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Research on Stress State Evaluation for Highway PC Bridge

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ABSTRACT

A study on applicability of non-destructive inspection methods to evaluate degree of soundness of PC bridges was conducted. An experiment for radio propagation characteristics of ultrasonic waves and impact elastic waves was conducted. First, for PC structures consisting of PC steels, reinforcing bars, and concrete, a study on a possibility of grasping the pre-stressing rate from the radio propagation characteristics was conducted. Also, experiments using model and real PC girders to study on the applicability to the real structures were conducted. As a result, a possibility to apply the non-destructive inspection methods was indicated.

Keywords. PC bridge, Non-destructive inspection method, Soundness evaluation, Ultrasonic wave, Impact elastic wave

1. Introduction

When the degree of soundness of a damaged PC road bridge is evaluated, it is necessary to evaluate the degree of soundness of the bridge including the estimation of the prestress conditions. Past studies to estimate prestress conditions include stress relief method (Niitani *et al.,* 2009), method of reinforcing bar dissection (Yokoyama *et al.,* 2004), and slot stress method (Asai *et al.,* 2004), etc., and they are used to estimate the prestress conditions introduced by relieving a part of stress of the PC structure. Since these methods involve partial destruction of structure, the load on the structure is significant, thus restrictions would be imposed on applicable locations and frequency depending on existing conditions. As described above, it is believed that the method to estimate the amount of prestress by using a non-destructive method has not yet been established at this time. Therefore, in this study, attention was focused on the non-destructive inspection technique using ultrasonic wave and impact elastic wave, to verify the possibility of estimating prestress conditions by using these methods.

2. Overview of experiment

In this study, following steps were implemented to verify the method to estimate the amount of prestress introduced with the non-destructive inspection technique.

1) Element experiment

To understand the basic relationship between the stress condition that acts on each element (PC steel, reinforcing bar, and concrete) composed of prestressed concrete members and propagation characteristics of ultrasonic wave as well as impact elastic wave, an element experiment was conducted using small scale specimens.

2) Model girder experiment

Based on the result of the element experiment, verification was conducted, with focus on the relationship between prestress level and ultrasonic propagation velocity as well as frequency characteristics, using model girders with varying amounts of prestress introduced.

3) Real PC girder experiment

An experiment using real post-tension T-beam (L=45m) was conducted to verify the applicability of method to estimate the amount of prestress introduced by the non-destructive inspection technique to an actual structure. In the experiment, verification was conducted with a focus on the relationship between the stress condition of concrete and ultrasonic wave as well as impact elastic wave propagation characteristics.

3. Element experiment

3.1 Content and result of each experiment

(1) PC steel

Specimens used for the element experiment included three beam specimens (L=7.6m) with varying amounts (100%, 50%, and 10%) of prestress introduced (Photo. 1). Ultrasonic method and impact elastic wave method were selected as inspection technologies applied,

Photo. 1. Beam specimen

Table 1. Experiment case with focus on PC steel

Applicable technology	Case	Observation point	Overview	Evaluation method	Result
Ultrasonic wave method	A	Specimen side face	Fixed sending location, varying receiving location	Propagation velocity	×
	B	Specimen side face	Constant send/receive distance	Frequency component	×
	C	One side bearing plate	Send/receive from one side bearing plate	Frequency component	×
Impact elastic wave method	D	PC Steel end parts + protective mortar	Send/receive from protective mortar surface	Propagation velocity	○
	E-1	PC Steel end parts	Send/receive from PC steel cross section	Propagation velocity	○
				Frequency component	×
	E-2	Both ends anchorage device	Send/receive from anchorage device cone	Frequency component	○
	E-3	One side anchorage device	Send/receive from anchorage device cone in one side	Frequency component	×
	F	Concrete surface	Send/receive from beam end concrete face	Frequency component	×

○: The correlation with prestress level was confirmed.
×: The correlation with prestress level could not be confirmed.

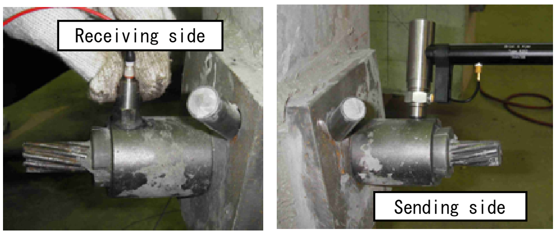


Photo. 2. Impact elastic wave method

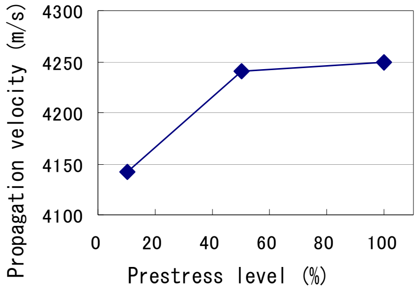
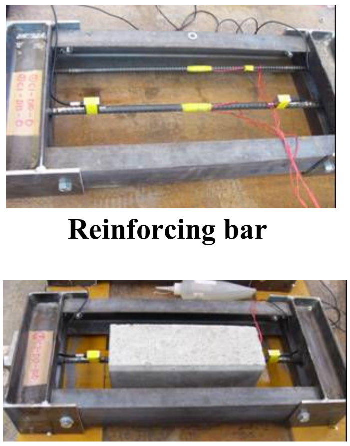


Fig. 1. Relationship of propagation velocity and prestress level (CaseE-2)

and experiment cases were configured in accordance with the send/receive locations, etc. (Table 1). Also, the evaluation method was implemented with focus on propagation velocity and frequency characteristics. The determination results by each evaluation method are also shown in Table 1. In the measurement (ultrasonic method) using surface wave method (send/receive to/from specimen side surface), only the wave propagating on the concrete surface could be measured, and the wave propagating the PC steel could not be confirmed. This is believed to be due to the fact that the input wave could not reach the PC steel because it was reflected on aggregate, air bubbles, and sheaths, etc. Meanwhile, in the measurements based on signals sent to and received from PC steel end parts (impact elastic wave method) (Photo. 2), the correlation with the prestress level was confirmed regarding the propagation velocity that propagates through PC steel (Fig. 1). However, it is thought that many challenges exist in applying this to existing structures because it is difficult to send/receive directly to/from PC steel end parts.

(2) Reinforcing bar

Two types of specimens were used; one was reinforcing bar alone to which tensile force was applied and the other was square column of 100×100×300 mm with concrete lining placed around reinforcing bars after tensile force was applied to the reinforcing bars (Photo. 3). Different diameter bar (D13) of SD345 that is commonly used for the road bridge was selected as the reinforcing bar, and for the tensile force applied to the reinforcing bar, the



Reinforcing bar

Reinforcing bar + Concrete lining

Photo. 3. Reinforcing bar specimen

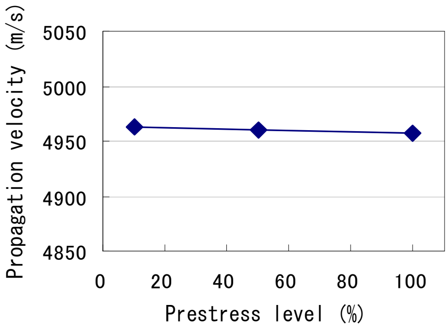


Fig. 2. Relationship of propagation velocity and prestress level

equivalent of the compressive strain applied to the reinforcing bar located in the bottom border at the span center point of the beam specimen used in the element experiment of PC steel, was applied as tensile strain. Ultrasonic method was selected as the inspection technology applied, and experiment cases are configured in accordance with the send/receive locations, etc. In the measurement of specimen of reinforcing bar alone, a tendency of a decrease in the propagation velocity of the ultrasonic wave as the tensile stress of reinforcing bar was increased, was observed (Fig. 2). However, the change in amount of propagation velocity was very small, and it is thought that a high-precision measurement with reproducibility is difficult. Also, when a measurement was conducted by surface wave method for the square column specimen with concrete lining, variability was observed among the propagation velocities, and correlation of propagation velocity and prestress level could not be confirmed. Materials such as aggregate etc. are thought to have caused this variability. As described above, it is thought that many challenges exist on a practical application level regarding the measurement with a reinforcing bar.

(3) Concrete

In this experiment, a square column specimen of 150×150×530 mm was used to measure the propagation velocity of ultrasonic wave when the concrete stress was varied from 0 to 15 N/mm^2 (Pho. 4). In the measurement by surface wave method (send/receive from specimen side face), a tendency in which the propagation velocity of the ultrasonic wave increased as the compressive stress increased, was confirmed (Fig. 3). From the above result, it was confirmed that detection of the difference of the stress conditions could be possible for concrete by analyzing the property of propagation velocity of the ultrasonic wave that propagated members with different stress conditions.

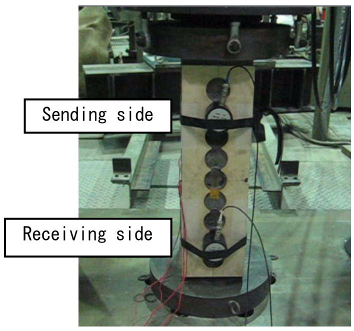


Photo. 4. Concrete element experiment

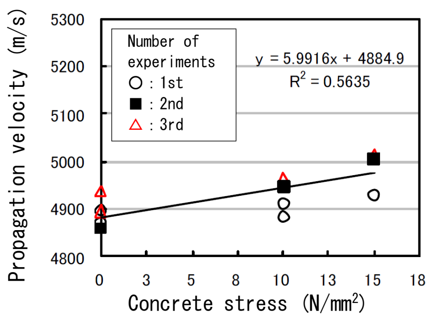


Fig. 3. Relationship of propagation velocity and concrete stress

4. Model girder experiment

4.1 Overview of experiment

Estimation of the amount of the prestress introduced based on the propagation characteristics of the ultrasonic wave was verified by using model girders with varying amounts of prestress introduced.

4.2 Experimental method

The model girder used in the experiment was a PC girder of 7,500 mm in girder length with a cross section of 750 mm high and 300 mm wide, in which PC steel was placed at 250 mm

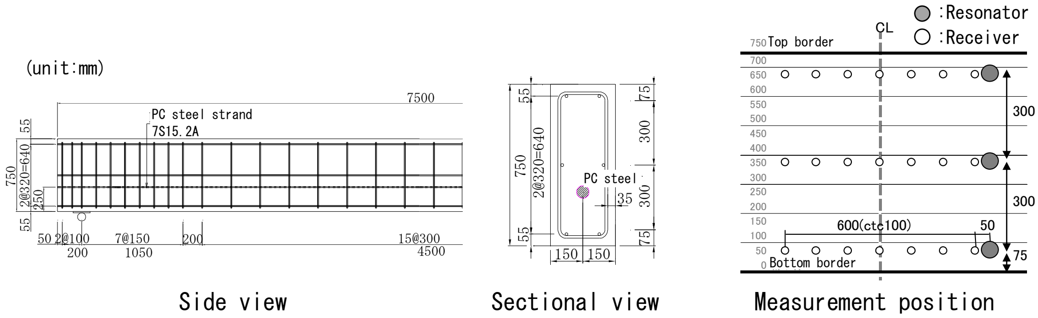


Fig. 4. Model girder schematic diagram

Table 2. Stress of model girder

Prestress level (%)	Amount of prestress introduced (kN)	Concrete stress (N/mm^2)	
		Top border	Bottom border
100	1165	0.97	7.85
70	816	1.01	4.98
50	583	1.05	3.53
0	0	1.20	-1.21

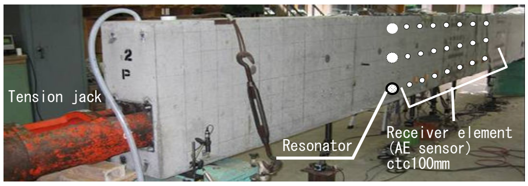


Photo. 5. Model girder experiment

from the bottom border in a linear fashion, as shown in Fig. 4. In terms of the prestress introduced, assuming the amount of the prestress that is equivalent to the extreme fiber stress at girder bottom of a standard girder bridge to be the reference value (100%), the propagation velocities of ultrasonic wave were measured under total of 4 cases based on the prestress levels that are 100%, 70%, 50%, and 0% of the reference value. Amount of the prestress introduced and concrete stress are shown in Table 2 respectively. The measurement of the ultrasonic propagation velocities was performed by receiving the surface propagation waves with seven wideband type sensors placed at distance of 100 mm on the same measurement line after inputting ultrasonic waves of 100 kHz to the member surface along 3 measurement lines of varying height positions. Sending/receiving locations of ultrasonic waves in this experiment and the experiment condition are shown in Fig. 4 and in Photo. 5.

4.3 Experimental result and discussion

Propagation velocities in each measurement line obtained in this experiment by sending/receiving ultrasonic waves through the model girders with 4 different prestress levels are shown in Fig. 5. The propagation velocity indicated a tendency to become smaller when the prestress level decreased throughout receiving points on each measurement line, and the reproducibility of element experiment was confirmed. Particularly, in the lower measurement line where stress change due to varying amounts of prestress introduced was significant, the tendency was clear regardless of the measurement intervals (propagation distance). Fig. 6 indicates the relationship of concrete stress and propagation velocity estimated at the relevant measurement line positions based on the results of three measurement lines in 550 mm of the measurement distance. Based on this, it was confirmed that there is clear relationship between the concrete stress and the propagation velocity of ultrasonic wave.

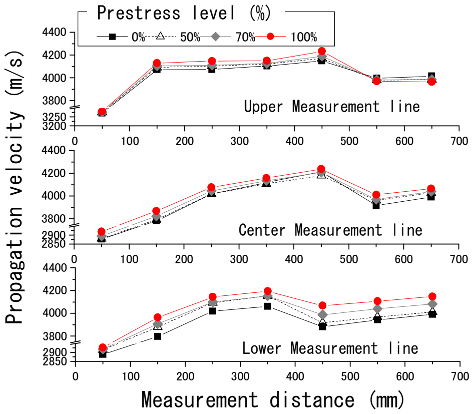


Fig. 5. Relationship of prestress level and propagation velocity

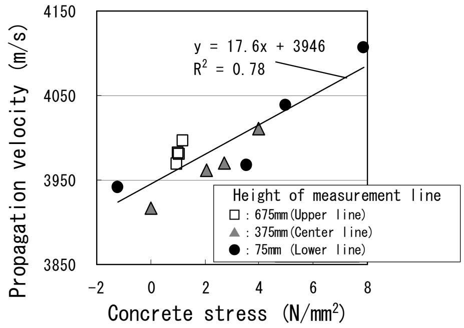


Fig. 6. Relationship of concrete stress and propagation velocity (Measurement distance 550 mm)

4.4 Review on analytical method

(1) Short-time frequency analysis

As a technology to detect amount of remaining prestress in an existing structure, the approach that represents the difference of propagation wave due to the difference of stress condition more clearly can be considered, by employing an analytical method focusing on the propagation time and the frequency to expand the combined information of those two (short time frequency analysis). In this study, the short time frequency analysis with the use of propagation time and frequency component of the ultrasonic wave that had been obtained from model girders was studied. Here, the short time frequency analysis is Short-Time Fourier Transform (STFT) that breaks down the signal into small time segments in order to perform analysis segmentally.

(2) Analytical result with model girder

Fig. 7 shows the result of short-time frequency analysis at distances of 150 mm and 550 mm from the sending sensor of the lower measurement line when the introduced prestress was varied (0%, 70%, 100%). High frequency waves were more frequently observed as prestress level became higher. And together with results at other measurement points, this

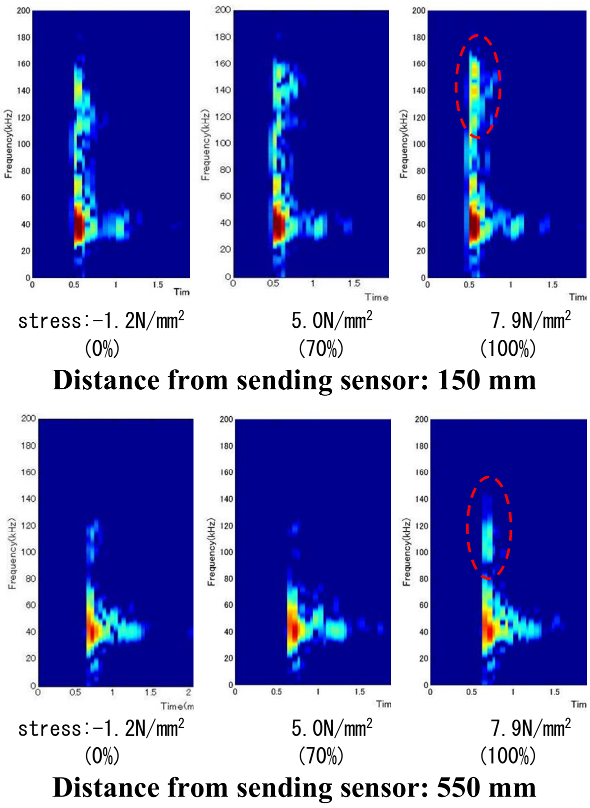


Fig. 7. Result of short-time frequency analysis

tendency was more noticeable as the distance from the sending sensor became larger. Based on this, the possibility of detecting the difference of concrete stress conditions by this analytical method was indicated.

5. Real PC girder experiment

5.1 Overview

Since the correlation between concrete stress and propagation velocity was observed in the element experiment and the model girder experiment, verification was conducted by the use of a real PC road bridge girder (Photo. 6). The PC girder used for this measurement was a post-tension T-beam bridge (45 m of girder length, 43.8 m of span length, and 2.5 m of girder height). The PC steel layout of the cross section at the center of span and the design values of stress condition are shown in Fig. 8.

Photo. 6. Real PC road bridge girder

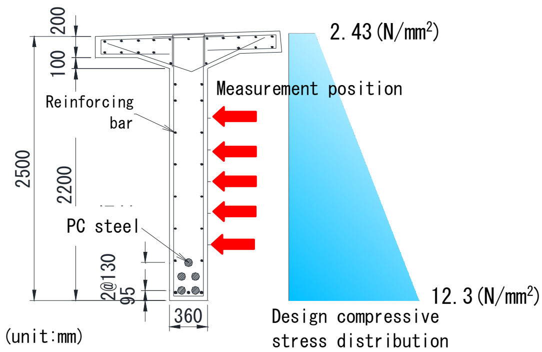


Fig. 8. PC steel layout and concrete stress

5.2 Content of experiment

(1) Penetration propagation characteristics of ultrasonic wave

In order to verify the influence of stress condition in the cross section on the ultrasonic wave propagation velocity penetrating in the web thickness direction, the time-of-arrival of the ultrasonic wave travelling from the one side of web to the other side was measured. In order to avoid the reinforcing bar installed and to cover the positions with varying concrete stresses, the grid of 150×300 mm within the range of the center of span area (measurement position "○" in Fig. 9) was selected as the measurement position. Additionally, after completion of testing, coring in the direction at right angle with the web was performed to

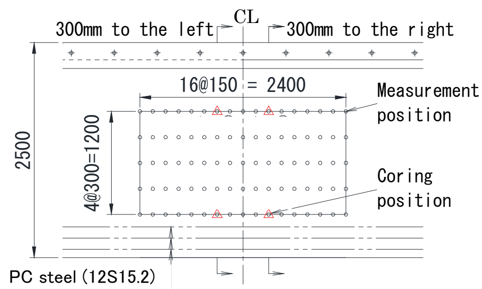


Fig. 9. PC steel layout and measurement position

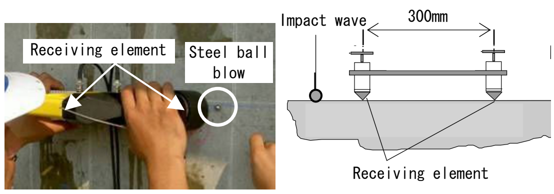


Fig. 10. Overview of impact elastic wave measurement

measure the penetration propagation velocity (measurement position "△" in Fig. 9).

(2) Impact elastic wave propagation property of concrete surface

It is considered that the penetrating ultrasonic wave may be affected by reinforcing bars and sheaths inside the concrete. Therefore, a study focusing the impact elastic wave propagation velocity in the region near the member surface was conducted. As for the impact elastic wave, its propagation velocity was measured based on arrival time difference of two points that receive the steel ball blow (φ9.6 mm) input at a regular distance (300 mm) (Fig. 10). The measurement was conducted for horizontal propagation velocity to evaluate the difference of the stress conditions, by varying the measurement line height in the direction of web height.

5.3 Result and discussion

(1) Penetration propagation characteristics of ultrasonic wave

The relationship of the design compressive stress and the propagation velocity measured is shown in Fig. 11 and Fig. 12. The tendency of varying penetration propagation velocities in the direction of girder height was observed, though there is variance in the result. Since it may also be influenced by the difference of concrete physical properties caused by installation operation (Amagasaki *et al.,* 1991), the penetration propagation velocity of the core specimen in the condition as it was collected was measured (Fig. 13). The result of measurement of core specimen penetration propagation velocity indicated that the

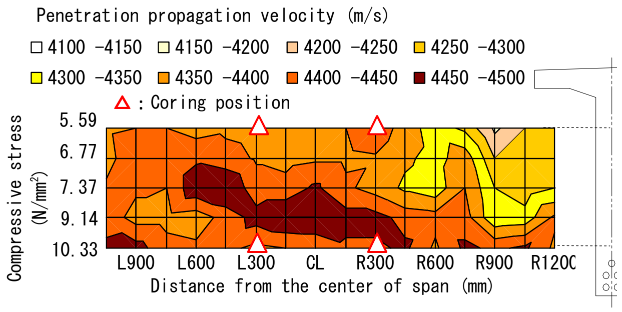


Fig. 11. Distribution chart of propagation velocity

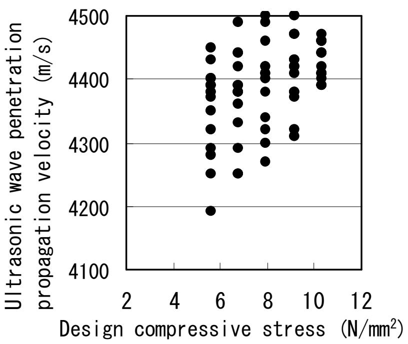


Fig. 12. Relationship of design compressive stress and penetration propagation velocity

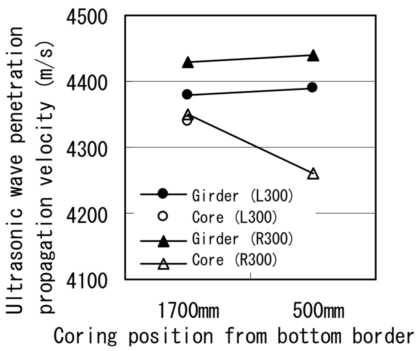


Fig. 13. Relationship of core specimen collected and penetration propagation velocity

propagation velocity of the core removed from the lower part of girder becomes smaller. Based on the above result, it is thought that evaluation can be performed by making a correlation between the concrete stress and the ultrasonic wave penetration propagation velocity despite a slight difference between them.

(2) Impact Elastic wave propagation property of concrete surface

The relationship of measurement result of the stress condition at the girder height position and the propagation velocity of elasticity impact wave is shown in Fig. 14. Correlation between the concrete stress and the propagation velocity was observed, and the tendency similar to the above-mentioned result of ultrasonic wave penetration propagation velocity was obtained. Additionally, the relationship of the penetration propagation velocities of the ultrasonic wave and the horizontal direction propagation velocities of impact elastic wave at the same measurement position is shown in Fig. 15. It is understood that the difference of propagation velocities between 2 points on concrete surface is larger than the velocity difference due to the difference of the stress conditions. Based on this result, it is thought that the concrete stress conditions may be evaluated by measuring propagation velocity of the wave propagating on concrete surface.

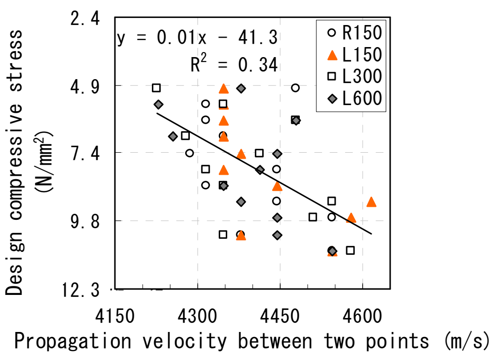


Fig. 14. Propagation velocity between two points

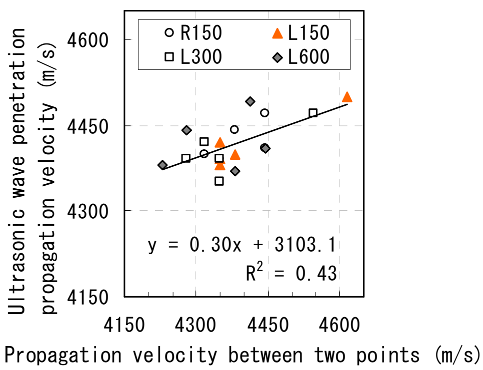


Fig. 15. Relationship of penetration propagation velocity and surface propagation velocity

6. Summary

An experiment was attempted to understand the amount of prestress by ultrasonic wave method and impact elastic wave method which are non-destructive inspection technique as a streamline evaluation method of the degree of soundness of a PC road bridge.

In the element experiment focusing on PC steel, reinforcing bar, and concrete that are components of a PC road bridge, it was confirmed that propagation characteristics varies depending on the amount of prestress in concrete while it is hard to gain an understanding of the amount of prestress in PC steel and reinforcing bar, indicating the possibility of detecting the difference of the stress conditions by analyzing the property of the propagating wave profile.

In the model girder experiment with varying amounts of prestress introduced and the experiment using a real PC road bridge girder, the result obtained from the element experiment was reproduced for changes in propagation characteristics due to the amount of prestress, and the possibility that propagation velocity and frequency distribution property could become indicators was shown. Additionally, the possibility that stress condition may be detected visually and more clearly was shown by the short-time frequency analysis focusing on propagation time and frequency component. Based on this, it is thought that the ultrasonic method and the impact elastic wave method can be selected as an approach to understand the amount of prestress in evaluating the degree of soundness of a PC road bridge.

Acknowledgment

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