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Development of high -accurate impact echo method and its application to filling evaluation of PC grout

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ABSTRACT: One of the problems with the standard impact echo method is the loss of the repeatability of the elastic wave waves. The peak of the target in the frequency domain is sometimes not clear. We have developed a more accurate impact echo method using multiple impacts and averaging their time domain signals. We applied this improved method of evaluating grout filling in tendon ducts. The time domain signals were superposed so that the reflected waves strengthened each other. We were successful distinguishing the presence of grout filling in tendon ducts with the diameter of 38 mm and the center depth 275 mm was possible.

1 INSTRUCTION

The problem of ungrouted tendon ducts in PC structures should be solved as soon as possible because the ungrouted tendon ducts may cause corrosion or severance of the PC steel bars/wires. The X-radar method, the radar method, the supersonic method and the impact echo method (Sansalone & Streett 1997) have been applied to evaluate grout filling in tendon ducts (Uchida et. al. 2005, Kawashima et al. 2005). However the performances of those methods are not accurate enough for the evaluation of grout filling in tendon ducts.

In this paper we discuss the improvement of the impact echo method. One problem of the impact echo method is the loss of the repeatability of the elastic waves passing through concrete bodies. The other one is that the peak of the target in the frequency domain may be unclear. The cause of these problems is the loss of the repeatability of the contact times of their impacts. The reasons of the loss of the repeatability are their surface roughness and the inhomogeneity of their concrete wall structures. We performed multiple impacts more than one hundred times and averaged their time domain signals. The loss of the repeatability of elastic waves has been reduced by averaging. We applied this improved impact echo method to the distinction of grout filling in tendon ducts. The diameter and the depth of the tendon ducts were 38 mm and 275 mm at the center. It is difficult to distinguish grout filling in the tendon duct by using the standard impact method.

2 EXPERIMENTAL METHOD

2.1 *Specimen*

Figure 1 shows the dimensions of the specimen for the impact echo tests. The mixture proportion of the concrete is cement of 296 kg/m^3, water of 167 kg/m^3, fine aggregate of 903 kg/m^3, and coarse aggregate of 1041 kg/m^3. The ratio of water to cement is 56.6 %. The maximum coarse grain size is less than 20 mm. The embedded tendon ducts are made from steel and are 38 mm in diameter. The ungrouted tendon duct is empty and the grouted tendon duct has a steel bar with a diameter of 32 mm at the center of the duct.

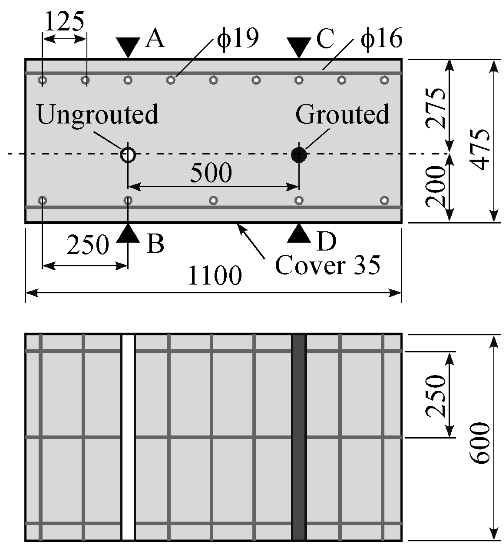


Figure 1. Specimen for impact echo tests.

2.2 *Experimental method*

Figure 2 shows the method of the experiment. The specimen wall was impacted by plastic balls. The speed of the balls just before hitting on the wall was about 70 m/s. The diameter and the weight of the balls were 6.0 mm and 0.12 g, respectively. Measurements were taken from two points on either side of the specimen in line with the target duct. The vibrations of the each point were measured by Laser Doppler vibrometers. The vibration on the back surface was used for the trigger of the measurements and for synchronizing of the time domain signals because the surface elastic waves were not reliable and the trigger times were not reliable.

2.3 *Impact points*

In the standard impact echo method we use the same distance between the impact point and the measurement point. Generally the distance is a couple of centimeters. In our experiment the impact points on the surface were chosen so that the elastic waves reflected from the tendon duct coincided with each other on the time domain. That is, the lengths of the elastic wave paths were made to be constant. Generally elastic wave paths are complicated. It is assumed that the reflected elastic wave from the impact point to the vibration measuring point passes through the shortest path from the impact point to the measuring point via the tendon duct.

Figure 3 indicates the elastic wave path. Let x and y be the horizontal distance and the vertical distance between the impact point and the measuring point on the surface, respectively. The length of elastic wave path becomes

$$L = \sqrt{\left(d + \sqrt{x^2 + d^2}\right)^2 + y^2} \quad . \tag{1}$$

If the point of $x = x_0$ and $y = 0$ in Figure 3 is impacted the length of elastic wave, L_0 becomes

$$L_0 = d + \sqrt{x_0^2 + d^2} \; . \tag{2}$$

We chose the impact points on the surface so that the elastic wave path is equal to the constant length, L_0. Put Equation (1) = Equation (2), we obtain the points on the surface as follows;

$$y = \sqrt{{x_0}^2 - x^2 + 2d\left(\sqrt{{x_0}^2 + d^2} - \sqrt{x^2 + d^2}\right)} \quad . \tag{3}$$

The impact points, when the lengths of the elastic wave paths are constant for x_0 = 8, 10 and 12 cm, are shown in Figure 4. The length-to-width ratio becomes about 1.4 when the center depth of the tendon duct is 275 mm. Then we adopted an impact ellipse with the radii of 10 cm and 14 cm.

When the lengths of the elastic wave paths are constant, by coinciding with the impact time, the reflected elastic waves from the tendon duct synchronize. Then we can expect that their noise reduces and the accuracy of the evaluation of grout filling will be improved by averaging their time domain signals.

3 RESULTS

Figure 5 shows the experimental results for one test. Figure 6 shows the results of four tests. The vertical axis indicates the surface velocity of the impact side and the horizontal axis indicates time. According to Figures 5 and 6, we can see the following;

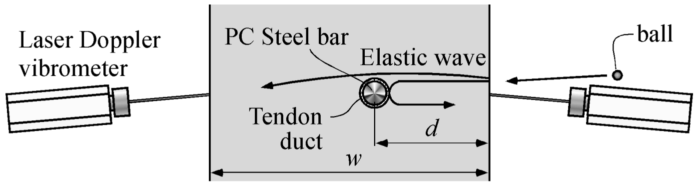


Figure 2. Experimental method.

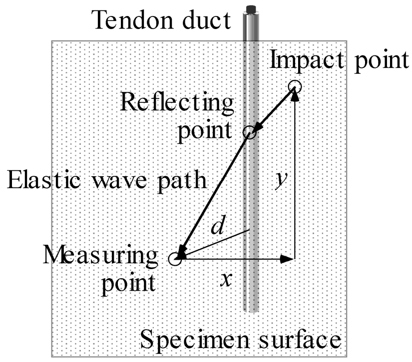


Figure 3. Elastic wave path.

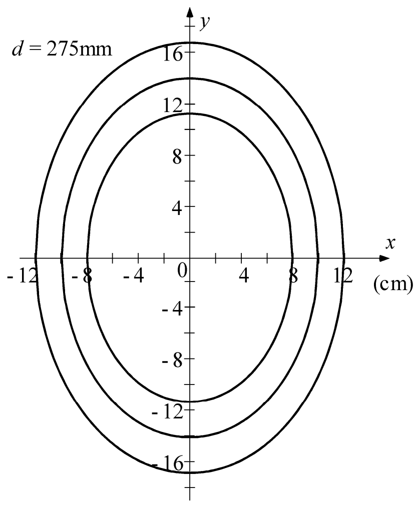


Figure 4. The impact points on the surface for the constant length of the elastic wave path.

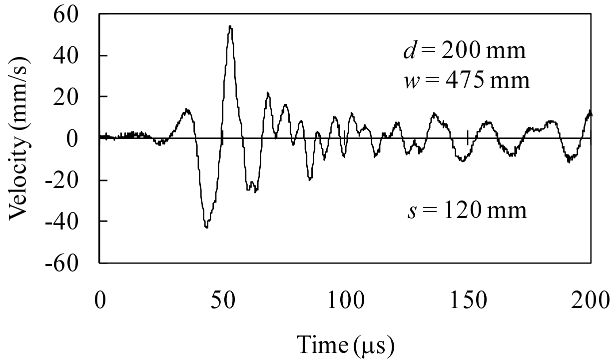


Figure 5. Surface velocity in time domain for one test.

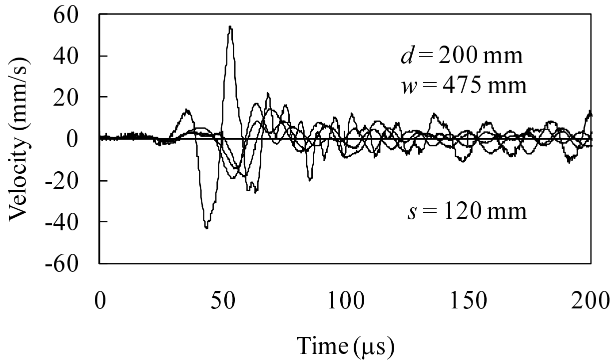
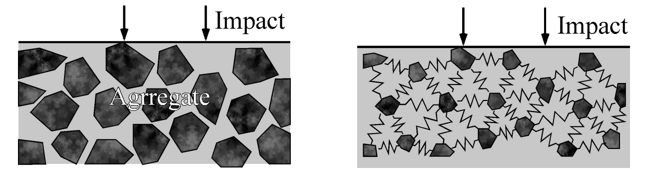


Figure 6. Surface velocities for four tests.



(a) Structure of concrete (b) Vibration model of concrete

Figure 7. Structure of concrete and its vibration model.

(1) The velocity signals due to one impact fluctuate randomly. The amplitude and the frequency of the wave also fluctuate.

(2) Each velocity signal from every impact is different each other.

(3) It may be difficult to evaluate the grout filling by using only one single velocity signal.

The reasons for the fluctuations are as follows;

(1) The contact time of the ball impacting to the surface is inconstant due to the surface roughness.

(2) The structure of the concrete is not homogeneous in comparison with the elastic wave length. They work as a complicated vibration system as shown in Figure 7 (b).

(3) The elastic waves are influenced by steel bars.

From the following results the velocity in the figures is expressed by relative value, because the absolute value of velocity is not important.

By impacting on an ellipse with the radii of 10 cm and 14 cm, we can reduce the influences of the structure of the concrete and the steel bars. Moreover the phase difference of the surface wave occurs and the influence of the surface wave can be reduced.

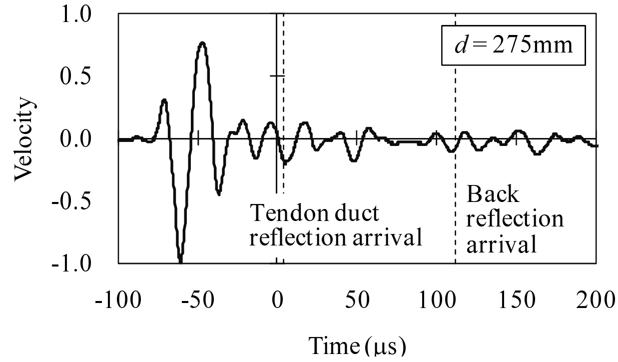


Figure 8. Averaged velocity of 100 results.

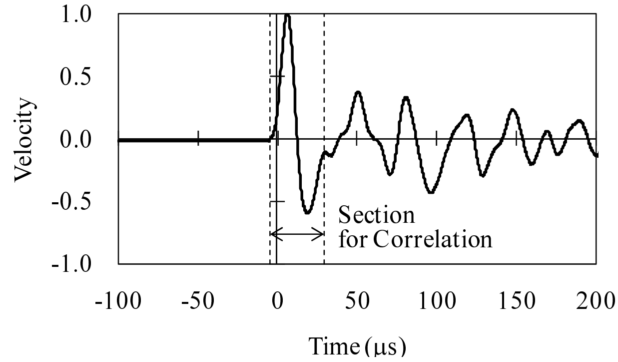


Figure 9. Velocity on back surface and section for correlation.

Figure 8 indicates a typical result of the velocity by impacting on an ellipse at regular intervals one hundred times. The dotted lies in Figure 8 show the arrival times of the elastic waves reflected from the tendon duct and the back surface, respectively.

We see from Figure 8 that it is difficult to evaluate the grout filling based on the velocity directory because the surface vibration remains and the amplitude and the frequency of the vibration velocity fluctuate.

4 DISCUSSION

Figure 9 shows the vibration velocity of the back surface. The direction of positive velocity is the normal direction perpendicular to the back surface. At the first stage the velocity increases and decreases to a negative value. This change means that the elastic wave causing this vibration is a compressive wave.

Free boundary reflection like the interface between concrete and air changes the phase of the elastic waves. Compressive waves become tensile waves. Then the reflected waves from the back surface become tensile waves. On the contrary rigid boundaries like the interface between concrete and grouted tendon ducts do not change the phase of the elastic waves. That is, the elastic waves reflected from ungrouted tendon ducts are tensile waves, and the elastic waves reflected from grouted tendon

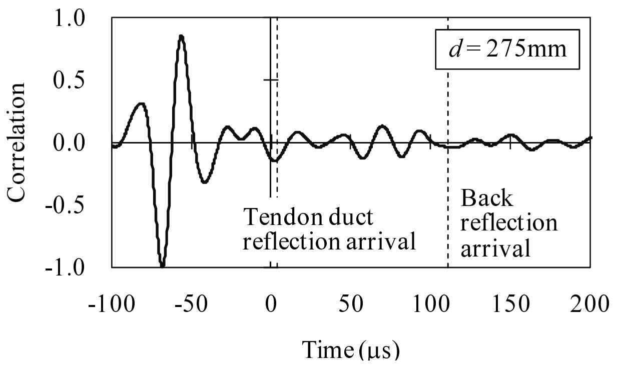


Figure 10. Correlation function for ungrouted tendon duct.

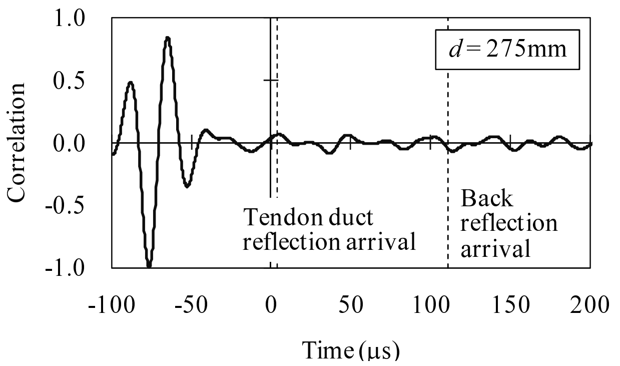


Figure 11. Correlation function for grouted tendon duct.

ducts are compressive waves. We try to distinguish the grout filling based on this difference.

The reflected elastic waves from ungrouted tendon ducts cause the change of the surface velocity from the negative to the positive because their waves are tensile waves. On the contrary the reflected waves from grouted tendon ducts cause the change of the surface velocity from the positive to the negative because their waves are compressive waves. The shapes of these reflected waves in the time domain are similar to the surface velocity of back surface as shown in Figure 9. The velocity signals of these reflected waves are symmetric against the time axis. Therefore, calculating the correlation (For example, Bendat & Piersol 1993) between the reflected waves and the surface vibration of the back surface, the value of the correlation between the reflected elastic waves from ungrouted tendon ducts and the back surface vibration is supposed to be negative. On the contrary the values of the correlation between the reflected wave from grouted tendon duct and the back surface vibration are supposed to be positive.

Figure 10 shows the correlation function between the surface velocity of the ungrouted tendon duct and that of the back surface velocity. As we can see, the value of the correlation function at the time of the reflected wave arriving is negative. The value at the time of the back reflected wave arriving is also negative.

Figure 11 shows the correlation function between the surface velocity of the grouted tendon duct and that of the back surface velocity. As we can see, the value of the correlation function at the time of the reflected wave arriving shows positive. The value at the time of the back reflected wave arriving is also negative.

We performed these experiments five times for the specimen with the center tendon duct depth, d = 275 mm. We obtained similar results to Figures 10 and 11. However we couldn't get good results for the specimen with d = 200 mm. In the case of d = 200 mm, the reflected waves from the tendon duct and the surface waves couldn't be separated because the surface waves remained when the reflected waves from the tendon duct arrived.

In this experiment we use the back surface vibrations. However, it may be difficult to measure the back surface vibration. In those cases we can substitute the surface vibrations for the back surface vibrations.

5 CONCLUSION

An improved impact echo method has been developed. The improvement in accuracy comes from the multiple impacts and averaging in the time domain. We applied this improved impact echo method to evaluation of grout filling in tendon ducts. According to the experimental results for the specimen with a tendon duct depth of 275 mm, the results are as follows;

(1) It is difficult to detect the presence of grout filling in tendon ducts by a single impact test.
(2) By impacting on concrete surface elliptically the reflected waves from a tendon duct synchronize and the noise is reduced.
(3) It is possible to detect the presence of grout filling in tendon ducts by calculating the correlation between the surface velocity and its criterional signal. The back surface velocity or the surface velocity can be used as the criterional signal.

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