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Detecting horizontal cracks in RC slabs with asphalt overlays using impact elastic-wave methods

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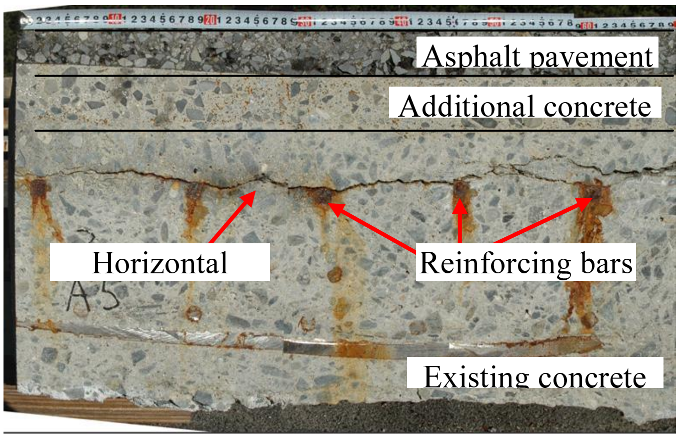
ABSTRACT: In this study, a reinforced concrete slab specimen with an asphalt pavement was prepared in which horizontal cracks were artificially simulated. Horizontal cracks were detected from the pavement surface by the impact elastic-wave method. Influence of varying frequency of input elastic wave on the detection of artificial flaws and applicability of detecting method was discussed. As a result, it was revealed that artificial flaws were highly detectable, by implementing the impact elastic-wave method from the asphalt pavement surface, in a specimen with an assumed thickness of an ordinary reinforced concrete high way bridge slab and horizontal cracks at assumed locations (depths). It was also found that a single optimum diameter of the steel sphere could be determined for the impact elastic-wave method as long as it would be used only for the detection of horizontal cracks in reinforced concrete highway bridge slabs.

1 INTRODUCTION

Recently, horizontal cracks have been found in cut cross-sections of deteriorated reinforced concrete highway bridge slabs in Japan (Photograph 1). The horizontal cracks occur at the interface between additional concrete and the upper surface of existing concrete and at the location of reinforcing bars in the existing concrete (Uchida et al. 2007). The occurrence or development of horizontal cracks is very difficult to detect by visual inspection from the top or bottom surface of slab. Establishing of a nondestructive method to detect horizontal cracks has therefore been required.

Against the above background, the authors created a slab specimen and artificially simulated internal horizontal cracks that could not be detected from the top or bottom surface of specimen. Horizontal cracks were detected using three different elastic-wave methods: impact elastic-wave method, ultrasonic method and electro magnetic hammer method. Studies were discussed the sizes and depths of horizontal cracks to which respective methods were applicable when detecting horizontal cracks. As a result, it was found that the impact elastic-wave method was capable of detecting horizontal cracks in the largest area among the above three methods. Specimens were also prepared that had asphalt pavements or waterproof layers, and the influences of these existences on the estimation of slab thickness by the impact elastic-wave method were also examined. As a result of testing, it was revealed that waterproof layers or asphalt pavements had little influence during the estimation of slab thickness



Photograph 1. Outline of horizontal cracks in cut cross-sections of deteriorated reinforced concrete slabs in Japan.

(Uchida et al. 2008). The applicability of the impact elastic-wave method to the detection of horizontal cracks was not yet fully indentified in the case where an asphalt pavement was installed. For reinforced concrete highway bridge slab in service, for slabs for which installing inspection scaffolding from the bottom surface of the slab is difficult in particular, establishing a method for detecting horizontal cracks from asphalt pavement surface is of great significance.

In this study, a reinforced concrete slab specimen with artificially simulated internal horizontal cracks was created to detect horizontal cracks from the surface of asphalt pavement using the impact elastic-wave method. Influence of varying frequency of input elastic wave on the detection of artificial flaws and applicability of detecting method was discussed.

2 PRINCIPLE OF DETECING HORIZONTAL CRACKS FROM ASPHALT PAVEMENT SURFACE BY THE IMPCT ELASTIC-WAVE METHOD

The principle of detecting horizontal cracks in reinforced concrete slabs by the impact elastic-wave method is shown in Figure 1. The method is based on the propagation of elastic waves produced by tapping a small steel sphere against the slab surface. The multiple reflections of the waves by the slab surface and bottom surface or the multiple reflections of the slab surface and horizontal cracks are received by sensors installed on the surface and are transformed into a frequency domain to obtain the peak frequencies (f_T and f_d in Fig. 1). Then, the thickness of the specimen T and the depth to the horizontal crack d are estimated based on the peak frequencies.

The specimen used in the test is simulated a reinforced concrete highway bridge slab shown in Figure 1. The slab was composed of an asphalt pavement, additional concrete above the existing concrete (for details, refer to Section 3.1). The elastic wave velocity in asphalt is lower than in concrete. It was therefore necessary to assume that the specimen was composed of two layers of different materials through which elastic waves propagated at different velocity. The theoretical peak frequencies corresponding to slab thickness and crack depth under the condition can be calculated by

$$f_T = \frac{1}{\frac{2T_1}{C_{p1}} + \frac{2T_2}{C_{p2}}} \tag{1}$$

$$f_d = \frac{1}{\frac{2T_1}{C_{p1}} + \frac{2(d - T_1)}{C_{p2}}} \tag{2}$$

where, f_T is the theoretical resonant frequency corresponding to the thickness of the specimen, f_d is the theoretical resonant frequency corresponding to the depth of horizontal crack, C_{p1} is the P-wave velocity through asphalt, C_{p2} is the P-wave velocity through additional and existing concrete (the velocity is considered equivalent), T_1 is the thickness of asphalt pavement, T_2 is the combined thickness of additional and existing concrete and d is the depth to a horizontal crack (Sansalone & Streett 1997).

3 OUTLINE OF TEST

3.1 *Specimen*

Examined in this study is a reinforced concrete highway bridge slab shown in Photograph 1. Additional concrete was placed above the existing concrete to increate slab thickness and an asphalt pavement was

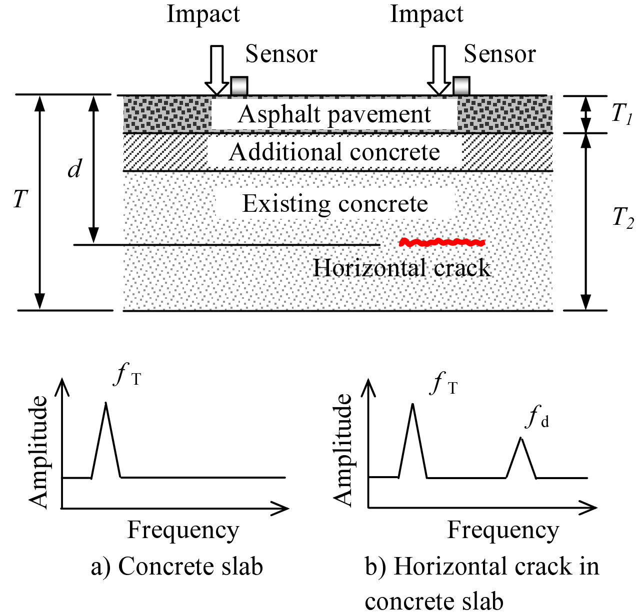
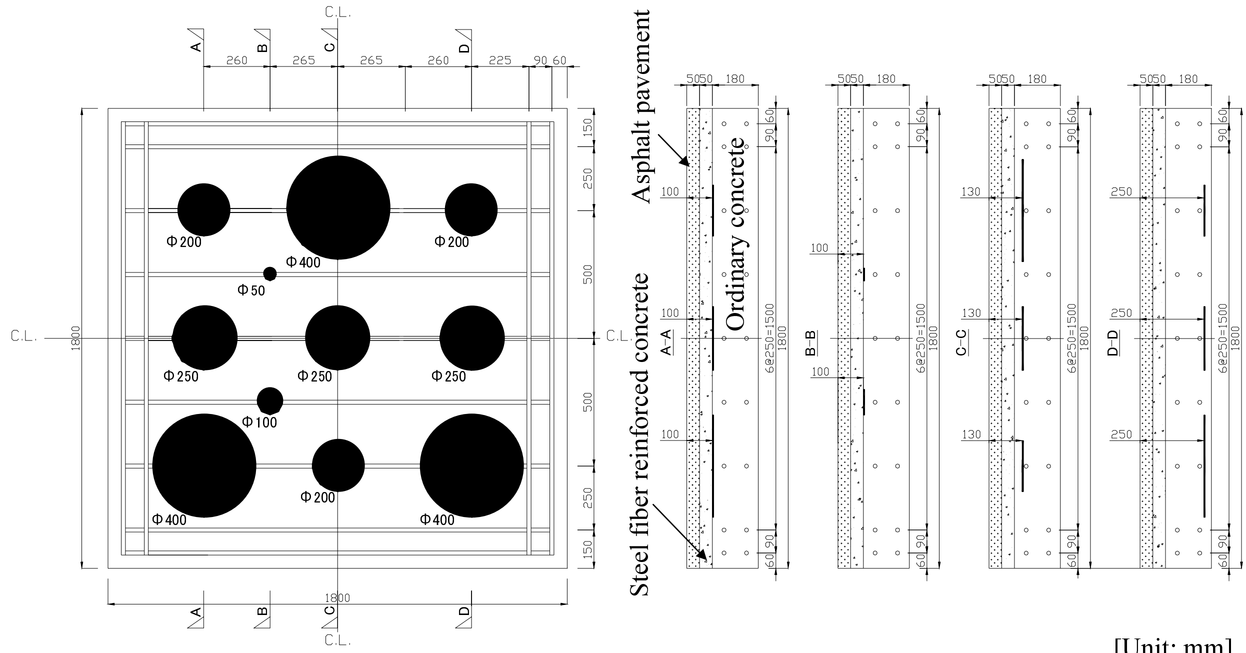


Figure 1. Schematic diagram of the principle of detecting horizontal cracks in reinforced concrete slabs by the impact elastic-wave method.

installed to overlay the concrete. A specimen simulating highway bridge slab was prepared in accordance with the "Upper surface thickness increase method - Design and construction manual" prepared by the Express Highway Research Foundation of Japan (1995). First, ordinary concrete of a thickness of 180 mm was placed as the existing concrete. Then, the concrete surface was chipped and steel fiber reinforced concrete of a thickness of 50 mm was placed on the upper surface. An asphalt pavement of a thickness of 50 mm was installed to overlay the steel fiber reinforced concrete. The thickness of the specimen amounted to 280 mm. The length and width of the specimen were set to be 1800 mm, sufficiently large for the thickness to minimize the effects of lateral reflections of waves. Figure 2 and Photograph 2 outline the specimen. The compressive strength of the ordinary concrete and the steel fiber reinforced concrete at 28 days were 30.5 and 32.6 MPa respectively. On the other hand, the elastic modulus of the asphalt was 10 GPa.

In order to simulate horizontal cracks in the specimen, polystyrene disks with a thickness of 6 mm and a diameter of 50, 100, 200, 250 or 400 mm were placed as artificial flaws. The artificial flaws were located at three different depths in view of the locations of horizontal cracks in the reinforced concrete highway bridge slab in service (Photograph 1). The artificial flaws were installed at the interface between the additional concrete and the upper surface of existing concrete, and at the locations of the upper and lower edges of reinforcing bar in the slab. The arrangement of artificial flaws are shown in Figure 2 and Photograph 3. The relationship between the diameter and depth of artificial flaws are listed in Table 1.



[Unit: mm]

Figure 2. Outline of specimen and arrangement of artificial flaws.

Photograph 2. Outline of specimen.

Photograph 3. Arrangement of artificial flaws.

3.2 *Measurement by impact elastic-wave method*

Photograph 4 shows the measurement by the impact elastic-wave method. Elastic waves were input and received on the points on the asphalt surface above artificial flaws. The distance between the points of elastic wave input and reception was 50 mm.

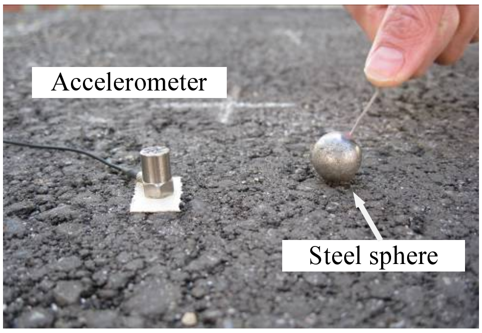
In order to investigate the influences of varying frequencies of input elastic wave on the detection of artificial flaws, steel spheres of five different diameters (4.0, 6.4, 11.0, 15.7 and 30.2 mm) were used. For receiving elastic wave, accelerometer with a response sensitivity range of 0.003 to 30 kHz was adopted. The signals received by the sensors were recorded in a waveform acquisition device as acceleration versus time signals. Fourier spectra of acceleration were analyzed by fast Fourier transform (FFT). Sampling time was 1μs.

Wave velocity through ordinary and steel fiber reinforced concretes were obtained by measurement using the impact elastic-wave method at the surface of steel fiber reinforced concrete before the construction

Table 1. Relationship between diameter and depth of artificial flaws.

Diameter (mm)	Depth (mm)		
	100	130	250
50	●	–	–
100	●	–	–
200	●	●	●
250	●	●	●
400	●	●	●

–: Artificial flaw was not placed.
●: Artificial flaw was placed.



Photograph 4. Measurement by impact elastic wave method.

of the asphalt pavement. If the peak frequency on the frequency spectrum and specimen thickness is known, the wave velocity can be estimated by

$$C_p = 2f'T' \tag{3}$$

where, f' is the peak frequency on the frequency spectrum and T' is the combined thickness of ordinary and steel fiber reinforced concrete (230 mm). C_p is the P-wave velocity through ordinary and steel fiber reinforced concrete. The wave velocity through ordinary and steel fiber reinforced concretes regarded as a single composite medium was set to be 3902 m/sec. based on the mean of measurements taken at multiple points. The velocity through the asphalt pavement was calculated by ultrasonic method using two probes that were installed on the surface of the asphalt pavement. The mean of measurement taken at multiple points was 2730 m/sec., which was nearly identical to 2800 m/sec., the wave velocity through asphalt pavements shown in an existing research (Sansalone & Streett 1997). In this study, therefore, a wave velocity of 2700 m/sec. obtained by measurement was adopted.

4 TEST RESULTS AND DISCUSSIONS

4.1 *Selection of steel sphere diameter*

When detecting horizontal cracks efficiently from the surface of asphalt pavement of a reinforced concrete highway bridge slab in service by the impact elastic-wave method, the number of diameters of the steel sphere used for inputting elastic waves should preferably be minimized. The thickness of reinforced concrete highway bridge slab is generally specified in manuals (Express Highway Research Foundation of Japan 1995) or other documents in most cases. The locations of horizontal cracks in the slab have also been identified by cutting the reinforced concrete bridge slab in service (Photograph 1). In this study, the thickness of the specimen was first estimated in the case with no flaws where the resonant frequency was assumed to be lowest. Then

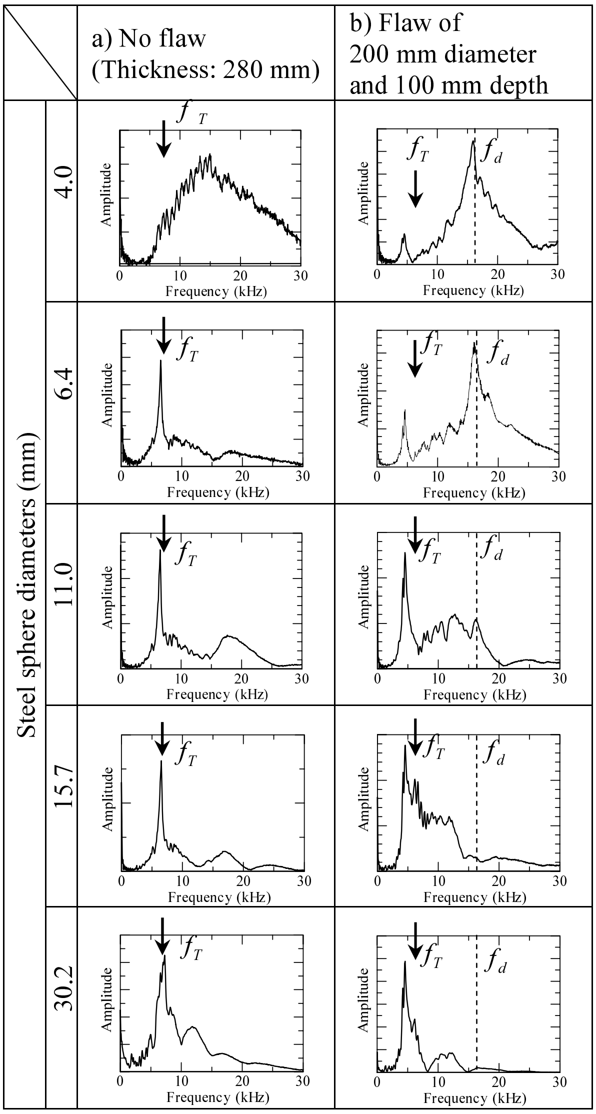


Figure 3. Frequency spectra obtained for respective steel sphere diameters.

easurements were made in the case of a flaw depth of 100 mm at which the resonant frequency was expected to be highest. A steel sphere that could be used for evaluation in both cases was considered to be fully applicable to flaws at depth of 130 mm and 250 mm (resonant frequency at these flaw depths was lower than at a flaw depth of 100 mm).

Figure 3 shows the frequency spectra obtained for respective steel sphere diameters. The arrows indicate the theoretical resonant frequency corresponding to the thickness of the specimen (f_T = 6.5 kHz). The broken lines indicate the theoretical resonant frequency corresponding to the artificial flaw depth (f_d = 16.1 kHz). In the frequency spectra in the cases with no artificial flaws (Figure 3 a)), a peak is clearly identified nearly at the position of f_T at all the diameters of steel sphere except 4.0 mm. It was thus found that the thickness of the specimen could be estimated in the case where a steel sphere diameter was 6.4, 11.0, 15.7, or 30.2 mm.

In the cases of a flaw of 200-mm diameter and 100-mm depth (Figure 3 b)), frequency peaks at a level lower than f_T regardless of the diameter of the steel sphere. The peak (approximately 4.6 kHz) tends to gradually become predominant as the diameter of the steel sphere increases. In the case where artificial flaws existed on the wave propagation route, waves got around the flaws. Then, the elastic wave propagation distance (the minimum distance from the point where the steel sphere was tapped to the bottom surface of the specimen) was longer than in the case with no artificial flaws (Fig. 4). As a result, resonant frequency corresponding to the thickness of the specimen f_T shifts toward a lower frequency as identified by a study of Sansalone & Streett (1997). A wave velocity of 2730 m/sec. through asphalt, a wave velocity of 3902 m/sec. through concrete and steel fiber reinforced concrete were assumed, and elastic wave propagation distance through asphalt was geometrically assumed to be 70.7 mm and wave propagation distance through concrete and steel fiber reinforced concrete was assumed to be 277.4 mm (including a thickness of artificial flaw of 6 mm). Then, the resonant frequency corresponding to the minimum distance from the point of tapping the steel sphere to the bottom surface of specimen (348.1 mm) was calculated using equation (1). The result was 5.2 kHz, close to the peak indicated in the figure (approximately 4.6 kHz). In this study as well as in the study of Sansalone, it was verified that the resonant frequency corresponding to the thickness of the specimen f_T shifts toward a lower frequency in the case where an artificial flaw exists.

Next, the frequency bandwidth in the vicinity of the resonant frequency corresponding to the artificial flaw depth f_d was examined. It was also evident that f_d was well in agreement with the peak in the frequency spectrum at steel sphere diameters of 4.0 and 6.4 mm. At steel sphere diameters of 11.0, 15.7 and 30.2 mm, f_d element in the frequency spectrum decreases as the steel sphere diameter increases. If a steel sphere of any of these diameters is used, therefore, detecting artificial flaws may be difficult.

The above discussions have revealed that a steel sphere diameter of 6.4 mm is appropriate when evaluating the thickness and artificial flaw depth for a specimen that simulates a reinforced concrete highway bridge slab. The result suggests the following. When using the impact elastic-wave method for detecting horizontal cracks in an ordinary reinforced concrete highway bridge slab from the pavement surface, steel spheres of varying diameters should first be used to calculate frequency spectrum. The steel sphere of the minimum diameter that can enable the verification of the peak frequency corresponding to slab thickness should be selected. Thus, a sole steel sphere diameter can be determined, and horizontal cracks can be detected efficiently.

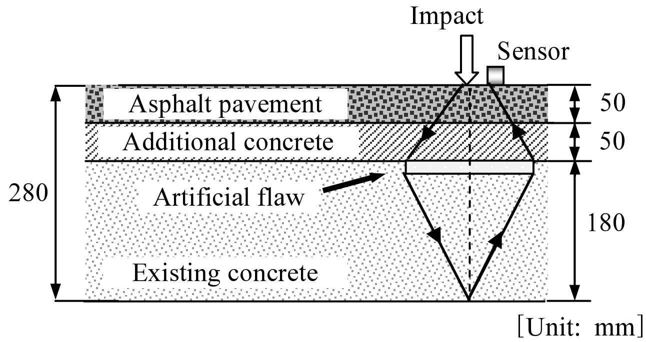


Figure 4. Schematic diagram in the case where artificial flaws existed on the wave propagation route.

4.2 *Characteristics of measured frequency spectra*

Based on the descriptions in the preceding section, a steel sphere of a diameter of 6.4 mm was used for inputting elastic waves. Figure 5 shows frequency spectra. As in Figure 3, f_T and f_d are indicated by an arrow and a broken lines, respectively. The results shown in Figure 5 can be classified into two categories: case of an artificial flaw of 50-mm or 100-mm diameter and 100-mm depth, and the other cases. In the former cases, the diameter of the artificial flaw is equal to (diameter/depth = 1.0) or smaller than (diameter/depth = 0.5) the depth. The artificial flaw is therefore not sufficiently large as the point of elastic wave reflection, and multiple reflections are unlikely to occur. This may be the reason why confirming a sole peak corresponding to the artificial flaw depth is difficult in the frequency spectrum. According to the results of a study that the authors conducted using a specimen simulating a reinforced concrete highway bridge slab with no asphalt pavement (Uchida et al. 2008), the minimum diameter/depth ratio of a flaw that that can enable the detection of the artificial flaw is approximately 1.0. In the case with an asphalt pavement, therefore, the elements of multiple reflections may be reduced in waveforms received at the pavement surface due to the attenuation or scattering of elastic waves by asphalt mixtures, and the capacity to detect flaws may be decreased.

In the latter cases, f_d (indicated by dotted lines in Figure 5) is evidently in agreement with the peak in the frequency spectrum in all of the cases. In the cases of a flaw diameter of 200 mm and a flaw depth of 100 or 130 mm, ft becomes predominant with the increase of flaw depth and f_d is reduced. The similar tendency is also found in the case of a flaw diameter of 250 or 400 mm. Elastic wave input by tapping a steel sphere generally propagate as spherical waves. In the case of a small flaw depth, the percentage of elastic waves that are reflected is higher at the location of the flaw than on the bottom surface of the specimen. This may be the reason why f_d is more predominant than f_T in the frequency spectrum. At a flaw depth of 250 mm (a flaw diameter of 200, 250

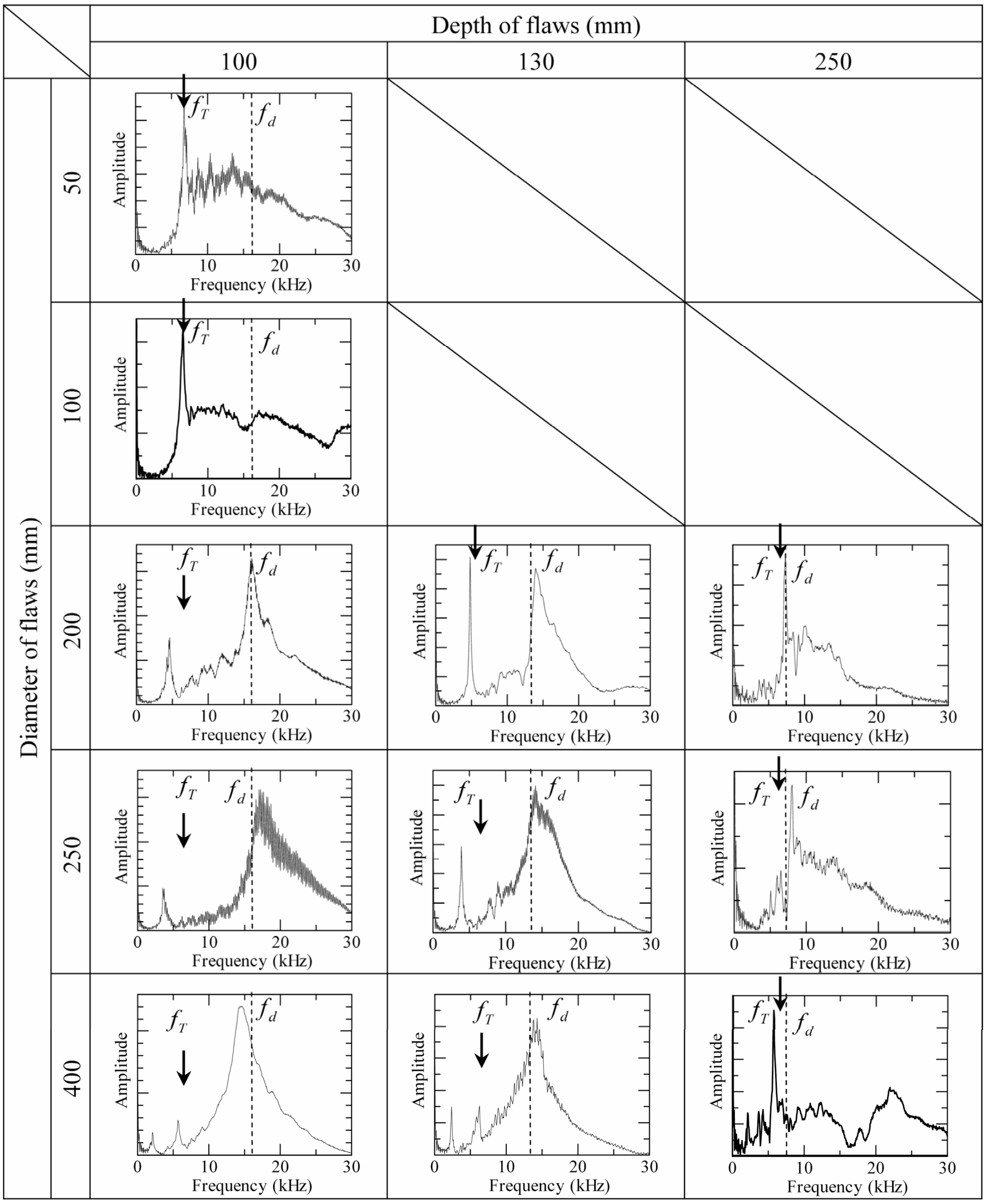


Figure 5. Frequency spectra for all test cases.

or 400 mm), the depth of the flaw serving as the point of wave velocity reflection is located nearly at the same depth as the bottom surface of the specimen (at a depth of 280 mm). Neither f_T nor f_d therefore can be confirmed simultaneously in the frequency spectrum. Next, focus is placed on the frequency spectrum in the case of a flaw depth of 130 mm (a flaw diameter of 200, 250 or 400 mm). As the flaw diameter increases, f_d is more predominant than f_T. This is because the reflector of elastic waves increased with the flaw diameter. The tendency is the same as in the case of a flaw depth of 100 mm.

4.3 *Diameter and depth of detectable flaws*

The relationship between diameter and depth for detectable flaws are listed in Table 2. In this section, the flaws for which peak frequency could be confirmed near f_d in the frequency spectrum were determined to be detectable (indicated by circled in Table 2) base on the results described in the preceding section. The other flaws were determined to be difficult to detect (indicated by crosses). The peak frequency in the case of a flaw depth of 250 mm shown in Figure 5 is nearly the same as the peak frequency in the case with no flaws (a steel sphere diameter of 6.4 mm) shown in Figure 3 because the flaw depth is nearly level with the bottom surface of the specimen (at a depth of 280 mm). At present, therefore, it is difficult to determine that there is flaw. The flaw is, however, determined to be detectable (indicated by triangles in Table 2) based on whether peak frequency is found or not. In the future, other parameters than peak frequency will be considered. A horizontal crack detection method will be built based on the shape of frequency spectrum and frequency analysis methods, and improved further.

Table 2. Relationship between diameter and depth for detectable flaws.

Diameter (mm)	Depth (mm)		
	100	130	250
50	×	−	−
100	×	−	−
200	○	○	Δ
250	○	○	Δ
400	○	○	Δ

−: Artificial flaw was not placed.

○: Detectable.

Δ: Difficult to determine that there is flaw.

×: Undetectable.

5 CONCLUSIONS

Conclusions are summarized as follows:

1) The impact elastic-wave method was applied from the asphalt pavement surface of a specimen that simulated an ordinary reinforced concrete highway bridge slab. As a result, it was revealed that artificial flaws simulating horizontal cracks in the specimen could be detected.
2) For reinforced concrete highway bridge slabs, the total thickness of the slab, and the thicknesses of existing concrete, additional concrete and asphalt pavement are mostly known. The depth at which horizontal cracks occur can also be predicted based on the thicknesses related to the slab. As long as horizontal cracks are detected in reinforced concrete highway bridge slabs with such characteristics as described above, a sole diameter can be selected for the steel sphere used for the impact elastic-wave method.

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