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APPLICABILITY OF WIDE-RANGE ULTRASONIC TESTING TO NON-DESTRUCTIVE INSPECTION OF GROUT CONDITION IN PRESTRESSED CONCRETE BRIDGES

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Complete grouting of tendon ducts is important for durability of post-tensioned prestressed concrete (PC) bridges. Voids in the ducts may induce failure of PC tendons, possibly causing a reduction in load capacity and collapse of the bridge. The wide-range ultrasonic testing (WUT) is one of the non-destructive inspection techniques. The focus of this study is to examine the applicability of the WUT to grout inspection. This paper summarizes the characteristics of the non-destructive methods available for the PC grout inspection and outlines the sensing and analyzing techniques of the WUT method performed in practice in PC bridge construction. The inspection accuracy of the WUT method was examined by comparison to a sensor-based inspection method. This paper also reports comparative investigation and discusses the advantages of the WUT method including inspection accuracy, cost performance, time efficiency and safety. It was confirmed in on-site application that the WUT method was capable of determining grout condition at a concrete cover depth of 250 mm.

Keywords: Incomplete grouting, Concrete cover, Measurement, XRT, IE.

1 INTRODUCTION

Among various non-destructive testing methods currently used in grout inspection on prestressed concrete (PC) bridges in Japan (Mutsuyoshi 2001), those capable of following the change in angle of the primary tendons are X-ray transmission (XRT) method, impact-echo (IE) method and wide-range ultrasonic testing (WUT) method. The XRT method uses characteristics of the transmitted X-ray intensity which varies depending on the material or thickness of the object. The condition of internal concrete is determined from the contrasts in radiographs which represent the differences in X-ray intensity. The upper limit of thickness for this method is typically 500 mm. The use of X-rays requires a specialized inspector (X-Ray Handling Supervisor) to be assigned and various safety measures to be taken for prevention of radiation exposure, including closure of the site and traffic restrictions on any roads above or below the site. The IE test is performed by applying an impact to a concrete surface using a hammer or the like to generate elastic waves and collecting the data of the reflected waves from the ducts. The grout condition is determined by analyzing the frequency characteristics of the received waves.

The test equipment is compact and easy carrying, and the procedure is simple to perform. However, determination by this method becomes difficult when the concrete cover depth to the tendon is excessively small or large, or when the diameter of the tendon duct is too small. It is well known that the upper limit of concrete cover depth for grout inspection by this method is typically 200 mm. In this study, the authors focused on the WUT which has a wider effective range and higher accuracy as compared to the other existing techniques, and investigated applicability of the method. Figure 1 shows a view of inspection using the WUT, and Figure 2 shows the measurement equipment required for this method.

Figure 1. Grout inspection using the WUT.

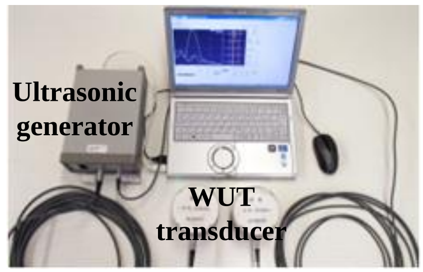


Figure 2. Required equipment for the WUT method.

For grout inspection using the WUT, transducers are installed by using a contact material to the concrete surface near the duct. Ultrasonic waves in different frequency ranges are input from a transmitting transducer, and the reflected waves from the duct are received by the receiving transducer. Grout condition is determined from the difference in characteristics of the received waves. The ultrasonic waves are reflected at voids or boundaries between different materials. Those reflected at voids are specifically large because voids cause almost total reflection. Since reflections from voids have a high frequency, waveforms with peaks in the high frequency range represent incomplete filling or presence of voids, and those with peaks in the low frequency range represent complete filling. This paper outlines the method of determining grout condition using the WUT, and reports the result of grout inspection performed on new bridges during construction to eliminate initial defects. A comparative verification was conducted by carrying out grout inspection using the WUT method and MS sensors. Based on the results of the comparative investigation, practical applicability of the WUT method was examined by comparison to the other non-destructive inspection methods, with the focus placed on the following five aspects: accuracy, applicable depth, cost performance, time efficiency and safety.

2 PRINCIPLES AND CHARACTERISTICS OF THE WUT METHOD

2.1 Inspection Procedure by the WUT Method

Figure 3 shows the procedure of the grout inspection by the WUT method. Multiple-points measurement is performed in order to cancel the noise and amplify the reflected waves from the duct. Figure 4 shows the schematics of the multiple-points measurement and its method.

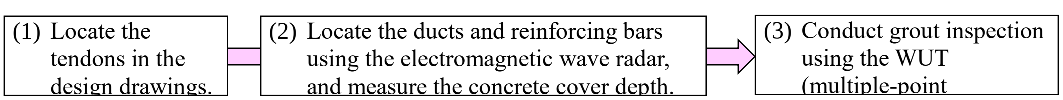


Figure 3. Procedure of grout inspection by the WUT method.

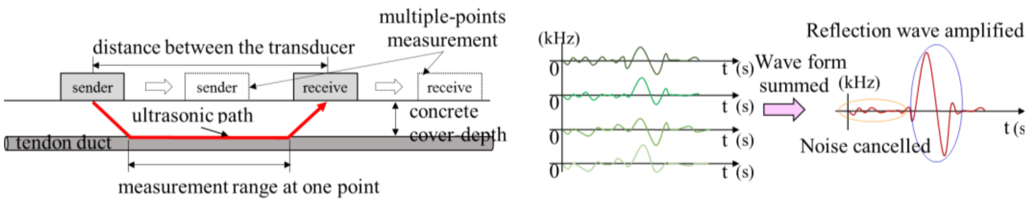
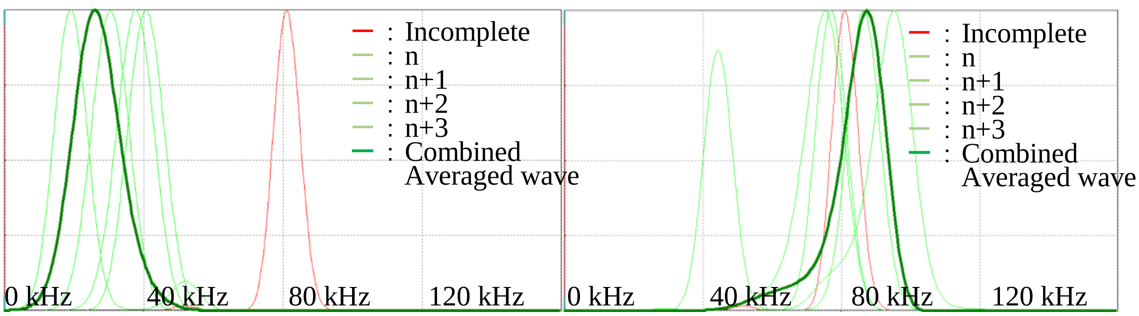


Figure 4. Schematics of multiple-points measurement and its method.

2.2 Determination of Grout Condition by the WUT Method

It is known that spectral peak patterns vary depending on how the duct is grouted. Figure 5 shows the waveform examples for known grout conditions. Although there can be variations depending on the age of concrete or other factors, the waveforms of the incomplete filling have spectral peaks at around 80 kHz in a higher frequency range as compared to those of the complete filling with peaks at around 20 kHz to 40 kHz. We can confirm the complete grouting from the averaged wave-peak of 80 kHz, and can detect the incomplete grouting from the peak in the range of 20 kHz to 40 kHz.



(a) Complete grouting. (b) Incomplete grouting.

Figure 5. Grout inspection results.

3 GROUT INSPECTION BY THE WUT METHOD

3.1 Grout Inspection by the WUT Method on New Bridges

Grout inspection using the WUT method was carried out during construction of the new bridges. Waveforms were measured before grouting on the web of main girder. In addition, the waves were measured after the hardening of grout. Based on the difference of these wave-peaks, the incomplete grouting can be detected. Table 1 gives the inspection results in six bridges. Waveforms shown in Figure 5(a) were observed in these inspections. Complete grouting was confirmed in all bridges.

3.2 Grout Inspection by the WUT Method on Existing Bridges

Grout inspection by the WUT method was also carried out on some existing PC bridges. After the non-destructive test by the WUT method, a drilling test was carried out for verification. The number of inspection points was 28, and concrete cover depth was 254 mm to 336 mm. Table 2 gives a confusion matrix based on the inspection results. The accuracy defined in (TP + TN)/(TP + FP + FN + TN) was approximately 86 %, and the precision defined in (TP)/(TP + FP) was 84 %.

3.3 Comparative Verification by Grout Inspection Test

Grout inspection was carried out on other new bridges using two different non-destructive methods for comparative verification. A conventional inspection device, MS sensors, were used during grouting in addition to the WUT method. The MS sensor consisting of a heater and a thermocouple can detect the grouting condition based on the thermal conductivity.

In this study, these grout inspections were carried out on two bridges shown in Table 3. The results of inspection by the WUT method after hardening of grout matched those using the MS sensors during grouting at all inspection points. It is noteworthy that the WUT method is highly accurate and applicable to non-destructive grout inspection after hardening of grout.

Table 1. Results of grout inspection by the WUT method on new bridges.

I.D.	Structural types	Number of inspection points		Concrete cover depth (mm)
		Before grouting	After grouting	
A	3-span continuous rigid frame box girder	2	12	145−220
B	3-span continuous rigid frame box girder	6	20	125−202
C	5-span continuous box girder	4	24	226−226
D	Simple composite girder	4	32	193−213
E	Simple composite girder	6	24	230−230
F	5-span continuous box girder	8	20	74−235

Table 2. Confusion matrix of the WUT method on existing bridges.

Concrete cover: 254 mm – 336 mm		Actual grout condition of the PC bridges	
		Complete	Incomplete (voids)
Inspection by the WUT method	Complete	TP: 16	FP: 3
	Incomplete (voids)	FN: 1	TN:8

Table 3. Comparative verification by grout inspection test on new bridges.

I.D.	Structural types	Number of inspection points		Concrete cover depth (mm)
		MS sensors during grouting	WUT method after hardening of grout	
G	Simple 3-cell box girder	123	94	88−89
H	Simple post-tensioned box girder	270	180	149

4 CASE STUDY: INVESTIGATION OF APPLICABILITY OF THE WUT METHOD

For investigation of applicability of the WUT method, the XRT, IE and WUT methods were compared with each other in terms of five factors: inspection accuracy; applicable concrete depth; inspection cost; inspection period; and safety. Each values used for the XRT and IE methods were determined by referring to previous literatures or those measured on existing bridges. The values used for the WUT method were the inspection results on the existing bridges described above. Two model cases were considered in the examination of inspection cost and time: (1) a T-girder bridge with 40 m long; and (2) a rigid frame box-girder bridge with 150 m long. The comparative investigation is based on the inspection points of 40 on primary tendons. It should be noted that the applicable depth for XRT is 250 mm which represents the half of web-thickness.

4.1 Inspection Accuracy

Table 4 shows a comparison of inspection accuracy results. The accuracy is expressed in percentages because of the difference in the number of inspection points between the three methods. Accuracy of the WUT method in detecting complete grouting was 100%, as well as the XRT method. Accuracy of the WUT method in detecting incomplete filling was almost equal to that of the IE method. It is significant that the negative detection for the incomplete grouting was 0%. This contributes the safety evaluation to detect the grouting condition.

Table 4. Comparison of inspection accuracy results.

		Actual grout condition of the PC bridges	
		Complete	Incomplete (voids)
Inspection by the XRT method	Complete	100%	0%
	Incomplete (voids)	0%	100%
Inspection by the IE method	Complete	92%	8%
	Incomplete (voids)	22%	78%
Inspection by the WUT method	Complete	100%	0%
	Incomplete (voids)	27%	73%

4.2 Applicable Concrete Cover-Depth

Figure 6 shows a comparison of the three methods for various concrete cover-depths. The WUT and XRT methods were found effective up to a concrete cover depth of 250 mm. The WUT method indicated the appropriate accuracy (84%) even in thicker concrete (up to 336 mm) which other methods cannot be used.

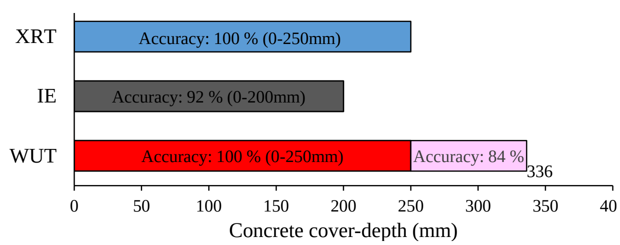
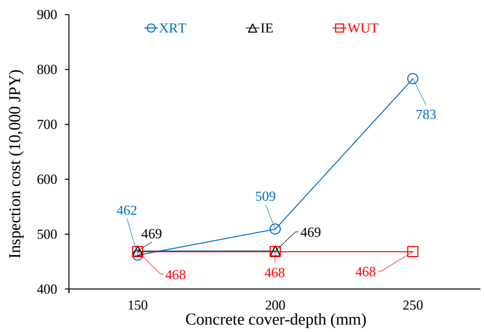


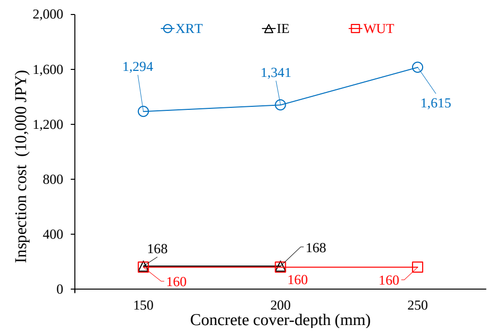
Figure 6. Comparison of applicable concrete cover-depth.

4.3 Inspection Cost

Figures 7(a) and (b) show inspection costs for the T and box girder bridges, respectively. Construction cost for required scaffolding was taken into account in the calculation where applicable: the scaffolding below the girder of the T girder bridge; and the scaffolding for the XRT method at the sides of the main girder of the box girder bridge. No significant difference was found between the three methods on the T girder bridge up to the concrete cover-depth of 200 mm. The cost increased for the inspection with the cover-depth of 250 mm which required two hours at each measurement point to obtain a radiograph. Similarly, the cost for the inspection by the XRT method on the box girder bridge was high due to the scaffolding construction cost. The WUT and IE methods were found to be advantageous in cost because inspection could be completed from the inside of the box girder, without a need for external operation.



(a) T-girder bridge.

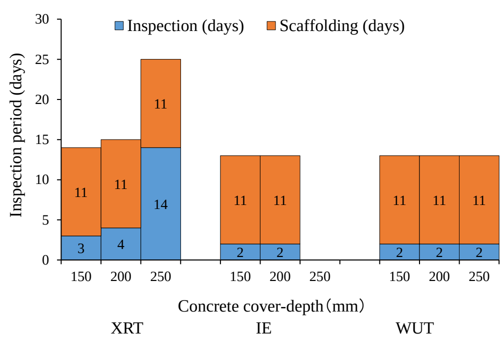


(b) Box-girder bridge.

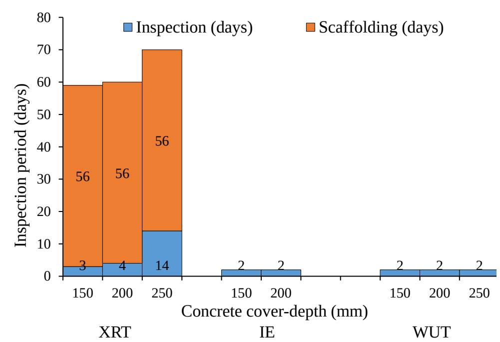
Figure 7. Inspection cost.

4.4 Inspection Period and Safety

Time required for the inspection was compared between the three methods. As done in the cost calculation, time for assembly and dismantling of scaffolding was considered where applicable. Figures 8(a) and 8(b) show the estimated inspection periods for the T and box girder bridges, respectively. The WUT and IE methods were also advantageous in safety due to the shorter inspection periods, while the XRT method was inferior to the other two methods due to the use of radioactive material.



(a) T-girder bridge.



(b) Box-girder bridge.

Figure 8. Inspection period.

5 SUMMARY

Conclusions in the study are listed below:

- The WUT and IE methods showed a high applicability in inspection period, cost and safety.
- Higher accuracy of the WUT method to detect complete filling was confirmed as well as the XRT method. In addition, the WUT method achieved the high accuracy of 84% up to the cover depth of 336 mm which other methods cannot be applicable.

References

Mutsuyoshi, H., Present situation of durability of post-tensioned PC Bridges in Japan, *Durability of post-tensioning tendons*, CEB-fib, Ghent, Belgium, 75-88, Nov. 2001.