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Application of Impact-echo Method to Degradation Diagnosis of Existing Coastal Structures

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ABSTRACT：Fishing port facilities are the main coastal structure in fishing village and form a large number of existing stocks for which introduction of life-cycle management such as durability upgrading and life extension measures is needed. To this end, degradation level of the facilities must be known and the degradation diagnosis must take into account the particularity of each facility. Hence, the scatter in diagnosis results by operator and inefficiency of diagnosis procedure should be eliminated by clear evaluation criteria and labor saving diagnosis procedure. This study aims at establishing a degradation index and simplification of diagnosis procedure applicable to the fishing port facilities. Applicability of impact-echo method using surface P-wave to the degradation diagnosis of fishing port facilities was investigated for the first time in terms of effects of moisture content and expansive cracks of concrete. Finally, accuracy and applicable range of the diagnosis method were studied using existing fishing port facilities.

KEYWORDS：*Fishing Port Facility, Concrete Structure, LCM, Degradation Diagnosis, Impact-echo Method*

1. Introduction

Fishing port, a major coastal structure in fishing village area, is approx. 3000 in number located in Japan forming a huge existing stocks. Construction of fishing port facilities started at the high-growth period and the fishing port facilities more than 30-year old dominates almost 40 percent. They are now subjected to updating with a fear of considerable deterioration (Fig. 1). Within the limited budget, the central and local governments should proceed appropriate maintenance including timely repair and rehabilitation for the existing stocks. In this circumstance, the Life Cycle Management (hereafter referred to as LCM) capable of optimizing the entire cost of repair, retrofitting and rehabilitation of the facilities in their service lives attracts attentions.

Basic concept of LCM for the fishing port facilities was outlined[1)] as shown in Fig. 2 while it is still under development leaving a number of tasks including selection of deterioration diagnosis method, advancement of accuracy in the diagnosis, simplification of inspection and diagnosis procedure, and advancement of precision in

Fig. 1 State of deterioration of concrete at fishing port.

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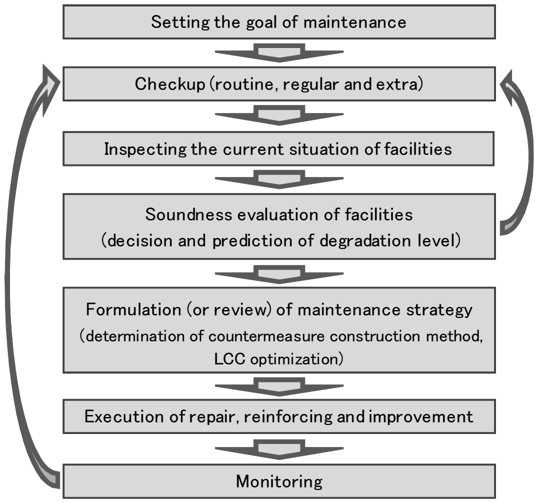

Fig. 2 Approximate LCM flow for fishing port facilities.

LCC estimation result. It was particularly pointed out that human factors such as operators' knowledge and skill and the geographical conditions of the facilities (immersion or hiding by wave-absorbing constructions) pose significant impact on the accuracy in diagnosis.

Taking into account the problems with maintenance of fishing port facilities, this study focused on the impact-echo method among other non-destructive, inexpensive and easy-operation methods applicable to large-scale concrete structures. Laboratory test was conducted to study the characteristics and applicability of the impact-echo method to fishing ports, which was then evaluated in the field test at existing fishing ports to examine the new application.

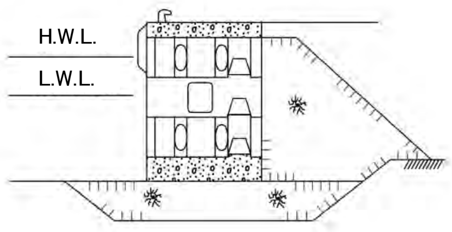

Fig. 3 Quaywall cross section .

2. Degradation diagnosis method applicable to fishing port facilities

2.1 Characteristics of degradation in the fishing port facilities

Fishing port facilities comprising huge amount of existing stocks show following characteristics.

(a) Shapes of concrete structures are generally elongated as typically seen in a breakwater.

(b) Because they are close to the coastal zone, chemical or physical degradation is easy to occur at concrete surfaces due to waves and seawater.

(c) Major facilities are made of reinforced concrete and sometimes of plain concrete in revetment facilities. (Almost 50 percent of the total length)

(d) Quay walls are normally backfilled as shown in Fig. 3 hence the approach to the facility for degradation diagnosis is limited, from the top or horizontally from the sea side.

2.2 Target of degradation diagnosis of the fishing port facilities

Fishing port facilities have been built as new or extension constructions without taking maintenance strategy into account and appropriate degradation diagnosis have never been attempted as yet. Managers of the fishing port facilities are aware of the necessity of diagnosis for the facilities dotted along the littoral regions, while they have no objective procedure and definite means for the necessary diagnosis in addition to the limitation in budget and management system. To manage this limitation, the following LCM must

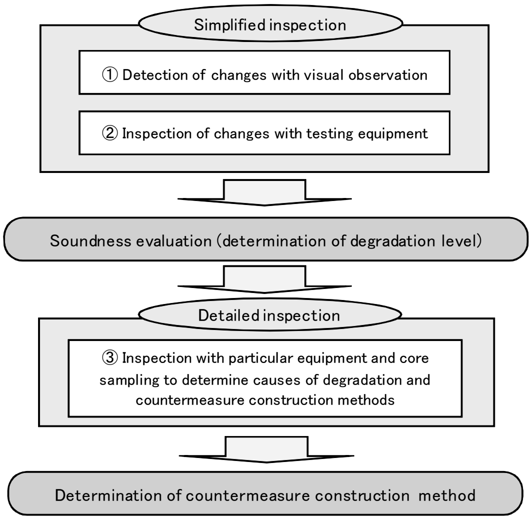

Fig. 4 Degradation diagnosis flow.

be introduced for the efficient and appropriate maintenance of the existing facilities.

(a) Selection of optimum repair construction method and smoothing the budget for the maintenance and update of the existing facilities.

(b) Development of efficient degradation diagnosis according to the step-by-step procedure as shown in Fig. 4 to accelerate the diagnosis of entire existing facilities

(c) Development of quantitative and easy diagnosis method applicable to elongated members to ensure universal and objective evaluation method for the soundness of structure.

However, considerable time and budget are needed to execute consecutive degradation diagnosis over the existing stocks, and any simple methods using visual observation and simple equipment may lead to a considerable scatter in the diagnosis results depending on the operators' skill and geographical conditions of the structure. In addition, detailed inspection requires high expertise and expensive inspection const. Hence, as stated in the previous section (c), development of an exact, reliable and accurate diagnosis method for the simple inspection is an ideal measure to execute rapid and efficient degradation diagnosis and to save labor, inspection cost and finally LCC.

3. Degradation diagnosis using impact-echo method

3.1 The impact-echo method

Non-destructive testing method is widely applied to on-site degradation diagnosis[2) 3)] and various equipment and analytical methods are under developing because it does not harm structures and relatively easy to figure out the degradation state.

Among non-destructive testing methods, the impact-echo method shows following advantages; it is relatively easy to use, rapid in measurement and inexpensive. Energy input by impact is large enough to cover a wide area of measurement. Effect of reinforcing steel and aggregate is small owing to the use of long-wavelength elastic wave. A variety of testing is possible including estimation of concrete compressive strength, internal flaw detection and crack depth measurement. It is thus very likely that the impact-echo method could be applied to the degradation diagnosis of fishing port facilities, which are mainly composed of reinforced concrete.

Impact-echo method can detect size and position of cracks and internal flaws in concrete using elastic wave that is generated by impact transmitter and received with a receiver both placed on the concrete surface. The applicable range depends on the frequency of the elastic wave and the transmission distance becomes longer at lower frequencies[4].

3.2 Characteristics of the impact-echo method

Some standard impact-echo methods for diagnosis of structures are known in overseas countries[5] while no standard is available in our country. However, estimation methods of strength[6], thickness and internal flaws[7,8] of concrete members has been proposed by the Ministry of Land, Infrastructure, Transport and Tourism.

Impact-echo method uses an elastic wave that is generated by a steel ball or impact hammer and received with a receiver placed on the surface of a concrete member. Elastic wave comprises compressive wave (P-wave) vibrating parallel to the traveling direction, shear wave (S-wave) vibrating perpendicular to the traveling direction and Rayleigh wave (R-wave) propagating along the surface as shown in Fig. 5. When a receiver of the elastic wave is placed on the concrete surface, waveforms of P-wave, S-wave and R-wave at the receiver can be given as schematically shown in Fig. 6 where P-wave reaches first[9]. Hence detection of the arrival time of the first elastic wave and the distance between the impact point and the receiver could give a P-wave speed that travels at the surface (hereafter called as surface P-wave) as shown in Fig. 7. Carino[10] compiled diagnosis methods using surface P-wave, and the strength estimation method proposed by the Ministry of Land, Infrastructure, Transport and Tourism uses surface P-wave speed.

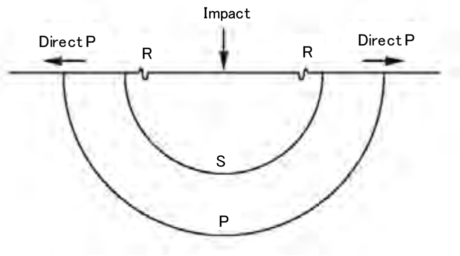

Fig. 5 Elastic waves generated by the impact on the surface of concrete member. [9]

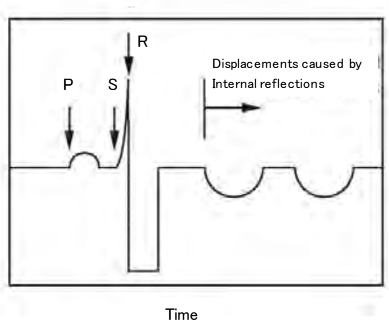

Fig. 6 Schematic representation of P, S and R-waves at arrival. [10]

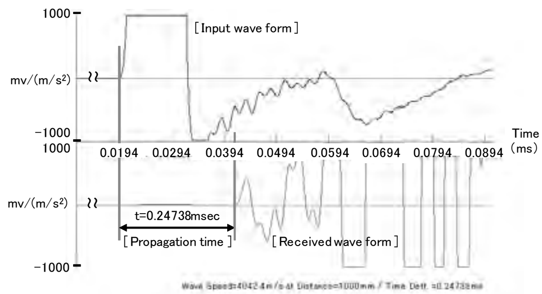

Fig. 7 An example of impact-induced wave forms.

3.3 Application of the impact-echo method to the fishing port facilities

A more accurate degradation estimation becomes possible when the impact-echo method with a large transmission length is introduced and an objective degradation criteria (degradation index) is established taking into account the characteristics of existing fishing port facilities as stated in 2.1. Regular monitoring of degradation of structures based on the quantitative degradation criteria using impact-echo method may contribute to the early detection of degradation of the huge existing fishing port facilities.

In this study, the degradation diagnosis method using surface P-wave, which has a large transmission length and can be favorably applicable to concrete structures among other non-destructive testing methods, is introduced to the simplified inspection as described in Fig. 4 ②. However, the existing studies of the application of the impact-echo method dealt mainly with new structures built on the land[7), 11), 12)], and those with old and coastal structures are quite few. It is a novel approach of this study that the degradation diagnosis using surface P-wave method was applied to the existing coastal structures having largely different degradation characteristics and structural systems from the land-based structures. On-site tests for the 30 to 40 year-old existing fishing port facilities as well as laboratory tests with various types of concrete specimens were conducted to figure out the transmission characteristics of the surface P-wave method. Because of its simplicity and perspicuity, the method using surface P-wave speed was adopted, and the applicability of the impact-echo method to the fishing ports was examined in terms of identification of “deterioration positions in concrete structure” and “evaluation of relative deterioration condition.” Particular care was paid for the surface P-wave transmission characteristics at a transmission length of few meters.

Table 1 Materials used.

Material	Type	Notation	Properties or ingredients
Cement	Ordinary portland cement	C	Density: 3.16 g/cc
Fine aggregate	Ooigawa crushed sand	S	Density: 2.59 g/cc F.M: 3.00.
Coarse aggregate	Fujigawa crushed rock	G	Density: 2.70 g/cc Max. size: 20mm.
Admixture	AE water reducing agent	AE	Lignin sulfonic acid and polyol compound
	Super plasticizer	SP	Polycarboxylic acid type
	Lime type expansion agent	E	Density: 3.16 g/cc Std. substitution: 20 kg/m^3.

Table 2 Mix proportions.

Series	No.	W/C	Unit content (kg/m^3)					Admixture (kg/m^3)	
			W	P		S	G	AE	SP
				C	E				
1	1	0.35	162	463	-	717	998	-	3.01
	2	0.50	162	324	-	819	1010	0.97	-
	3	0.65	172	264	--	866	986	0.66	-
2	4	0.50	162	324	0	819	1010	0.97	-
	5			304	20				-
	6			274	50				-
	7			244	80			1.62	-

4. Laboratory tests

Before applying to the fishing port facilities located closed to the coast, performance of the impact-echo test system and reproducibility of the past research results were examined in the laboratory. Especially, the effects of seawater were concerned in application, hence the effects of surface deterioration and expansive cracks due to corrosion and frost damage on the surface P-wave transmission were studied.

4.1 Testing methods

(1) Effects of compressive strength

Effects of compressive strength were examined in the test series 1 and 2 and the materials used and mix proportions are shown in Tables 1 and 2. Water-cement ratio was 0.35, 0.5 and 0.65 to have three compressive strength levels. Specimens for the surface P-wave speed measurement were produced using a metal form with a size of 150 x 150 x 900 mm. Specimens were unmolded 24 hours after placing and subjected to under water curing of 20±1°C for 27

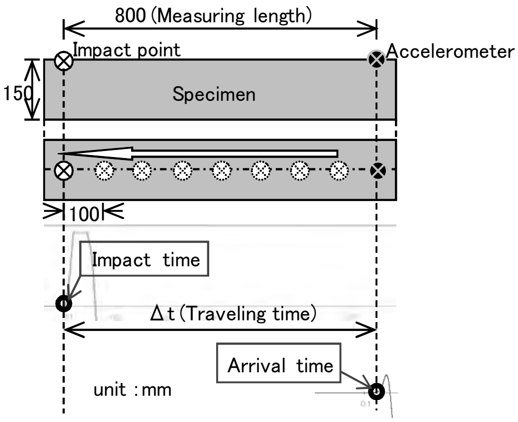

Fig. 8 Concept of the laboratory test for surface P-wave speed.

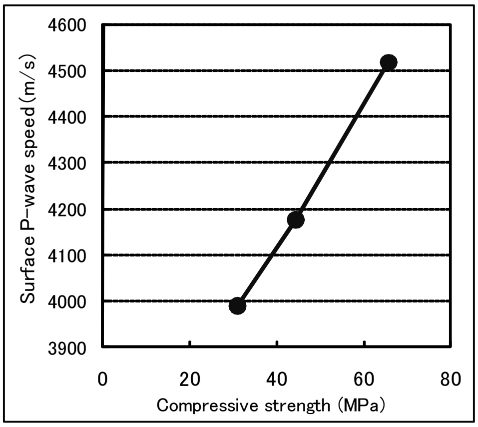

Fig. 9 Relationship between surface P-wave speed and compressive strength of concrete.

under water curing of 20±1°C for 27 days. Concept of the laboratory test for surface P-wave speed is shown in Fig 8. Accelerometers working as a receiver (Manufactured by company P with a sampling frequency of 0.5 μs) were glued to ensure the contact with the concrete surface at any positions. Impact source was an impact hammer with an impact accelerometer working as a transmitter which introduced an impact at every 100 mm spacing within 800 mm distance from the receiver[13]. Traveling times at each distance were recorded and subjected to the least-square regression analysis. Surface P-wave speed was obtained as the gradient of the regression line. The age of the concrete specimen was 28 days.

(2) Effects of moisture content

Specimens were the same as used in the test of the effect of compressive strength and hence had three compressive strength levels. At the age of 28 days, specimens were cured in air until the age of 160 days and, after the measurement of dry mass and surface P-wave speed, immersed in water for 7 days. Wet mass and surface P-wave speed was measured immediately and after air drying of 1, 2, 14, 42 and 45 days. After 42-day, specimens were subjected to oven drying at 105 °C for 3 days. Measuring method of surface P-wave speed was the same as used in section (1), and changes in moisture content of concrete were calculated based on the mass loss of specimen.

(3) Effects of swelling and expansive cracks

Materials used and mix proportions are shown as series 2 in Table 1 and 2 where water-cement ratio was 0.5 throughout and unit contents of expansive agent replacing cement were four levels; 0 20 50 and 80 kg/m^3. Because the standard dosage of expansive agent is 20 kg/m^3, excessive dosage was intended to form expansive cracks in concrete. Specimens subjected to surface P-wave speed measurement were manufactured with the same metal form as described in section (1). Specimens were cured under water for 7 days and subsequently in air. Surface P-wave speed measurement was performed with the same method as described in section (1) at a concrete age of 28 days. Length change measurement was also executed according to JIS A 1129-2001 to confirm the amount of expansion.

4.2 Results and discussion

(1) Effects of compressive strength

Relationship between surface P-wave speed and compressive strength of concrete is shown in Fig. 9. It is shown that surface P-wave speed increases with an increase in compressive strength of concrete specimen. Neglecting the contribution of Poisson's ratio to the wave speed, the P-wave speed is given approximately by the following equation,

$$v = \sqrt{\frac{E}{\rho}} \qquad (1),$$

where v is wave speed (m/s), E is elastic modulus of concrete (Pa) and ρ is bulk density of concrete (kg/m^3), increase in compressive strength corresponding to higher elastic modulus resulted in the increase in surface P-wave speed.

(2) Effects of moisture content

Mass change rate of specimens immersed in water for 7 days and subsequent air-drying are shown in Fig. 10(a). Mass change rate is calculated using Eq. 2.

$$\Delta m = \frac{m_d - m_0}{m_0} \times 100 \qquad (2)$$

where Δm is mass change rate (%), m_d is a mass when a wave measurement is performed and m_0 is the mass before immersion. Relationship between surface P-wave speed and mass change rate of concrete is shown in Fig. 10 (b). It is shown that surface P-wave speed increases slightly during immersion and when drying proceeds, decreased with decrease in mass change rate showing a peak in surface P-wave speed. This tendency agrees with the study of Tatsumi *et al.*[14] while Iwano *et al.* [15] reported that the transmission elastic wave speed increase with decrease in moisture content without exception.

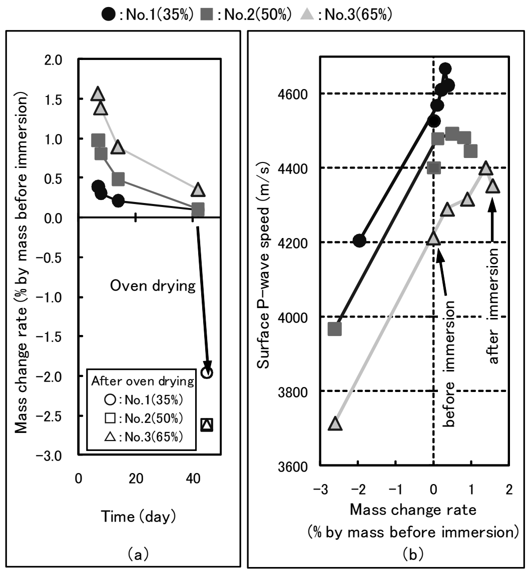

Fig. 10 Relationship between surface P-wave speed and mass change rate of concrete.

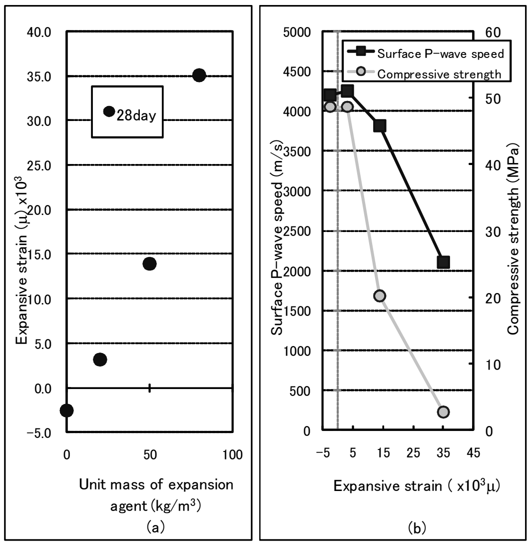

Fig. 11 Relationship between surface P-wave speed and expansion strain of concrete.

According to the nature of wave speed as shown in Eq. (1), surface P-wave speed may be affected by the following two factors: decrease in ρ with drying leads to an increase in surface P-wave speed and changes in moisture content affects changes in E[16].

(3) Effects of expansive cracks

Expansion strain of concretes at the age of 28 days is shown in Fig. 11 (a). Relationship between expansion strain, surface P-wave speed and compressive strength is shown in Fig. 11 (b). It is shown that both surface P-wave speed and compressive strength decreased in the same manner with an increase in expansive strain. Specimens with particularly large expansive strain showed abrupt decrease in compressive strength and surface P-wave speed. This may be attributed to cracks in the specimen generated by excessive expansion.

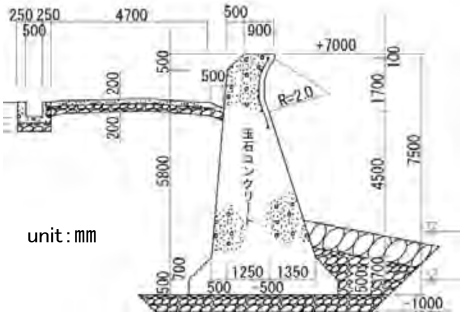

Fig. 12　General cross section of the targeted facility in Odawara fishing port.

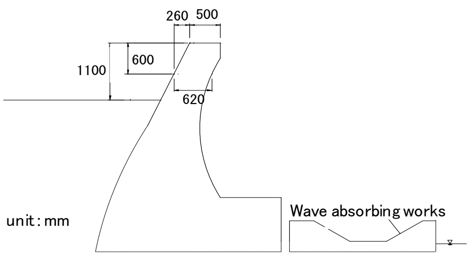

Fig. 13　General cross section of the targeted facility in Naru fishing port.

5. On-site inspection

To examine the applicability of the impact-echo method using surface P-wave speed, on-site inspection of existing fishing port facilities was executed both in Odawara (Kanagawa Pref.) and Naru (Nagasaki Pref.) fishing ports.

5.1 Location

(1) Odawara fishing port

Odawara fishing port located in the western part of Sagami bay is a type-3 fishing port under jurisdiction of Kanagawa prefecture. The targeted facility was a revetment built in the latter half of 60th as shown in Fig. 12.

(2) Naru fishing port

Naru fishing port located in the Goto islands at the western part of Nagasaki Pref. is a type-3 fishing port under jurisdiction of Nagasaki prefecture. The targeted facility was a revetment built around 70th as shown in Fig. 13.

5.2 Diagnosis procedure

Detection of changes with visual observation, as shown in Fig. 4 ①, was first performed over the entire facilities of Odawara and Naru fishing ports and the testing positions of the on-site inspection were determined so as not to stride the joint of the structure.

The impact-echo testing was performed both in Odawara and Naru fishing port facilities using a dedicated apparatus[7] starting with the measurement of surface P-wave speed. Measuring method of the surface P-wave speed on-site was the same as that of the laboratory testing as

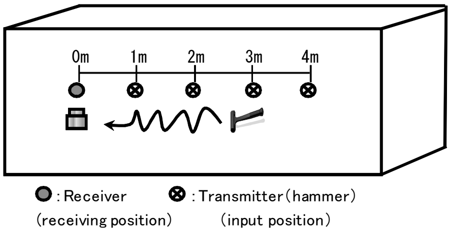

Fig. 14 Surface P-wave measurement configuration for the on-site testing.

Fig. 15 State of concrete surface at Odawara fishing port.

Fig. 16 Impact-echo testing at Odawara fishing port.

shown in Fig. 14. Accelerometers working as a receiver were glued to ensure the contact with the concrete surface at any positions. Impacts were introduced with an impact hammer at several positions with a specified distance from the receiver and the input-output waveforms were recorded. Surface P-wave speed at each distance was calculated with the traveling time and the distance.

As shown in Fig. 15, surface deterioration such as exposure of aggregates due to chemical weathering of waves and seawater was observed at the Odawara fishing port facilities while visible cracks were not detected. To evaluate the change in wave speed over time in Odawara fishing port facilities, a newly built concrete block with a dimension of 2.5 x 5.0 x 2.0 m was subjected to surface P-wave speed measurement (see Fig. 16) and the results were compared to that of the existing facilities. No cracks or flaws were observed in the new concrete block during the visual inspection.

To examine the crack-detecting capability of the impact-echo method, surface P-wave speed measurement was performed striding over a visible crack in the Naru fishing port. As described later, concrete surfaces in the existing fishing port facilities are likely to be deteriorated by waves and seawater thereby polishing the deteriorated surface may be necessary. To examine the effect of surface conditions on the result of measurement, surface P-wave measurement before and after polishing was performed.

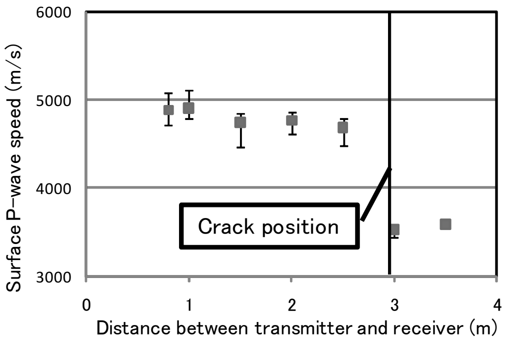

Fig. 18 Changes in surface P-wave speed across the visible crack in the Naru fishing port.

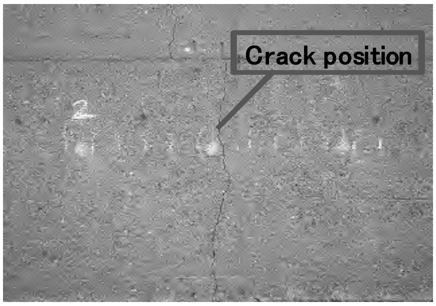

Fig. 19 Surface condition of concrete and a visible crack at Naru fishing port.

5.3 Results and discussion

Relationship between surface P-wave speed and distance between transmitter and receiver is shown in Fig. 17. The surface P-wave speed is an average of five measurements at a point. It is shown that surface P-wave speed of the new concrete block stays almost constant regardless of the distance between transmitter and receiver, while that of existing facilities shows decrease at a distance between 3.0 to 5.0 m. Because the decrease in surface P-wave speed may be in proportional with the extent of deterioration such as number of cracks, some flaws lowering the surface P-wave speed could probably be present at the existing structure of Odawara fishing port. Relationship between surface P-wave speed and the distance between transmitter and receiver is shown in Fig. 18. As seen in Fig. 19, measurement was performed striding a visible crack between transmitter and receiver. It is shown that the surface P-wave speed drops abruptly at the distance between 2.5 and 3.0 cm, which corresponds to the position of visible crack shown in Fig. 19. This implies that the proposed method may be able to detect cracks and their positions.

It is shown that the surface P-wave speed becomes lower than that of the sound part due to the presence of cracks or surface deterioration and the P-wave transmission characteristics through deteriorated concrete found in the laboratory tests was confirmed also in the on-site tests. This leads to a possibility of quantitative evaluation of deterioration progress in structure, without limiting to the detection of local flaws, provided that the changes in surface P-wave speed is continuously recorded at a specific position of the structure. This method is easier in operation and shorter in testing duration than those of core strength test and rebound method, and has an advantage over other elastic wave methods proposed by the government such as fixed

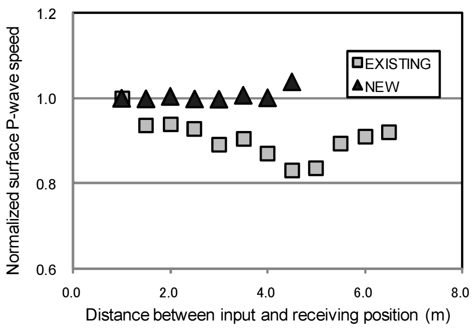

Fig. 17 Changes in surface P-wave speed at new and existing concretes.

method (measuring distance of 30 cm) and average method (measuring distance from 20 to 100 cm), because this method can evaluate deterioration progress of relatively long section of structure at one-time. This is particularly useful when yards of fishing port facilities are subjected to diagnosis, while its applicable range and accuracy have to be more researched in the future.

6. Conclusions

Problems with maintenance of existing fishing port facilities were discussed and applicability of the impact-echo method for the degradation diagnosis was examined. The major findings are as follows.

Examination of reproducibility in the laboratory.

(1) Surface P-wave speed of concrete is proportional to its compressive strength.

(2) Surface P-wave speed of concrete is affected by change in elastic modulus due to wetting and its moisture condition.

(3) Both surface P-wave speed and compressive strength decrease when expansive cracks are present.

Examination of applicability at the existing fishing facilities.

(4) Measurement of surface P-wave with different distances between transmitter and receiver could result in detection of cracking position and relative development of deterioration.

(5) Among impact-echo techniques, surface P-wave speed measurement can diagnose degradation degree of relatively long section of structure at one-time. This is particularly useful when yards of fishing port facilities are subjected to diagnosis.

As the next tasks, the degradation diagnosis results with the surface P-wave method is subjected to an effective use as supplementary indexes for a simplified inspection, such as (a) supplementary data for the simplified diagnosis, (b) estimation of degradation by changes in wave speed and (c) degradation check through the regular inspection points. To establish the degradation diagnosis method, the impact-echo method using surface P-wave shall be more elaborated in applicability and accuracy through collaborative laboratory and on-site testing including changes in wave speed according to crack width and depth.

The present research results will be reflected in the LCM Manual for the Fishing port Facilities, which is under consideration for publishing by the Fisheries Agency.

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既設沿岸コンクリート構造物の劣化診断への衝撃弾性波法の適用

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要旨：漁村地域における主要な沿岸構造物である漁港施設は，膨大な既存ストックを有しており，多くの施設が更新期に近づいておりその劣化が懸念されている。そのため，要求される機能の適切な維持を図るため，性能向上や延命化に努めるなどライフサイクルマネジメントの導入が求められている。これらの導入には，対象施設の劣化度を的確に把握することが不可欠である。しかし，診断者の違いによる劣化度評価のバラツキの抑制や劣化診断の効率化といった課題があり，明確な判定基準と診断手順の設定および診断の省力化が求められている。本報告では，漁港施設の劣化度の指標化と劣化診断手順の簡易化を指向し，これまでに適用事例がない既設漁港施設を対象に劣化診断手法としての表面Ｐ波を用いた衝撃弾性波法の適用性について，コンクリートの含水率や膨張性ひび割れが表面Ｐ波の伝播特性に及ぼす影響について検討した。更に，劣化した既存漁港施設を対象に本診断法の精度，適用範囲等について検討した。

キーワード：漁港施設，コンクリート構造物，LCM，劣化診断，衝撃弾性波