarized in Table 5.

In cases 1-11 and 3-7-2, Tetrapods rolled down toward the toe of the Tetrapod slope. In these cases, tests were conducted after standard placement with sufficient interlocking. In cases 4-1, 4-2

and 4-3, each instrumented Tetrapod moved down a distance equal to approximately 1/2-1 of the block height. In case 4-4, the instrumented Tetrapod moved down a distance of 1/2 the block height, and continued to roll down toward the toe of the slope. In these cases, tests were performed after each instrumented Tetrapod was placed so that it would fall down easily.

				The maximum impact strain $(X10^{-6})$				
Case	Т	н	Ns ³	Tetrapod No.1		Tetrapod No.4		
No.	(sec)	(m)		ε tmax	εcmax	εtmax	εcmax	
1-1 1 1-10-2	4.0	1.04 1.51	33.6 ĭ 72.1	0	0	0	0	
1-10-3	4.0	1.51	72.1	26	-32	0	0	
1-11	4.0	1.51	72.1	Falling	g down	0	0	

Table 3(a) Measured Impact Strain for Tetrapods Rocking Slightly

Table 3(b) Measured Impact Strain for Tetrapods Rocking Slightly

				The maximum impact strain $(X10^{-6})$				
Case	т	Н	Ns ³	Tetrapo	od No.2	Tetrapod No.3		
No.	(sec)	(m)		εtmax	εcmax	εtmax	εcmax	
3-1 1 3-4	6.0	1.60	85.8	0	0	0	0	
3-5	6.0	1.60	85.8	3	-4	0	0	
3-6-1	6.0	1.60	85.8	12	-19	0	0	
3-6-2	6.0	1.60	85.8	26	-25	0	0	
3-6-3	6.0	1.60	85.8	9	-10	0	0	
3-7-1	6.0	1.60	85.8	10	-13	0	0	
3-7-2	6.0	1.60	85.8	Falling down		25	-20	
3-7-3	6.0	1.60	85.8			19	-30	
3-8-1	6.0	1.60	85.8	Not me	asured	17	-22	
3-8-2	6.0	1.60	85.8	100L IIIC	asureu	11	-10	
3-8-3	6.0	1.60	85.8			20	-27	

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Just before No.1 fell down (case 1-11)

Fig. 4(a) Behavior of Tetrapods in Case 1



Fig. 4(b) Behavior of Tetrapods in Case 3



Fig. 5 Behavior of Tetrapod Rocking Easily and Repeatedly in Case 4

Case	Т	н	Ns ³	The maximum impact strain (X10 ⁻⁶)	
No.	(sec)	(m)		εtmax	εcmax
4-1	4.0	0.97	19.1	20	-20
4-2-1	4.0	1.04	23.6	29	-23
4-2-2	4.0	1.04	23.6	30	-30
4-3	4.0	1.18	34.4	19	-20
4-4	4.0	1.35	51.5	27	-30

Table 4 Measured Impact Strain for Tetrapods Rocking Easily and Repeatedly in Case 4

Table 5 Measured Impact Strain for Tetrapods Falling Down

Case	Т	Н	Ns ³	The maximum impac strain (X10 ⁻⁶)	
No.	(sec)	(m)		εtmax	εcmax
1-11	4.0	1.51	72.1	62	-60
3-7-2	6.0	1.60	85.5	92	-80
4-1	4.0	0.97	19.1	38	-93
4-2-1	4.0	1.04	23.6	58	-61
4-2-2	4.0	1.04	23.6	45	- 64
4-3	4.0	1.18	34.4	11	-28
4-4	4.0	1.35	51.5	40	-65
5	Drop test			36	-44

5.DISCUSSION

5.1. Impact Strain and Wave Properties

Because impact strain was significantly influenced by Tetrapod placement, correlations between impact strain and wave properties could not be clarified. After waves began to hit the test Tetrapods placed in standard layers, even when wave heights were large, corresponding to Ns³ = 70 - 85, the impact tensile strain was found to be $3 - 12 \times 10^{-6}$ because interlocking was sufficient. However in the three test cases, impact tensile strain was measured to be approximately 25×10^{-6} prior to the instrumented Tetrapod falling or after adjacent Tetrapods fell down. It can be seen that this value was

almost the same as that obtained in the case where the instrumented Tetrapod was placed without sufficient interlocking. When such strain occurred, the instrumented Tetrapod was not in a condition of interlocking. Therefore, such strain was classified into category No.2. When impact tensile strain had just exceeded 25×10^{-6} , one of two things occurred : i.e. the instrumented Tetrapod fell down or the impact strain decreased gradually again even though waves were continuously generated. The latter indicates that Tetrapods are inclined to move from unstable positions to more stable ones under wave action.

In the case where the instrumented Tetrapod was placed without interlocking, behavior of the Tetrapod followed the wave action repeatedly. The measured impact strain when leg 1 crashed into Tetrapod A was larger than that when leg 2 collided with Tetrapod B (as mentioned in 4.2.). It can be deduced that when incident waves hit the test Tetrapod the block accelerated, and when it returned, its behavior depended mainly on gravity.

The maximum impact strain on one instrumented Tetrapod pushed down manually from the crown of the dike into still water was not so large as that generated by the wave down rush even though the falling distance was long. It was observed that when Tetrapods fell down under wave action, their fall accelerated due to wave run-down. Their collision speed also increased.

5.2. Estimation of Impact Strain on 50t Tetrapods

From the test results, the impact strain in 50t Tetrapods under wave action was estimated applying eq. (6) as follows.

 $\varepsilon_{50t} = 3.12 \varepsilon_{50kg}$

(8)

where e_{50t} ; impact strain in 50t Tetrapods e_{50kg} ; impact strain in 50kg Tetrapods

The maximum values of impact tensile strain on 50t Tetrapods ϵ_{50t} tmax were calculated and tabulated in Table 6.

Behavior of Tetrapods	ε ₅₀ ttmax
Rocking slightly	37x10 ⁻⁶
Rocking easily	94x10 ⁻⁶
Falling down the distance equal to 1/2-1 their size	181x10 ⁻⁶
Falling down toward the toe of the slope	287x10 ⁻⁶
Falling down in the still water condition	112×10 ⁻⁶

Table 6 Estimated Maximum Impact Strain on 50t Tetrapods

When the maximum impact tensile strain on a 50kg model Tetrapod was found to be 92×10^{-6} as in case 3-7-2, cracks or breakage did not occur. On the other hand, Terao et al (1982) carried out drop tests using prototype Dolosse and showed that the maximum impact tensile strain measured without breakage was larger than 250×10^{-6} . However it could not be verified whether breakage of Tetrapods would occur or not under wave action from only the information mentioned above. It must be considered that occurrence of breakage would be influenced by not only the magnitude of strain but also the distribution of strain. Therefore, it was necessary to perform a series of drop tests using the model and prototype Tetrapods in order to examine in more detail the critical impact tensile strain when Tetrapods break.

6.CONCLUSIONS

The following conclusions were derived through the experiment.

- (1) When 50kg Tetrapods are used, the similitude relations on impact stress and strain between the model and prototype are satisfied even under wave action.
- (2) In cases where Tetrapods fall down under wave action, impact strain generated is larger than that in the still water condition.
- (3) It is necessary to examine in more detail the critical impact tensile strain when Tetrapods break.

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