Vibration Propagation Analysis of Road Pavement Using Thin Layer Method for Fiber Optic Distributed Acoustic Sensing

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ABSTRACT

Distributed Fiber Optic Sensing (DFOS) has gained widespread utilization as a tool for Structural Health Monitoring (SHM) in recent years. This technology enables the measurement of strain and temperature distributions along a fiber. Among the various DFOS measurement technology, this study focuses on the use of a Distributed Acoustic Sensing (DAS) system, which primarily measures longitudinal strain caused by vibrations. The utilization of DAS for vibration propagation analysis has not been widely practiced. Thus, to confirm the authenticity of the recorded values, we constructed a mockup consisting of multiple layers including a surface layer, base layer, upper layer roadbed, lower layer roadbed, and subgrade, with DFOS installed at multiple locations in each layer. We are trying to improve our modeling by comparing the analytical road model to the DAS measurement results. When pavement is subjected to vibration, caused by either people or vehicles passing by, it can be expected that the amplitude of the vibration will decrease as the depth increases. However, when we measured the vibrations using DAS, we observed that the amplitude of the surface layer and the subgrade was larger than that of the other layers. Therefore, we applied the thin layer method, which is widely used in the field of geotechnical engineering to investigate the factors that led to the increase in amplitude of the subgrade. In the thin layer method, the ground is considered a homogeneous continuum in the horizontal direction, while the depth direction is analyzed discretely in the plane of layer partition. This method has a smaller computational load than the finite element method. We performed sensitivity analysis by using shear wave velocity, Poisson's ratio, and density as input parameters. The sensitivity analysis revealed that changes in shear wave velocity strongly contributed to the amplitude. To validate the analytical values obtained from the thin layer method, we conducted the Falling Weight Deflectometer (FWD) test, which provided us with the actual physical properties of the road pavement, including the deflection of the surface layer under 5t excitation forces. We reflected these results into the thin layer method's parameters and compared the analytical values with the DAS measurement results of the exciter test. Through these procedures, we confirmed the suitability of the thin layer method as an analysis method for DAS.

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INTRODUCTION

In the maintenance of infrastructure, it is essential to measure dynamic values such as cyclic loads and vibrations to monitor the condition of civil structures to keep them in use over the long term. In recent years, optical fiber sensors have gained popularity as a means of structural monitoring. In civil engineering, these sensors are increasingly being used for construction management and maintenance of structures, including bridges, tunnels, and underground facilities [1]. Optical fiber sensors allow for distributed measurements of physical changes, such as strain and temperature. In this study, we focus on the Distributed Acoustic Sensing (DAS) system for measuring dynamic strain in a distributed manner [2]. The DAS system can measure very small dynamic strains of a few nε and offers numerous benefits for structural monitoring. For instance, when buried in the ground, the system can detect vibrations caused by not only vehicles but also people and animals, even when the excitation force is relatively small [3]. Although structural analyses often produce continuous results based on various theories, these results may not fully reflect real-world conditions. Therefore, it is necessary to verify the accuracy of analytical values by installing sensors on the test specimen or actual structure to measure the results. However, traditional point-type sensors are limited to discontinuous comparisons, which may not sufficiently ensure the reliability of the analyzed values. For instance, consider the comparison of analytical and measurement values aimed at vibration. One study used FEM analysis to calculate the vibration response of a model and then attached point-type sensors to a road bridge to measure static and dynamic strain to estimate vehicle weight and speed and determine if overloading or overspeeding was detected [4]. Replacing traditional sensors with DAS in such studies can enable continuous evaluation of analytical and measured values. This approach can improve modeling accuracy in terms of analysis and expand the detection range and objects to be measured, treating the paved road itself as a sensor. By developing this approach, it will be possible to estimate physical properties in an inverse analytical manner from the DAS and analytical model.

This paper is organized as follows. Section 2 shows the analytical method employed in this study. Section 3 describes the road pavement embedded with optical fibers that we employed in the research and procedure and outcomes of the Falling Weight Deflectometer (FWD) test conducted on the road pavement. We present the FWD test results to demonstrate the pavement's structural characteristics under a static load. Next, it describes the procedure and outcomes of applying vibration to the pavement using a shaker to evaluate its dynamic response. We compare the experimental data with the analytical values to assess their validity. Finally, Section 4 summarizes the findings of the study and draws conclusions based on our analysis.

ANALYTICAL METHOD

The thin layer method is a technique employed to analyze sinusoidal wave propagation in elastic grounds. This method divides the ground into horizontal semi-infinite thin layers and treats it as a homogeneous continuum in the horizontal direction while discretizing it in the depth direction at the plane of division. Generally, the solution of wave propagation in the elastic ground is expressed as an infinite integral concerning the wave number, which is computationally cumbersome. However, the thin layer method obtains this infinite integral analytically and provides the solution in closed-form. This is extremely beneficial in terms of computational efficiency. The thin layer method is commonly used in the field of architecture to study the dynamic interaction of embedded foundations and group piles. This study applied the thin layer method to pavement since it employs uniform materials for each layer, which is deemed compatible with the thin layer method. For a theoretical solution of the amplitude for vertical excitation, refer to Reference [5].

EXPERIMENTAL EVALUATION

To compare the vibration response in the pavement with the analytical values, an experimental pavement was constructed, and optical fibers used in the DAS measurement were installed in the pavement. The figure illustrates the overview of the pavement. The roadbed is comprised of a five-layer structure, including the subgrade, RC-40 for the lower layer roadbed, recycled asphalt as a cost-effective roadbed for the upper layer roadbed, and recycled asphalt mixture for the base and surface layers. Optical fibers were buried in trenches dug in the four layers from the subgrade to the base layer during construction. The optical fiber used for this purpose was Sumitomo Electric Industries' indoor cable with a 0.25 mm strand type.

Figure 1. Road pavement overview: (a) View of construction, (b) Installation of optical fiber, (c) At the time of completion of construction

FWD Test

The Falling Weight Deflectometer (FWD) test is a nondestructive device that measures the deflection of a pavement surface when subjected to a weight dropped at various points. This test is cost-effective and allows physical properties to be determined during the experiment without damaging the pavement. The test conditions for FWD are shown below.

TABLE I. Test conditions

Exciting Force [tf]	Measurement Point [cm] (Deflection Sensor)
5	0, 20, 30, 45, 60, 75, 90, 120, 150, 200, -30

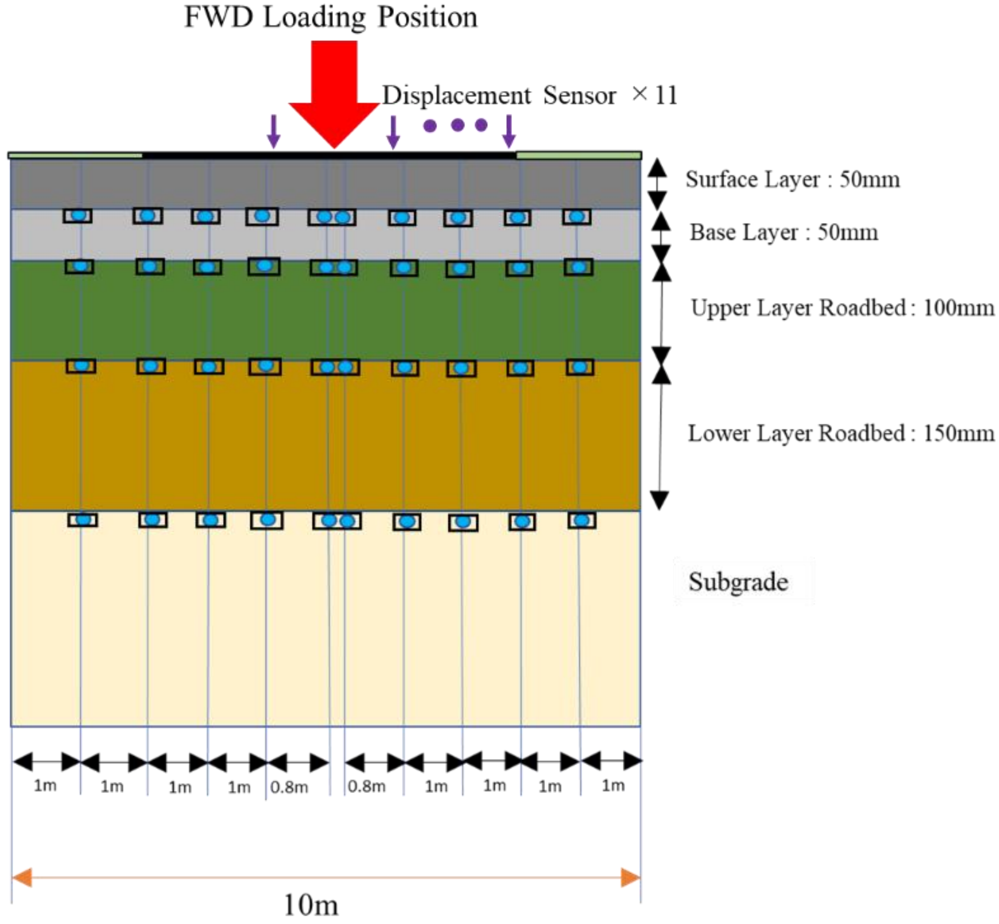

Figure 2. Cross section of road pavement

Results

The physical properties of each layer obtained in this test were incorporated into the analysis, and the maximum vertical amplitude of the surface layer was compared with the deflection amount to evaluate the validity of the analytical values on a point-by-point basis. The physical property values and deflection values obtained from the FWD test are presented below. Since density values alone cannot be obtained from the test, density values obtained from previous borehole tests were used for the subgrade, and values from reference [6] were used for other layers. The vertical axis represents the amplitude, and the horizontal axis represents the position of the deflection gauge when the excitation point is set to 0 m. Although there is some difference near the excitation point, there is almost no discrepancy between the analytical and deflection gauge values beyond 1 m. This finding indicates that the analytical results of the thin layer method for vertical excitation and vertical direction are valid.

TABLE II. The result of physical property

Component		Surface Layer	Base Layer	Upper Layer Roadbed	Lower Layer Roadbed	Subgrade
Material		Recycled Asphalt Mixture	Recycled Asphalt Mixture	Recycled Asphalt Roadbed	RC-40	Loam
Elastic Modulus	[MPa]	2000	2000	1200	360	195
Thickness	[m]	0.05	0.05	0.10	0.15	80.0
Poisson Ratio	[-]	0.35	0.35	0.35	0.35	0.40
Density	[t/m3]	2.35	2.35	2.35	2.35	1.40
Shear Wave Velocity	[m/s]	544	544	421	231	223

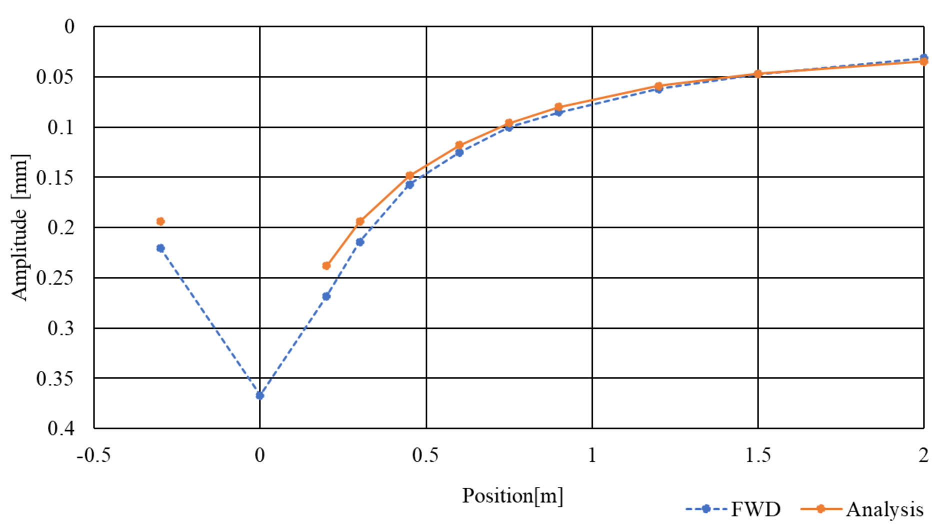

Figure 3. Comparison of analyzed and measured values

Excitation Test

To assess the reliability of the analysis and the DAS, it was necessary to evaluate the pavement response in the horizontal direction, in addition to the vertical direction, which was the only direction evaluated by the FWD test. To this end, we employed a shaker (Air Brown, Model 400) and an accelerometer (RION, PV-83C) to measure the vibration response of the pavement in both vertical and horizontal directions during vertical excitation. Simultaneously, DAS (NB, SR-S4000B) measurements were also taken. A summary of the test is presented below.

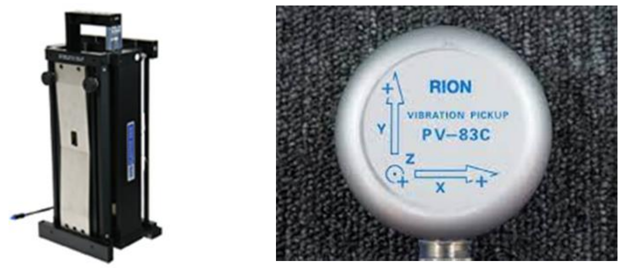

Figure 4. Equipments (left: Shaker, right: Accelerometer)

TABLE III. Measurement conditions

Measurement Range [m]	Spatial Resolution [m]	Sampling Frequency [Hz]
4000	2.8	500

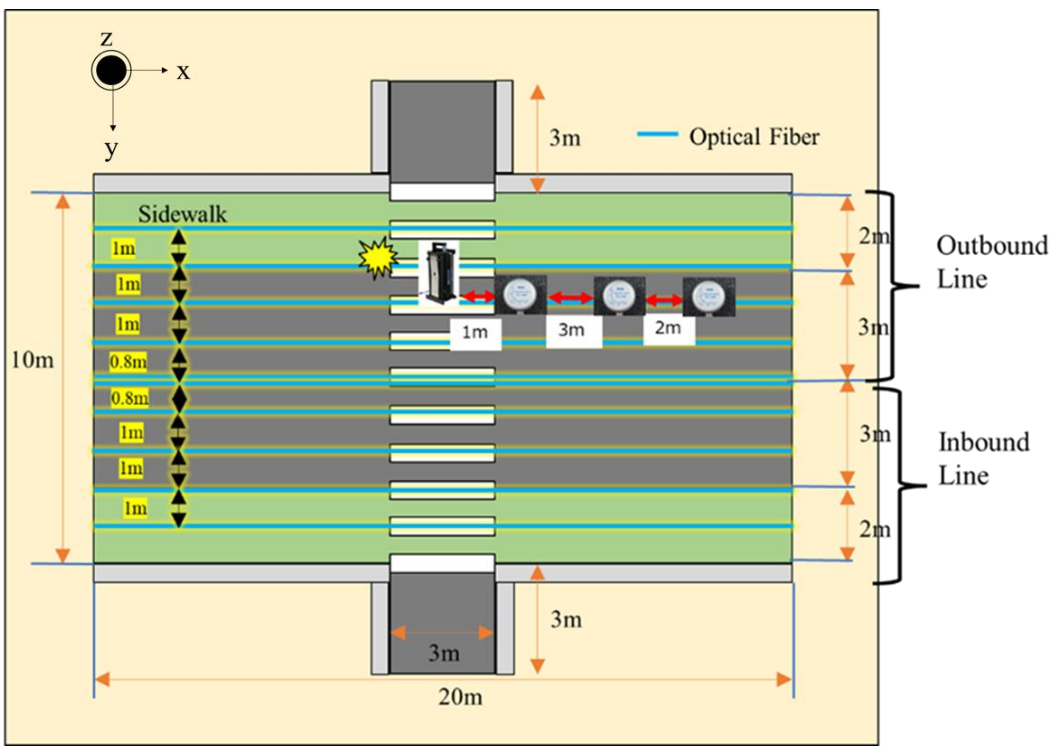

Figure 5. The location of the equipments

Comparison of Analysis Values and Accelerometer Values

The amplitudes of the surface layer at each frequency, obtained by the analysis and the shaker, are presented below. The vertical axis shows the amplitude, while the horizontal axis indicates the frequency of excitation. Large deviations between the analyzed and measured values were observed in the low-frequency range below 7-8 Hz, in all directions. This is thought to be because the exciting force could not be output sufficiently at low frequencies, especially below 5 Hz, and also due to the vibration caused by a vehicle running that could not be eliminated around the test site. However, good agreement between the values was observed in the frequency band over 10 Hz, particularly in the Z direction.

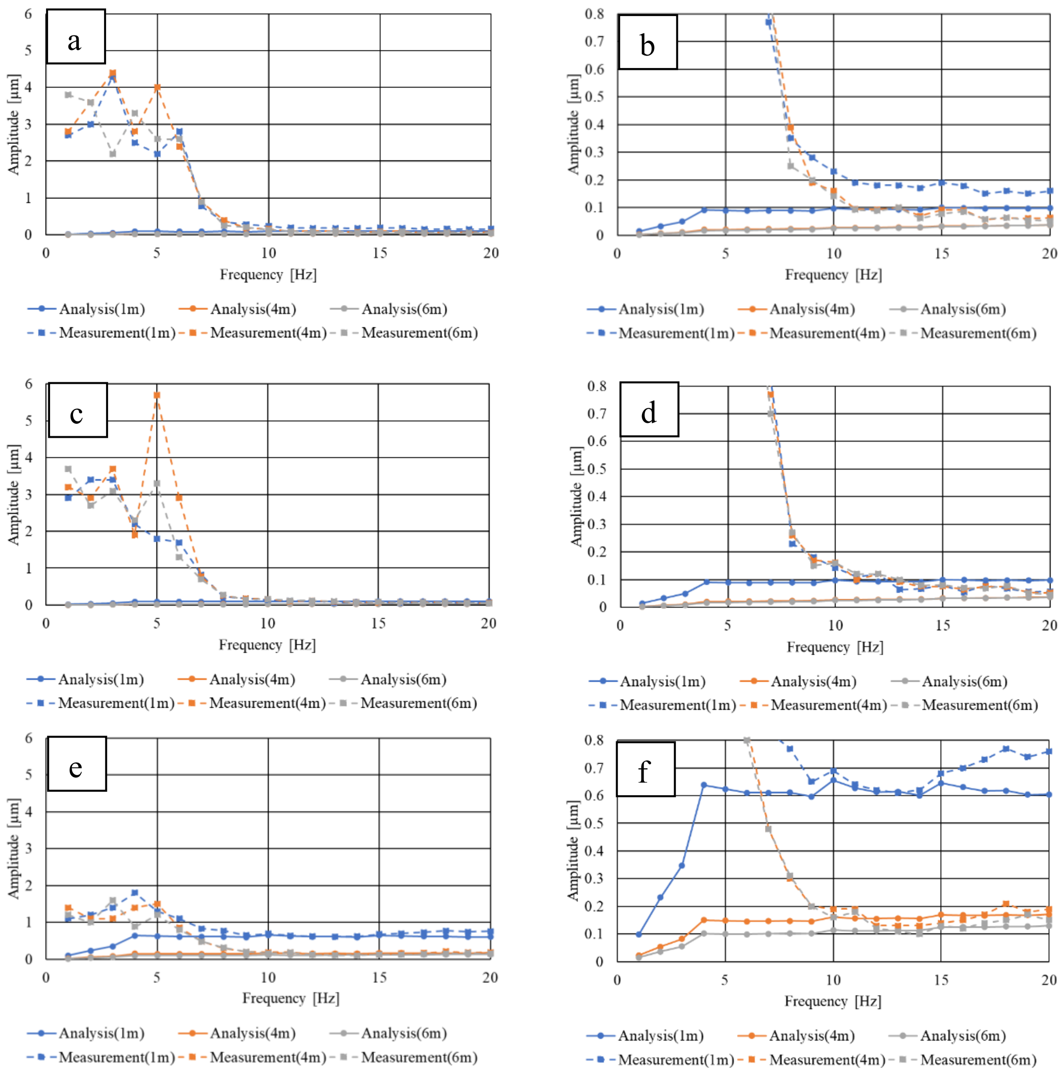

Figure 6. Comparison of analyzed and measured values: (a) x-direction, (b) enlarged view in the x-direction, (c) y-direction, (d) enlarged view in the y-direction, (e) z-direction, (f) enlarged view in the z-direction

Comparison of Analysis Values and DAS Values

The maximum amplitude in the x-direction of each layer obtained from the analysis and the maximum amplitude obtained from DAS are presented below. The vertical axis represents the amplitude, and the horizontal axis denotes the frequency. While it is expected that the amplitude attenuates as the distance from the excitation source increases, the findings reveal that the subgrade, which is the lowest layer, has a larger amplitude than the upper layer and lower layer roadbeds.

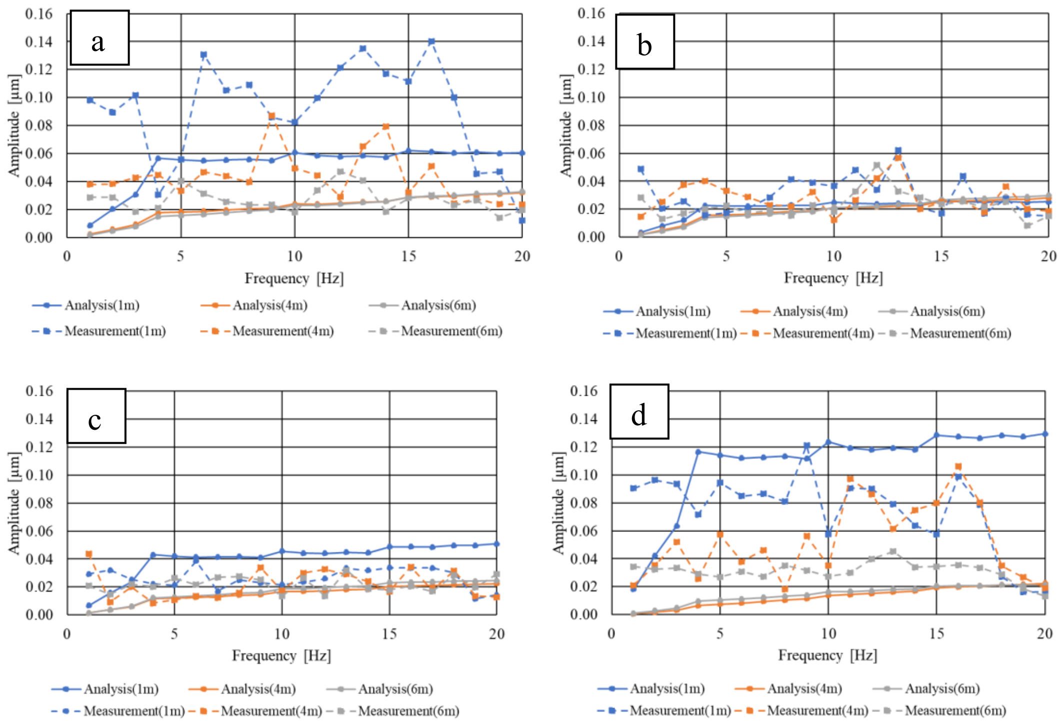

Figure 7. Comparison of analyzed and measured values: (a) base layer, (b) upper layer roadbed, (c) lower layer roadbed, (d) subgrade

CONCLUSIONS

Optical fibers were utilized to comprehend the pavement structure and were compared with analytical values derived using the thin layer method. While the analytical values corresponded well with the Z-direction of the deflection gauges and accelerometers, they did not align well with the horizontal measurements of the accelerometers and the DAS trend. However, a qualitative assessment could be made, indicating that the subgrade produced larger measurements than the other layers. In the future, we plan to enhance the accuracy of structural assessment by combining optical fiber and analysis, considering methods for quantitatively assessing amplitude and strain amplitude, eliminating noise in the low-frequency range, and addressing the directivity of the sensor.

REFERENCES

1. Cedric Kechavarzi, Kenichi Soga, Nicholas de Battista, Loizos Pelecanos, Mohammed Elshafie, and Robert Mair. 2016. *Distributed Fibre Optic Strain Sensing for Monitoring Civil Infrastructure*. Institution of Civil Engineers, pp. 133-240.
2. Ying Shang, Maocheng Sun, Chen Wang, Jian Yang, Yuankai Du, Jichao Yi, Wenan Zhao, Yingying Wang, Yanjie Zhao, and Jiasheng Ni. "Research Progress in Distributed Acoustic Sensing Techniques," *Sensors 2022*, 22, 60.
3. Peter G. Hubbard, Ruonan Ou, Tianchen Xu, Linqing Luo, Hayato Nonaka, Martin Karrenbach, and Kenichi Soga. 2022. "Road Deformation Monitoring and Event Detection Using Asphalt-embedded Distributed Acoustic Sensing (DAS)," *Structural Control Health Monitoring., vol. 29*.
4. Kengo Suzuki, Osamu Maruyama, Hidehiko Sekiya, Takuyo Konishi, and Chitoshi Miki. 2016. "Basic Consideration of Weigh-In-Motion using Control Theory," Proceedings of JSCE A2, Vol.72, No.2, pp. I_45-I_51.
5. Architectural Institute of Japan. 1996. *An Introduction to Dynamic Soil-Structure Interaction*. pp.161-172.
6. Kanagawa Prefectural Government. 2017. Standard Cost Estimating Standards for Civil Engineering Works (Civil Engineering Works) [II] pp.IV-1-①-8