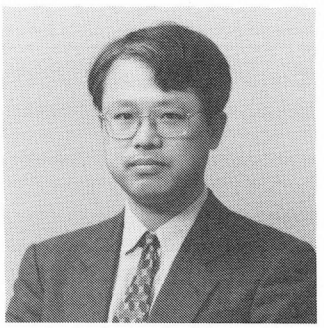
CONCRETE LIBRARY OF JSCE NO. 15, JUNE 1990

NON-DESTRUCTIVE TESTING METHOD FOR GROUTING CONDITION IN PRESTRESSED CONCRETE STRUCTURES

Manabu FUJII



Toyoaki MIYAGAWA

SYNOPSIS

The concrete structure is of a highly durable type of construction if properly designed, executed and maintained; particularly, the prestressed concrete structure is expected of its durability for a long time in view of the quality of concrete used in it and its power of controlling the generation of cracks. In recent years, however, cases of damage that have happened in the prestressed concrete of the posttension system caused by faulty grouting have began to be reported.

In this paper, general review on the methods of non-destructive inspection that are applied to the concrete structures is made first and then, explanations are made on the methods used for estimating the condition of the unfilled portion of PC grout. Thereafter, some examples of the investigation on the supersonic wave and AE method are stated, several cases of the investigation and study on the X-ray method about which various results are being reported in these days are introduced and the present status of the non-destructive inspection method of the unfilled portion of PC grout is summarized, with a glance over the radar method that is expected of its future development though its actual results are still scarce yet.

M. FUJII is Professor of Civil Engineering at Kyoto University, Kyoto, Japan. He received his Doctor of Engineering Degree from Kyoto University in 1972. His current research activities are stressed on optimal design of prestressed concrete cable-stayed bridges, structural safety evaluation and durability of concrete structures. He has written some 50 papers on these subjects. He is a member of ACI, JSMS, JSCE and JCI.

T. MIYAGAWA is lecturer of Civil Engineering, Kyoto University. He received his Dr. Eng. from Kyoto University in 1985. He is the author of a number of papers dealing with durability of reinforced concrete structures and is a member of ACI, JSMS, JSCE and a number of technical committees.

---

1. INTRODUCTION

The concrete structure is a highly durable type of construction if properly designed, constructed and maintained. Among others, the prestressed concrete (hereinafter abbreviated PC) structure is expected to have particularly long durability. Various reasons can be cited for this, but in the case of the PC structure of the post tension system, it is because the prestressing tendons are arranged within the sheaths and supposed to be fully protected against corrosion by being grouted with fine cement paste.

However, in these years there have been reports[1] on the emergence of deterioration phenomena of the PC structures that should be highly durable, at an unexpectedly early stage after their completion. These phenomena of deterioration may be devided into those that are generated similarly to common reinforced concrete (hereinafter abbreviated RC) structures and the phenomena of deterioration proper to the PC structures. In other words, the former is the damage by salt due to the use of marine sand with insufficient desalting or marine salt or the damage by expansion due to alkaline aggregate reaction and the latter is the damage due to the injury at the anchoring zones of PC tendons or corrosion of steel material caused by improper gouting. Among the PC structures, for the structures of a large scale of relatively high importance, the post tension system is often adopted. In case of the post tension system, filling up the clearance between the sheath and the PC tendons with grout is essential to protection of the steel bars, while application of non-corrosive materials such as alamid fiber has been tried energetically[2], their properties have not yet fully clarified, leaving various problems alamid for further study. Therefore, grounting is supposed to be going to occupy the most important position for the PC structure in the future.

Although the importance of the grouting operation is made clear as mentioned in the above, when viewed from the aspects of design and construction of the PC structures, grouting is an operation of a quite unnoticed nature and it is getting clearer that it is unexpectedly difficult job to finish with sufficient reliability. For instance, according to the inspection of the conditions of filled grout in the actual bridges, there were reports on some cases of the space left unfilled (Fig. 1-5). Among them, there was a report that water was found in the sheath. As the causes of these unfilled spaces, various ones are considered such as choking, careless failure of grouting, etc. The unfilled space that is generated from these causes is highly probable to constitute a serious defect for the durability of the PC structure. Therefore, confirmation of the degree of filling of grout is one of the most important items in the inspection upon completion of new structures or examination of their durability. However, with regard to the methods, no established methods for non-destructive inspection are not available yet at present, though there have been examples in which inspection by boring or inspection by the naked eye helped by the use of optical fiber apparatus is made.

In this paper, a general view on the methods of non-destructive inspection that are employed for concrete structures is going to be introduced first and then explanations will be made on the methods used in estimating the unfilled space in PC grout. After that, several cases of the investigation on the supersonic and AE methods that have been applied to practice most often among those are described, and introduction of the examples of the investigations and studies with regard to the X-ray method about which the results of various investigations have been published is made. Then, after making a brief comment on the promising radar method, though its experience is rather poor, the present status of the non-destructive inspection for the unfilled space of PC grouting is going to be summarized.

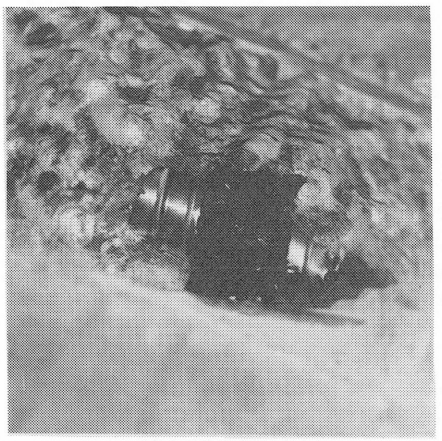


Fig. 1 Condition of grout fully filled

Fig. 2 Condition of grout in which partial cavities can be seen

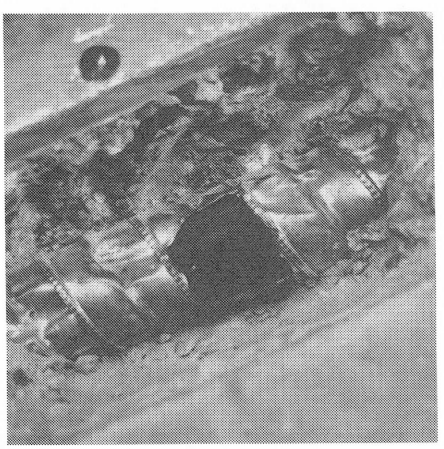


Fig. 3 Condition of the sheath in which a large cavity is seen

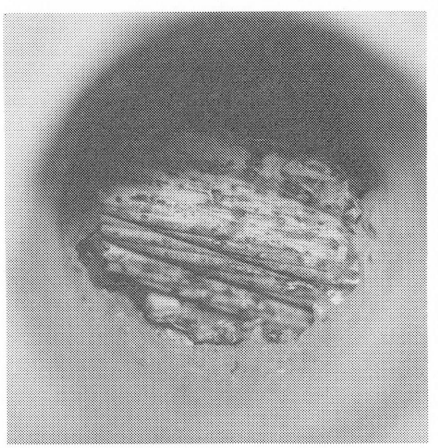


Fig. 4 Example of the appearance of PC steel wires at the unfilled portion of grout

Fig. 5 Leaking water due to unfilled portion of grout

2. NON-DESTRUCTIVE METHODS OF INSPECTION FOR THE CONCRETE STRUCTURES

Trials of quite a number of methods of non-destructive inspection have been undertaken to apply to concrete structures up to now. For instance, in BS 1881 : Part 201 : 1986[3], such kinds as shown in Table 1 are cited as the methods of non-destructive inspection for concrete structures. The methods shown in Table 1 are not always equal in their reliability or degree of development and it may not be adequate to present them in a single table, but it serves as a guidance to know what are conceived as the object of application of those tests. With regard to the strength of concrete, an example of the report as shown in Table 2[4] is available on the reliability of the estimated values which will be useful as criteria of a sort in using the measured values. However, among the non-destructive methods of inspection, what have relatively numerous experiences and what may be discussed on their reliability would be those that are concerned in the strength of concrete as clearly seen from the examples in Table 2. Although there are some methods for other properties than the strength, few of them would be applied to the verification of the degree of grout filling.

The methods with which informations could be obtained in some form or other, including those now being investigated may be classified into the following two types. Namely, the one is to estimate the unfilled space by grout directly and the other to estimate the deterioration generated by failure in filling grout. The former includes the methods by the velocity of propagation of supersonic waves, acoustic emission, X-rays and so forth and among the latter, there are the methods by the natural electric potential, polarization resistance etc.[5] mainly for the purpose of dealing with the corrosion of PC tendons. In this paper, the outline of the principle and special features of the former, or the methods of direct estimation is going to be discussed.

(1) Supersonic Wave Method

The supersonic wave method is intended to get various information by the propagation characteristics of the supersonic wave pulses. This is generally called the supersonic wave method as the wave motions whose frequency range exceeds that of the audible one (below 20 kH) are input. Such devices as the supersonic spectrocopy are proposed which was hit upon by noticing the frequency components of the supersonic pulse that has transmitted, but the most popular method at present would be the evaluation by the velocity of propagation. By the way, the velocity of the longitudinal wave that is supposed to propagate the fastest is given by the following formula if the mother material of propagation is an elastic body :

$$V_p = \sqrt{(1 - \nu)E/\rho(1 + \nu)(1 - 2\nu)}$$

where, V_p : velocity, ρ : density, ν : Poisson's ratio, E : modulus of elasticity

However, in case defects such as cracks or cavities exist in concrete, the pulse propagating within concrete makes a detour around them or generates echoes, thus the characteristics of the received wave are changed. From these informations, it is possible to estimate the degree of filling of grout theoretically. By the way, for the methodological detail, refer to the literatures 6), 7) and so on.

(2) AE Method

Acoustic emission (hereinafter abbreviated AE) is a phenomenon that happens when a solid material breaks down, the strain energy stored within the system is released abruptly and a part of it turns into the transient and instant aneous

Table 1 Applicability of Non-destructive Testing Method

Method	Object of Application					
	Quality control	Study on standardization of workability	Control of removal of form, introduction of prestress and releasing of load	Comparison of the quality of concrete in actual structures	Study on diagnosing durability	Study on fire, freezing, chemical reaction
Pull-out test (burial)	×		×			
Pull-in test (boring)	×		×	×		×
Interior destruction	×		×	×		×
Break-off test	×		×			
Pull-off test	×		×	×		
Penetration resistance	×		×	×		
Surface hardness	×		×	×	×	
Scratch test	×			×	×	
Dynamic response	×	×		×		
Measurement of the velocity of propagation of the super sonic pulse wave	×	×	×	×	×	×
Acoustic emission		×			×	
Electro-magneticmeasurement of cover concrete	×	×			×	
Radar		×		×		
Radiation transmission method		×				×
γ-rays	×	×		×		
Neutron water content measurement				×	×	
Depth of neutralization				×	×	×
Initial surface obsorption of water				×	×	
Surface water permeation					×	
Measurement of electric resistance				×	×	
Measurement of natural electric potential						
Measurement of strain		×	×	×	×	×
Infrared ray image method					×	×
Measurement of maturity			×			
Resonant frequency	×					

Table 2 Reliability[4] of the Strength of Concrete Estimated at the Construction Site

Method	Accuracy of estimated strength (limit of reliability at 95 %)
Core "large diameter" (>100 mm)	± 6 %
"small diameter"	±18 %
Pull-out	±10 %
Pull-off	±15 %
Break off	±20 %
Penetration resistance	±20 %
Velocity of propagation of supersonic wave pulse	±20 %
Repulsion hardness	±25 %
Interior destruction	
Direct tension	±20 %
Torque meter	±28 %

elastic wave and propagates, but in a wider sense it is defined as the elastic wave phenomenon that is generated by an infinitesimal destruction within the solid material or a process of energy release similar to it. An example of the system for measurement of AE is shown in Fig. 6[8]. In case the informations for the degree of filling of grout are required, a simulated AE phenomenon is caused to occur by giving a supersonic pulse or a blow and from the propagation characteristics within concrete, various informations are obtained. Therefore, this is an AE that belongs to the AE in a wider sense and essentially identical with the supersonic wave method.

(3) Method of Penetration by Radioactive Rays

Radioactive rays mean the radiation of particles released due to the radioactive fission (α-rays, β-rays and γ-rays) and include other rays that have the energy equivalent to or higher than theirs (X-rays, Cosmic rays etc.). Among others, X-rays are the electro-magnetic wave having the wave length of around 1Å that ranges from several handreds Å to 10^{-2} Å and they have often been applied to the trials for the non-destructive inspection inside the concrete structures. Generally, by fixing the X-rays that have penetrated the structure on the X-ray film etc. steel material or portions that include no void ← can be obtained.

(4) Radar Method

By emitting the transmission wave in a form of the pulse whose breadth is in the order of 1~6 ns from the transmitting antenna into concrete and by receiving the wave reflecting at the boundary surface between concrete and other substances that has different electrical properties (dielectric constant), for instance, steel material, vacant space etc., this method attempts to know the conditions within concrete (See Fig. 7 and Fig. 8). However, with respect to the degree of filling of the interiors of the sheaths, it is supposed to be very difficult to know it in the present stage of development, because reflection by the sheath is not easily distinguished from that by the cavity.

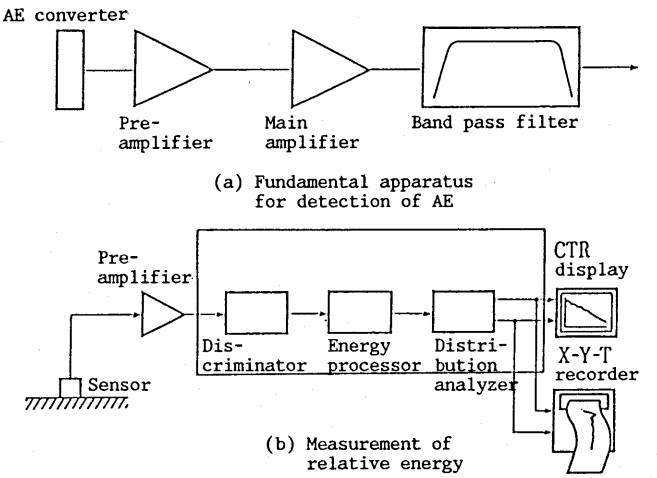


Fig. 6 Example of the measurement system of AE[8)]

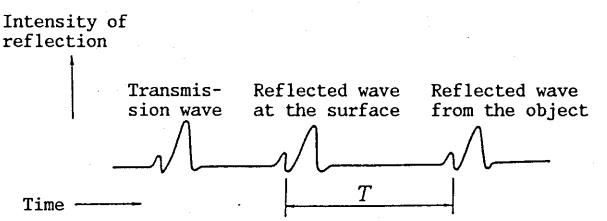


Fig. 7 Reflected wave

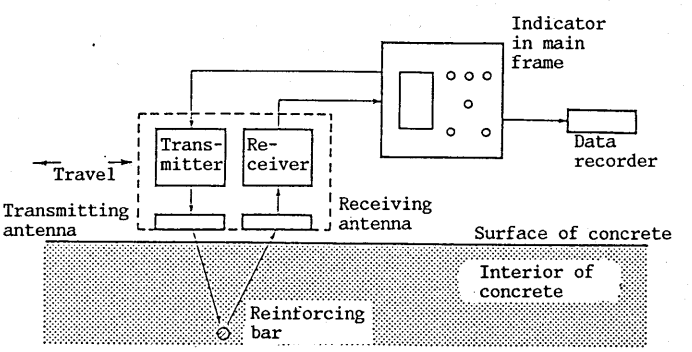


Fig. 8 Principle scheme of radar method

(5) Infrared rays image method

The surface temperature of concrete varies due to the differences among the responses caused by the differences in the specific gravity, thermal conductivity etc. depending upon the material that composes it. Areas of the surface of concrete that have diffferent thermal properties, or in other words, the portion of the surface of concrete below which there is a cavity and the sound portion present difference between their temperatures as shown in Fig. 9. The infrared image generating apparatus is intended to present the temperature differences mentioned in the above as an image by detecting them by the infrared sensors. It has mainly been applied to the peeled parts of the outside wall of the concrete buildings etc. (Fig. 10 ~ Fig. 11), and besides there have been examples of application to the separation of asphalt on the road slabs. With regard to the degree of filling of PC grout, no altemp has been made yet, partly because the ratio of the space left unfilled with grout to the whole mass of concrete is too small.

As mentioned in the above, there are numerous methods of inspection with regard to the search for the unfilled space with grout. However, since the possibility of estimating the unfilled portion by the measurement of the corroded PC steel tendons that has been resulted from failure of filling is still limited at the present stage of development of this method and besides it is difficult to estimate in case no corrosion is generated yet, it is difficult to cope with such situations by taking early care or preventive maintenance. In these circumstances, direct methods for estimation enable them to take the measures for maintenance of a preventive nature, though they have their own limits of application and are on the different stages toward their completion, and are supposed to conform with the purpose of this paper. Therefore, the principal methods for direct estimation are going to be introduced hereunder, referring to the examples of application at the construction site from time to time.

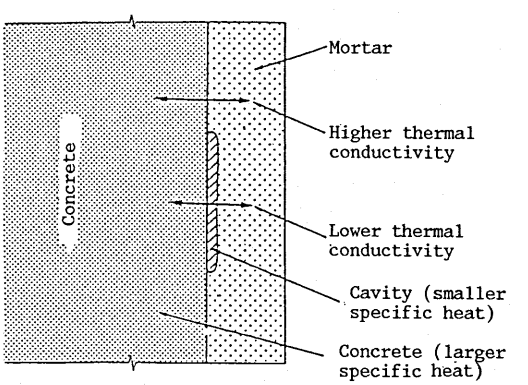


Fig. 9 Difference of the thermal conductivity due to cavity

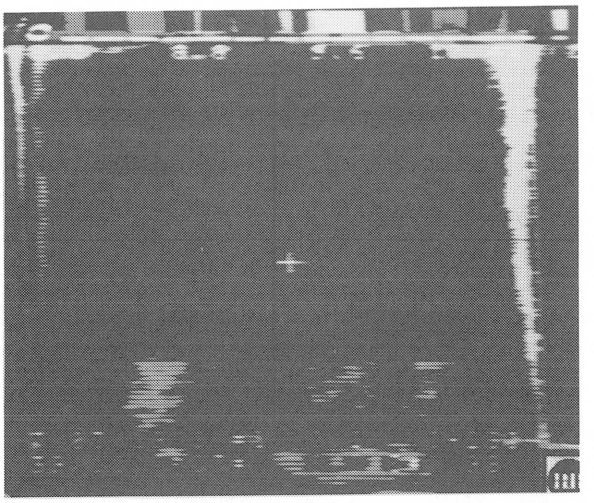


Fig. 10 Infrared ray image of the peeled part of the exterior wall (Peelings are observed around + mark)

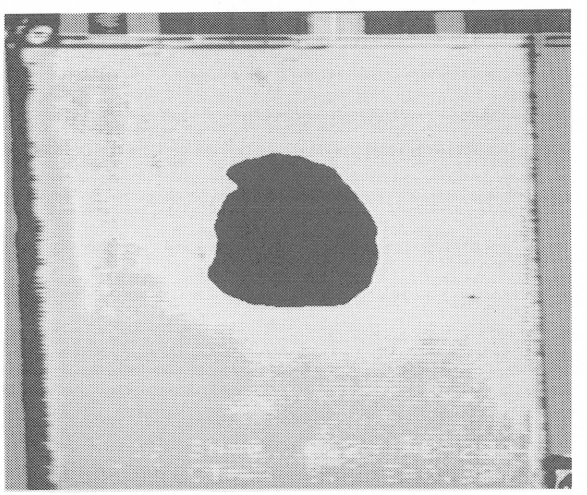


Fig. 11 Infrared image after receiving the image processing (The infrared image is binarized by processing and the peeled part is extracted)

3. SUPERSONIC/AE METHOD

Many attempts have been made to estimate the hollow portion such as the unfilled part with grout within the sheath by way of the supersonic method. The unfilled part with grout is supposed to be essentially the same as the hollow portion in general so far as its estimation is concerned, though there exists the sheath around it. Here in this section, the cases in which investigations were made on the unfilled portion with grout within the sheath.

(1) Inspection by the Velocity of Propagation

The velocity of propagation in concrete differs little from that in metallic materials. Since the damping of the supersonic wave is greater, the supersonic wave of a lower frequency that gives poor directivity is chosen. Thus, the penetration method is applied more often than the reflection method. As an example, the case in which leakage of water was found from a portion of the PC girder of the post tension type is introduced hereunder. In this case, the space unfilled with grout is estimated by applying the penetration method of the supersonic wave in which oscillators with the resonant frequency of 50 kHz are used for transmission and reception as shown in Fig. 12. An example[6], thus estimated from the velocity of propagation is shown Fig. 13. The apparent

velocity shows a clear drop at the unfilled portion which makes it possible to estimate it. The girder on which the investigation is made is the one that was completed 13 years ago. The leakage is supposed to be caused by permeation of puddle of water due to rainfall etc. on the surface of the road througth the defective parts in the pavement and the body of the girder.

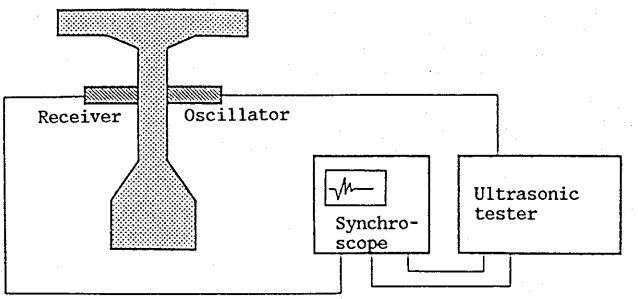


Fig. 12 Method of measurement of the velocity of propagation of the supersonic pulse

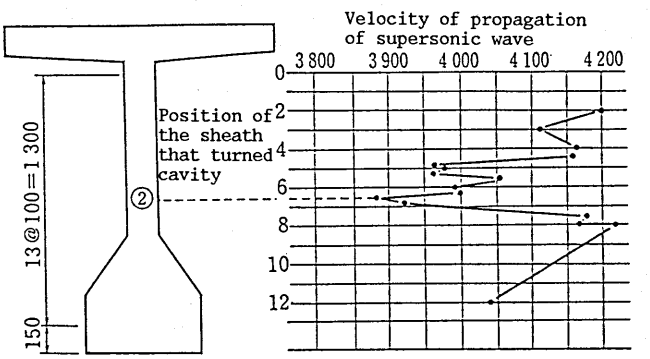
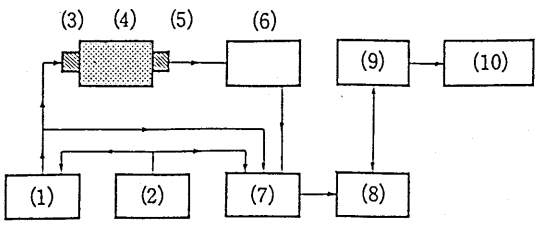


Fig. 13 Drop of sound velocity[6] due to cavities within the PC girder

(2) Evaluation by Spectroscopy etc.

Among the applications of the supersonic method, if evaluation is made not simply by the difference of the velocity of propagation but by adding other informations gained by the spectroscopy, the reliability would rise the higher. An experiment is conducted using the measuring device as shown in Fig. 14[9] by the authors. The specimens used are the concrete blocks in which 3 sheaths of 45 mm dia. holding PC wires (12 × ϕ7) through them are buried at the intervals of 20 cm each. The oscillator and the receiver having the resonant frequency of 40.5 kHz are used and an impulse of the rectangular shape with the breadth of 500 ns and the voltage of 22V is impressed to the oscillator. Measurement is made indoors and the result is shown in Fig. 15[9]. The lower the degree of filling of grout becomes, both the velocity of propagation of the supersonic wave and the maximum energy of the response function come down. However, while the drop in the velocity of propagation in the case of no grouting at all is only in the order of 1 % as compared with the case of 100 % grouting, the maximum energy shows the drop in the order of 50 %, which may suggest that it enables to estimate the degree of filling with higher accuracy than the evaluation only by the difference in the velocity of propagation.

The AE method that is applied to the investigation of the degree of filling of



(1) Signal generator (2) Signal controller
(3) Oscillator (4) Specimen
(5) Receiver (6) D.C. Amplifier
(7) Digital memory (8) Signal analizer
(9) Personal computer (10) Plotter

Fig. 14 Block diagram of the measuring apparatus[9)]

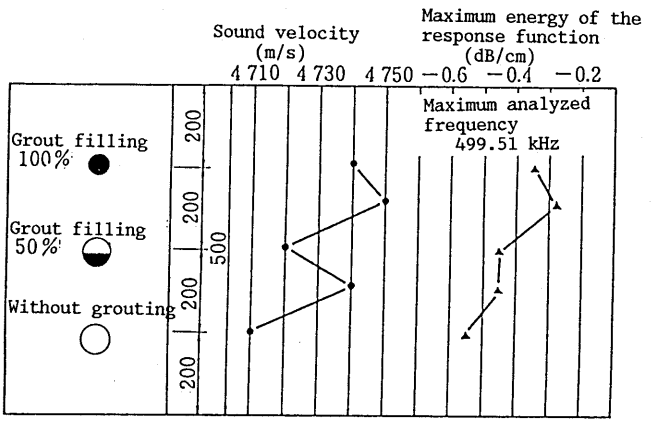


Fig. 15 Change[9)] in the sound velocity and the maximum energy due to the condition of grout filling

grout may essentially be deemed to be a sort of the supersonic wave method, especially a sort of the spectroscopy. For instance, examples[10)] of the measurement made by changing the quantity of grout in the sheath using the wall-shaped specimen as shown in Fig. 16 (sheath tubes 5 × ϕ38.1 mm, PC steel bars 5 × ϕ26 mm) are shown in the followings. For the purpose of making measurement, an AE sensor (resonant frequency 150 kHz) is attached at the top surface of the PC steel bar or on the anchor plate, and then the sheath tube is struck with the striker. The energy transmitted at that time is measured. As shown in Fig. 17, as the point of stroke gets farther away from the position of the AE sensor, the ratio of AE energy (Assuming it to be 1.0 when the point of stroke coincides with the position of the sensor, its value is calculated on the assumption that the energy is proportional to the cube of the voltage gained) decreases and displays sharp change at the border between the fully filled portion and the unfilled one as well. By the way, when the point of stroke is taken at 7 m below the top end, the larger the ratio of the unfilled portion becomes, the larger the ratio of the AE energy rises as shown in Fig. 18.

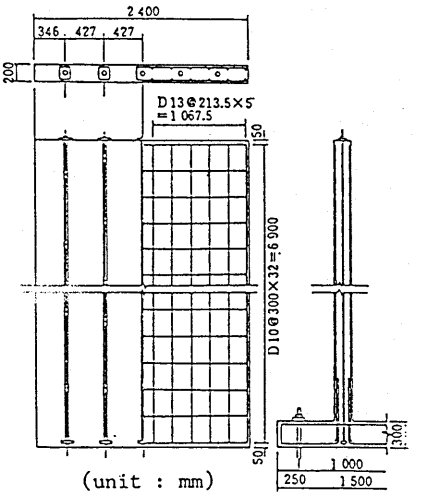


Fig. 16 Prestressed concrete wall[10)]

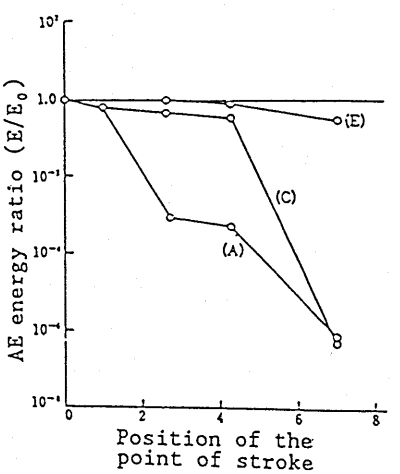


Fig. 17 Relation between the distance of the point of stroke from the top of the specimen and AE energy ratio[10)]

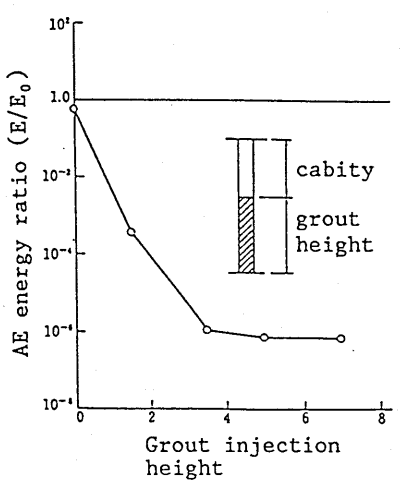


Fig. 18 Relation between the height of grout injected and AE energy ratio for the height of the point of stroke

Therefore, it is supposed to be possible to use the AE method as an indication of the degree of filling of grout.

4. X-RAY METHOD

The X-ray method has been drawing attention in these years among the methods of inspecting the degree of filling of grout. Though not fully established yet in some respects, this method has often been tried recently. In this section, the special features of the X-ray method and its examples are introduced.

(1) X-ray Penetration Photograph

When the X-rays transmit a substance, there happen mutual reactions mainly between them and the electrons which cause various problems in making measurement. The mutual reactions occurr in various forms, but principal ones are those of the four kinds as mentioned hereunder : ① Photoelectric effect, ② Thomson scattering, ③ Compton scattering and ④ Electron pair creation. Due to these mutual reactions, the intensity of the X-rays after penetration differs depending upon the kind and thickness of the substance. The technique to represent the undulation of intensity of the X-rays after penetrating a substance is called the X-ray penetration photography. There are three kinds of X-ray photography, namely (1) direct method, (2) indirect method and (3) fluoroscopic method, out of which the direct method is used most often. According to this method, the photographic film is exposed to the transmitted X-rays directly to make the image and observation with the naked eye is made after the process of development is finished.

The sensitivity of the film to the X-rays is far poorer than that to the natural light. Therefore, the film for X-rays for the industrial use whose sensitivity is raised by covering its both surfaces with thick coating of photographic emulsion is used in consideration of the cost as well. In order to raise the sensitivity further, in most cases the films of sandwich-like structure made by covering their both surfaces with intensifying screen are used.

(2) Processing of the Image

The images gained by simply applying the method of (1) are often very much blurred ones and they generally receive image processing. In these day, the term of image processing generally means the digital image processing in which the computer is used as processing apparatus. This system has been made a remarkable progress in these years owing to the emergence of low cost computors with high performance due to the development of the technique for the integrated circuit. Processing the image means the followings in a broader sense : ① to catch the object as an image, ② to digitize the image, ③ to input the informations of the image thus digitized into the computer, ④ to apply various operational processes to the digitized informations of the image by the computer, ⑤ to output the processed image.

For guidance, the usefulness of the image processing is going to be briefly introduced hereunder : ① The informations of the image can be made visible to human eyes or turned to some thing that attracts human attention; ② Accumulation of the informations of the image is made possible; ③ It can gather the density, colors and the two-dimensional expanse (size, location etc.) of the image as the information.

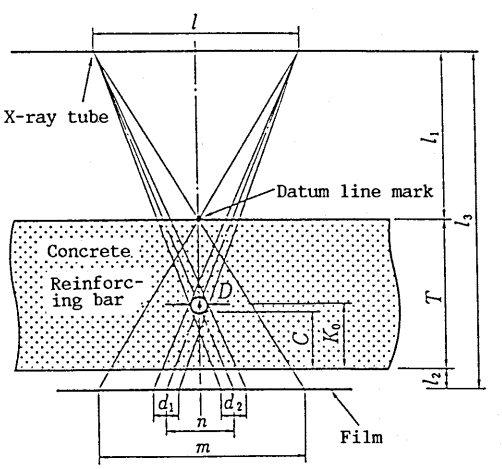
(3) Example of Inspection of the Reinforcing Bars[12)]

Prior to introducing the examples of PC grout, the examples of inspection made on the reinforcing bars as the fundamentals are described.

a) Method of measurement

By applying X-rays from 2 directions toward one sheet of film, two images are obtained for the same steel bar. From this film, the diameters of the images of the reinforcing bar (d_1, d_2), the distance of shift between two images of the reinforcing bar (n) and the distance of shift between two images of the datum line mark (m) can be measured as shown in Fig. 19. Then, since the distance of shift of the X-ray tube (l), the distance from the X-ray tube to the concrete surface on the incident side (l_1) and the distance from the film to the concrete surface on the exist side (l_2) are known quantities, the cover on the reinforcing bar (C), the diameter of the bar (D) and the thickness of concrete (T) are calculated (Formula ①~④).

The film obtained by the X-ray penetration is taken into the image apparatus and the graduation of the film image is digitalized and input. The image processing is spplied to the film image and the boundary between the bright and dark parts are determined by automatic binarizing statistical processing. In so doing, the position of the boundary of density is determined without including any human judgement and as aforementioned, the diameters of the reinforcing bar (d_1, d_2), the distance of shift of the reinforcing bar (n) and the distance of shift of the image of the datum line mark (m) are measured automatically.
By substituting the values measured into the formulas ①~④, the thickness of concrete (T), the diameter of the reinforcing bar (D) and the cover concrete (C) are obtained.



Formula for calculation

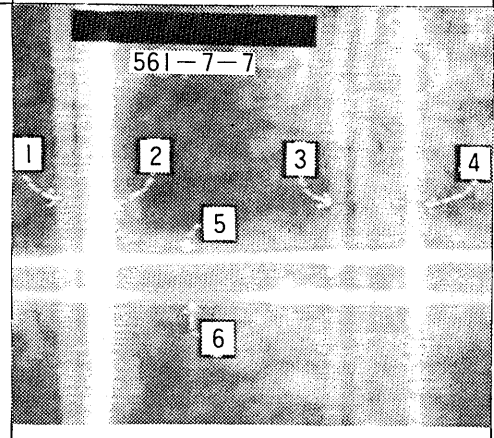
① Thickness of concrete (T)
$T = (l_1 \cdot m/l) - l_2$

② Distance from the center of the reinforcing bar to the surface of concrete (K_0)
$K_0 = \{n \cdot (l_1+T) - l \cdot l_2\}/l+n)$

③ Diameter of the reinforcing bar (D)
$D = \{(d_1+d_2)/2\} \cdot [\{l_1+(T-K_0)\}/l_3]$

④ Cover concrete (C)
$C = K_0 - (D/2)$

Fig. 19 Diagram for calculation to find the position, diameter and thickness of concrete

Investigated part	Arrangement of reinforcing bars (pitch of the bars)	Thickness of concrete T	No.	Diameter of bars A	Diameter of bars B	K_0	Cover concrete C C_u	Cover concrete C C_d
4SA		128	1	10.6		85	38	
			2	10.5		20		15
			3		8.9	82	42	
			4	8.0		24		20
			5		8.9	32		27
			6		8.9	73	51	
			7					
			8					
			9					
			10					

T: When the values gained from two films are not the same, their average value is recorded.
A: Distance of hollow-hollow of the deformed bar
B: Distance of rib-rib of the deformed bar
K_0: Distance from the surface of concrete on the film side to the center of the reinforcing bar.
Cu: Cover concrete on the top bar
Cd: Cover concrete on the bottom bar

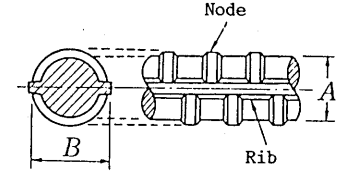


Fig. 20 Example of the investigation of the arrangement of reinforcing bars (unit : mm)[12]

b) Examples of measurement

The result of inspection on the conditions of the arrangement of the reinforcing bars is shown in Fig. 20. Estimation of the diameter and the cover concrete are possible and the top bars and the bottom bars can be distinguished as well. From the result of the actual measurement made on the steel bars No.1 and No.5 in Fig. 20 after chipping concrete off, it is known that the difference between the estimated values and the actual ones are in the order of 0.2 mm~0.5 mm.

Furthermore, according to the measurement made on the specimens having the maximum thickness up to 506 mm and the maximum cover up to 360 mm, carried out for the purpose of investigating the accuracy of measurement, it is known that measurement can be made even in case of the thickness of concrete of 506 mm. Accuracy for the diameter of the steel bar and cover concrete calculated by the formula below is shown in Fig. 21 and Fgi. 22.

Accuracy of measurement

= (Measured value - estimated value) × 100/measured value (%)

Accuracy for the diameter of the steel bar is within ±5 % and that for cover concrete ±7 %. Besides, an example of accuracy of measurement that was made on an existing structure is shown in Fig. 23. With regard to the diameter of the steel bar, it shows similar variation to that of the specimen that is within ±5 %, however, for cover concrete, its values show wider variation of within ±10 % than ±7 %, although the thickness of concrete of the existing structure is smaller than that of the specimens mentioned in the above. Therefore, it is recommendable to asume errors up to 10 % might occur with respect to cover concrete.

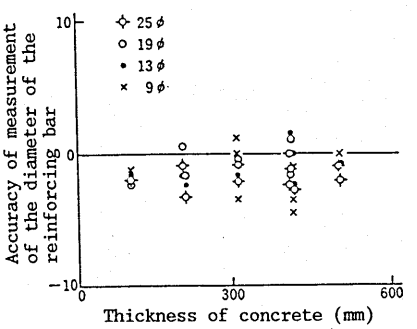


Fig. 21 Accuracy of measurement of the diameter of the reinforcing bar[12)]

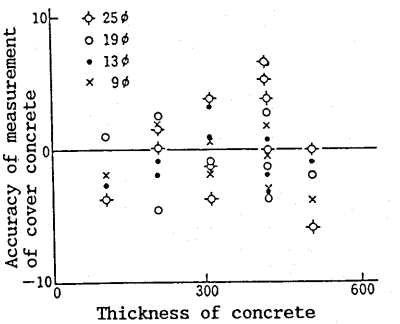


Fig. 22 Accuracy of measurement of cover concrete[12)]

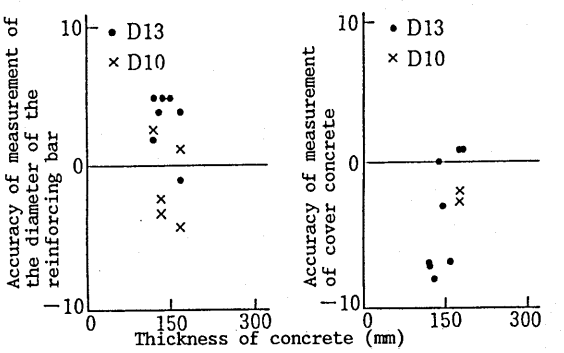


Fig. 23 Accuracy of investigation of the floor slab on the spot[12)]

(4) Examples of Inspection of the Degree of Filling of PC Grout

a) Method of measurement

Taking the pictures of PC steel bars and sheaths on a photographic film, image processing is applied to them. The conditions of grout filling are estimated from the image, density distribution and the position of the boundary of density between the sheath and the steel bar thus obtained.

b) Example of measurement

The examples measured on the specimens are shown in Fig. 24 and Fig. 25. On the right side of the diagram, the photographic image and on the left side, the density distribution (hereinafter called profile) along the white line drawn on the image are shown. While in the specimen without grouting shown in Fig. 25, dark parts can be seen on the both sides of the steel bar, in the specimen with grouting in Fig. 24, they are not observed. Besides, the positions of the boundaries of density determined by the method which does not include any human judgement (The automatic binarizing statistical processing is applied to the small area that includes the density boundaries between the sheath and the steel bar in the image.) are also presented in Fig. 24 and Fig. 25. Out of the four positions of the density boundaries thus obtained, the inside two are supposed to correspond to the positions of the exterior ends of the diameter of PC steel bar and the outside two are supposed to correspond to the sheath. The diameter of the PC steel bar and that of the sheath are shown in Table 3 in comparison with the calculated values gained by converting these calculated from the arrangement of the X-ray tube, PC steel bar, sheath and the film. According to this table, the calculated values and the measured ones show good conformity.

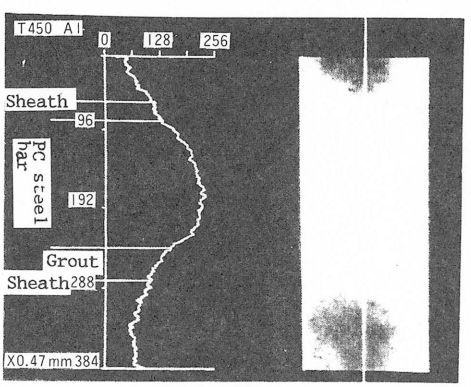


Fig. 24 Example 1 of X-ray image of PC girder specimen (thickness of concrete = 450 mm with grouting)

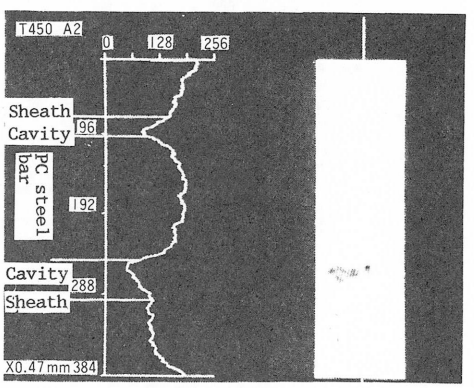


Fig. 25 Example 2 of X-ray image of PC girder specimen (thickness of concrete = 450 mm without grouting)

In addition, the examples of measurement made on the actual structure (see Fig. 26) are shown in Fig. 27 and Fig. 28. It is estimated that grout is filled from Fig. 27 and unfilled from Fig. 28. The sheath shown in Fig. 28 is inspected with the naked eye after drilling a hole to the sheath and confirmed that it is unfilled.

However, from these results, a clear conclusion can not necessarily be given on whether this method could be applied universally as it is, and further investiga-

(Unit : mm)

	TYPE-1		TYPE-2	
	Calculated value	Measured value	Calculated value	Measured value
Diameter of sheath C_1	98	100	102	100
Diameter of PC steel bar C_2	69	69	72	72
Diameter of sheath D_1	68	66	71	72
Diameter of PC steel bar D_2	39	42	41	43

Table 3 Comparison of the calculated values with the measured ones of the diameter of the sheath and that of the PC steel bar on the film[12)]

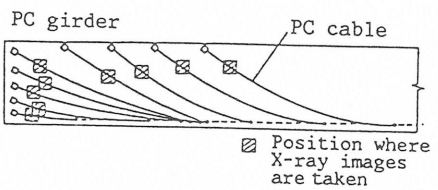


Fig. 26 X-ray image of PC girder

tions are supposed to be necessary.

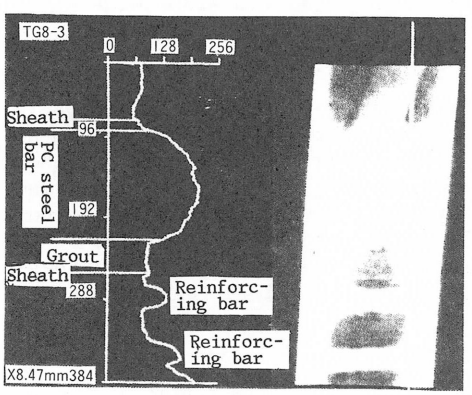


Fig. 27 Example 3 of X-ray image of PC girder (Thickness of concrete = 420 mm, with grouting)

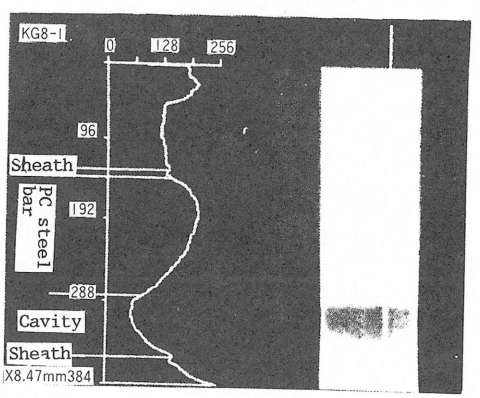


Fig. 28 Example 4 of X-ray image of PC girder (Thickness of concrete = 420 mm, without grouting)

5. RADAR METHOD

Cases of application of the radar method to the inspection of the degree of grout filling for PC have been few, but much is expected of its application to the detection of steel materials[13]. Therefore, some briefing will be made here.

The location of the reinforcing bars etc. (depth D) is estimated by the length of time after the electric wave in a pulse form is transmitted from the antenna until it is received again by the antenna. Denoting the velocity of the electric wave in a pulse form within concrete with V, the following formula is gained :

$$D = VT/2$$

The velocity of the electric wave within concrete (V) is approximately represented by the following formula denoting the dielectric constant of concrete with ε_r :

$$V = 3 \times 10^8/\sqrt{\varepsilon_r}$$

The position of the steel bars in the surface within concrete normal to the direction of the depth is gained by moving the antenna along the exterior surface of concrete as shown in Fig. 29. The patterns of the reflected wave from the steel bars emerge presenting the hump-like shape as shown in Fig. 30. The summits of these humps indicate the positions of the steel bars.

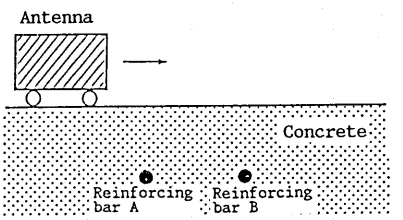


Fig. 29 Inspection of concrete profile by the radar

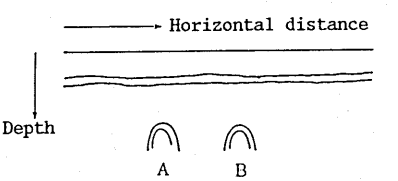


Fig. 30 Example of radar image

The examples of inspection of the steel bars within concrete and the cavities within the road slabs are shown in Fig. 31 and Fig. 32. From Fig. 31, the thickness of cover concrete of about 50 mm and the average pitch of the reinforcing bars of 200 mm can be read out. Fig. 32 shows the result of inspection from above asphalt pavement and existence of a cavity of about 300 mm in length at around 80 mm below the surface is estimated. These two examples are the result gained by applying the radar detector for general use to concrete, but the radar detector specialized for concrete is going to be developed.

So far as reinforced concrete is concerned, the present apparatus is capable of measuring the concrete cover of 1 cm at the minimum and up to about 18 cm at the maximum and its accuracy is around ±1 cm. With regard to the pitch of the reinforcing bars, the errors are in the order of 10 cm ± 1 cm at the minimum. In view of the accuracy in the above, application to the measurement of the diameter of the steel bar is very difficult at the present stage. In addition to the problems of accuracy of the measurement and resolving power, another problem that judgement of the image requires high skill is left for the future.

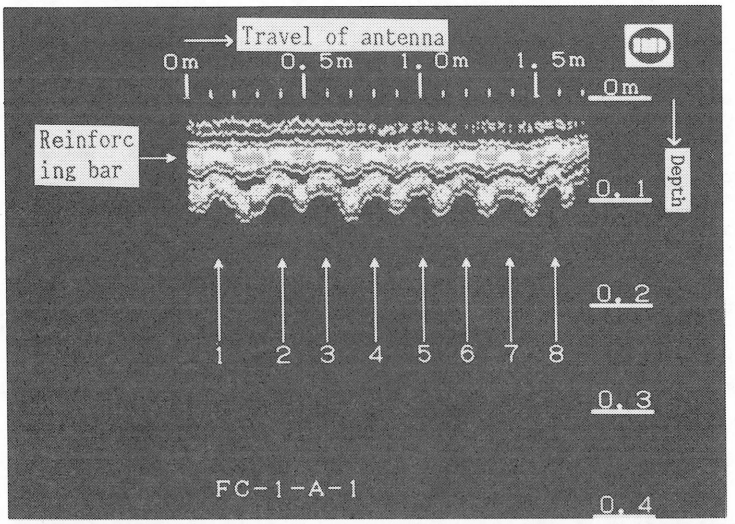


Fig. 31
Radar image of reinforcing bars within concrete detected

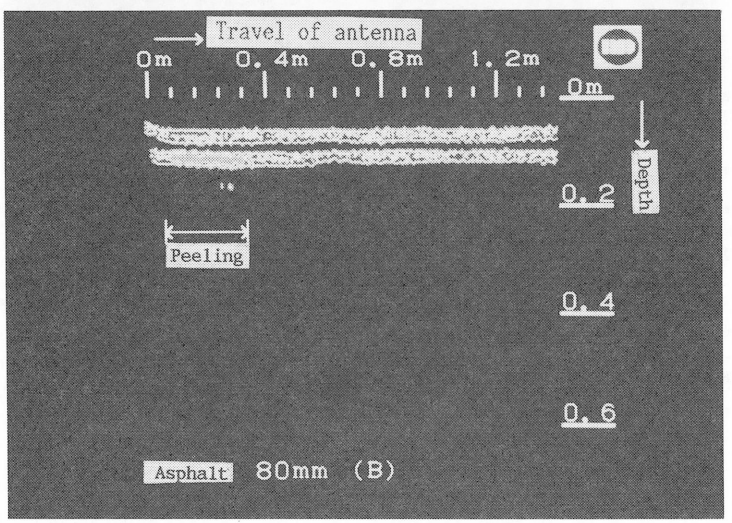


Fig. 32
Radar image of cavities in a floor slab detected

6. POSTSCRIPT

As stated in the above, various methods have been tried as the method of detecting the degree of unfilled PC grout. The methods of measurement were originated on their own unique concepts and have their own limits of applicability respectively. In the present stage of development, it is extremely difficult to make decision which method is the best one and it may be said no final method has been established yet. The authors expect that the informations on the studies of these sorts will be accumulated and methodology on this will be established.

In finalizing this paper, the authors appreciate the cooperation offered by the people in the Institute of Comprehensive Technological Study on the Structures Co. Ltd.

References

[1] S. Iwamatsu, "Durability and maintenance of prestressed concrete structures", Jour. of JPCEA, Vol. 25, No. 5, pp. 10 ~ 15, 1983.9.

[2] K. Kobayashi et al., "Recent progress of fiber reinforced plastics", Jour. of JPCEA, Vol. 30, No. 5, pp. 7 ~ 67, 1988.9/10.

[3] BS 1881 · Part 201, "Testing concrete, Part 201, "Guide to the use of non-destructive methods of test for hardened concrete", 1986.

[4] J. H. Bungey, "Planning site investigations", Concrete bridge engineering-performance and advances, pp. 1 ~ 24, Elsevier Applied Science Publishers, 1986.

[5] T. Miyagawa, S. Inoue, K. Kobayashi and M. Fujii, "Non-detructive testing method and its evaluation technique for corrosion of reinforcing steel in concrete", Proc. of JCI Symposium on Durability Diagnosis of Concrete Structures, pp. 85 ~ 90, 1988.5.

[6] T. Akashi, "Studies on non-destructive testing of concrete", Proc. of JSCE, No. 390/V-8, pp. 1 ~ 22, 1988.2.

[7] T. Akashi and S. Amasaki, "Evaluation of concrete by ultrasonic spectroscopy", Cement & Concrete, No. 489, pp. 23 ~ 30, 1987.11.

[8] Masayasu Ohtsu, "Characteristics and Theory of Acoustic Emission, Morikita Publishing Company, 1988

[9] K. Suzuki and S. Amasaki, "Evaluation of concrete by responce function", Annual Meeting of JSCE, Part 5, pp. 430 ~ 431, 1988.10.

[10] Takehito Uomoto and Yoshihisa Shudoh, "Method of evaluation of the degree of filling of grout within the sheath of pre-stressed concrete by measuring the acoustic emission", Study of Production, Vol. 39, No. 4 pp. 141 ~ 144, 1987.4.

[11] The Japanese Society for Non-Destructive Inspection, "Textbook for Chief X-ray Operator, pp. 7 ~ 40, 1973.

[12] H. Maeda, A. Hasegawa and M. Goami, "Application of X-ray photograph method to examination of reinforcement details", Proc. of JCI Symposium on Durability Diagnosis of Concrete Structures, pp. 109 ~ 114, 1988.5.

[13] Tadaaki Kakuo and Yoshikazu Ohkubo, "Investigation of the arrangement of reinforcing bars and covering thickness by the radar", Proceedings of the 3rd Sub-committee of the Japanese Society for Non-destructive Inspection, pp. 38 ~ 43, 1988.

[14] Y. Kasai and T. Fuji, "Non-destructive evaluation of concrete structures", Jour. of JSNDI, Vol. 37, pp. 206 ~ 221, 1988.3.

[15] Association of Technical Inspection of Japan, "Application of the non-destructive inspection technic and its accuracy", Lectures and Discussions, 1986.10.

[16] Association of Technical Inspection of Japan, "Method of diagnosing the deterioration of the concrete structures, 1987.10.