

# Elastic Wave Measurement System Using FWD for Asphalt Pavement

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**ABSTRACT:** This paper describes stiffness estimation methods for the base layer of asphalt pavement using quasi-static back-calculation, dynamic back-calculation and transit elastic wave measurement system. These techniques are based on FWD devices: FWD (50kN load capacity), a portable type of FWD (15 kN load capacity) and a new type of portable of FWD (25 kN load capacity). The surface acceleration is measured by outer accelerometer of FWD devices. The system consists of a portable PC, a sampling A/D card, an acceleration system, FWD or a portable FWD and MATLAB-based software. It revealed that the stiffness of base layer was less influenced by dynamic back-calculation or transit elastic wave measurement system. It was confirmed that the transit elastic wave measurement can be used to evaluate the stiffness characterizing the mechanical response of the pavement at each tested site.

**KEY WORDS:** *FWD, stiffness, back-calculation, elastic wave, base layer.*

## 1 INTRODUCTION

Unbound granular aggregate is one of the most popular materials used in both base and subbase layers of pavements. They should have adequate stiffness, strength and resistance against damages caused by traffic load. This paper concerns the stiffness evaluation on the base layer of unbound granular aggregates in asphalt pavements.

Recent developments of in-situ testing devices have made it possible to estimate the layer stiffness modulus of pavement from a direct measurement during construction. The Falling weight deflectometer (FWD) testing is performed at each site to characterize the mechanical response of the pavement. Light versions of FWD (hereafter it is called as a portable FWD or pFWD) have zero, 1 or 2 outer and movable accelerometers. It was developed to measure the stiffness of road base and underlying layer during the construction of flexible pavement. It is very helpful to collect field data in terms of layer stiffness during the road building. However, the deflections in the base layer constituted by unbound granular aggregates are affected and varied with number of drops impacted by FWD or pFWD. These are related to the rate of compaction. Seating factor was introduced to characterize the degree of compaction (Gurp, 2000). Since the base layer is compacted by impact loading with FWD or pFWD, its stiffness might differ from the original one. It is desirable to evaluate stiffness of the remainings apart from the loading point. Here, we focused on estimating stiffness modulus using the elastic-wave method during construction. Based on this method, the strain level in the stiffness

measurements is so small that the original stiffness is slightly influenced. Such a method is progressing in seismology and geology.

With a falling weight and outer accelerometers of pFWD, the short-term goal of this study is to develop an elastic wave method to estimate the stiffness of base layer, which is compared with a finite element method. And the long-term objective is to develop an applicable system to directly predict the original stiffness of base layer in asphalt pavements.

## 2 CONDITION OF TEST FIELD

As a first step in this study, a base layer was selected as typical base materials used for heavy traffic in Japan, as shown in Figure 1. The cross section is of 55cm crushed stone. The base layer was compacted in 15cm lifts. The soil properties of tested field are given in Table 1.



Figure 1: Test field.( Root 230, A national road between Sapporo and Asahikawa)

Table 1: Soil properties of tested field

Layer	Material	Water Content	Mass Density (kg/m <sup>3</sup> )
Base	Limestone (0-40mm)	9.0%	2010
Subgrade	Silty Clay	23.2%	1800

## 3 ELASTIC STIFFNESS EVALUATION USING QUASI-STATIC BACK-CALCULATION

The FWD is well known as a pavement evaluation device. It applies an impulsive force on a pavement surface through a 30cm steel bearing plate in diameter, and measures surface deflections at several locations including a point of loading. The duration of loading pulse is of 25 msec. Surface deflections can be recorded automatically with eight (20, 30, 45, 60, 75, 90, 150, 200 cm) spaced velocity transducers.

Two pFWD devices, as shown in Figure 2, comprise a mass that is raised and dropped onto a 10 to 30cm steel bearing plate in diameter by manual control, which depends on the material type under testing. The large type in left shown in Figure 2 has a maximum falling mass 30kg, a maximum loading 24 to 35kN, and a maximum falling height 1m. On the other hand, the standard type in right shown in Figure 2 has a maximum falling mass 20kg, a maximum loading 10 to 15kN, and a maximum falling height 0.6m. The duration of loading pulse is of 50 msec. Surface deflections can be recorded automatically with six (20, 40, 60, 80, 100, 120) spaced movable accelerometers. The applied loads and surface deflections can be used to

back-calculate individual layer stiffness. Currently, there are several available back-calculation procedures. The elastic stiffness of base layer in this test field is estimated using LMBS that is one of the quasi-static back-calculation programs available in Japan from a web site (JSCE, 1998), and based on a linear multi-layered elastic theory.



Figure 2: Portable FWDs.

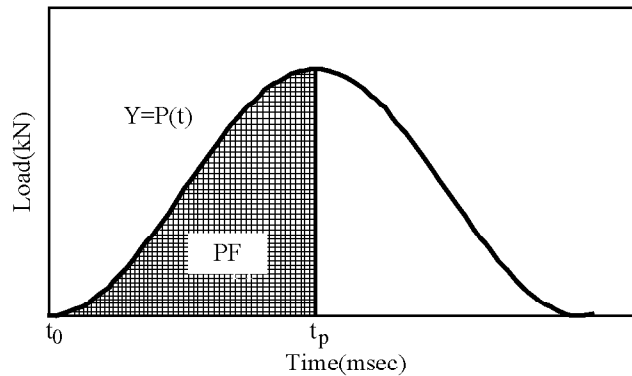


Figure 3: Defination of Power Factor of loading.

In this study, using the applied loads and surface deflections measured by FWD and two pFWD devices, the elastic stiffness of the base layer was estimated by LMBS computer program.

The area under loading history curve  $P(t)$  from  $t_0$  to  $t_p$  is defined as Power Factor of loading ( $PF$ ) shown in Figure 3. The expression is defined as follows:

$$Area = PF = \int_{t_0}^{t_p} P(t)dt \quad (1)$$

This factor relates to the falling weight mass and the velocity just before the mass contacts the loading plate. Figure 4 shows the relationship between the elastic stiffness and Power Factor for the base layer. The following equation is fitted from Figure 4.

$$E_s = 1.33X + 42.0 \quad (R^2 = 0.93) \quad (2)$$

where  $E_s$  is the elastic stiffness of base layer in MPa, and  $X$  is Power Factor of loading in Nsec. This stiffness is estimated using a backcalculation method ( Himeno, 1990).

This expression means that the elastic stiffness of base layer  $E_s$  could be estimated by FWD device through introducing Power Factor of loading.

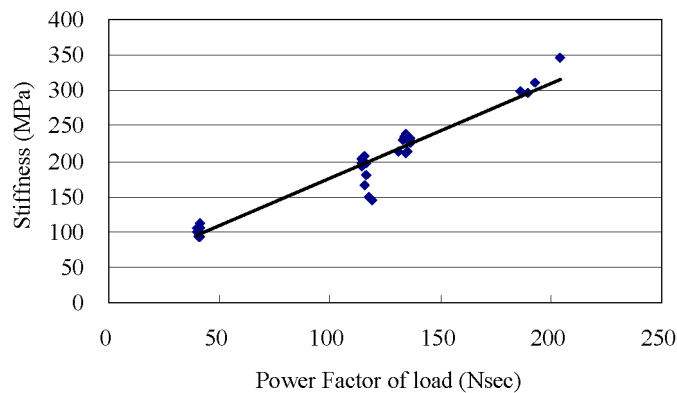


Figure 4: Relationship between stiffness and Power Factor of loading.

#### 4 FAST FOURIER TRANSFORM (FFT) ANALYSIS

The FWD applies an impulsive force to the base layer that generates elastic wave traveling at finite velocities, and it is recorded in time series by the outer sensors. To analyze the loading and deflection history generated by FWD or pFWD devices in the frequency domain is very useful. Figure 5 shows the results of FFT analysis for the elastic waves generated by the FWD and the pFWD. In this Figure, s.pFWD means the standard type of pFWD, and L.pFWD means a large type of pFWD. Fre Ratio is, here, defined as the ratio of the power spectrum of each frequency to the maximum power spectrum for FWD or pFWD devices. As can be seen from Figure 5, the main peaks of FWD devices were classified in the range under 50Hz. The results of dynamic loading measurements by a standard type and a large type of pFWD devices are very much similar to those conducted by FWD.

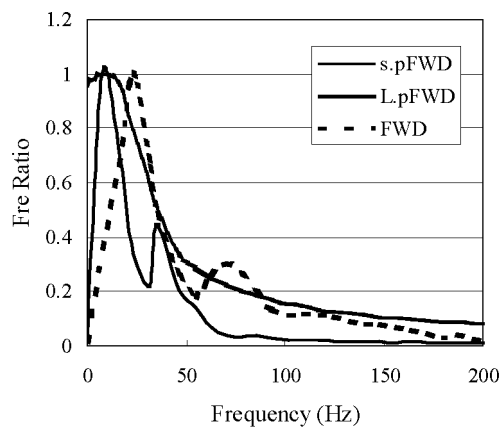


Figure 5: The relationship between Fre Ratio and frequency.

#### 5 ELASTIC WAVE TESTS

Various methods based on the point to source or point to near receiver technique that utilizes transient elastic wave response have been proposed in the field of nondestructive evaluation

of pavements and soil. In this study, a standard type of pFWD was used to generate the transient elastic wave accelerations in the base layer. The vertical velocity in the transient elastic wave is estimated by the wave transit time ( $t_L$ ) and distance ( $L$ ) between the first and second receivers. In this study, accelerations picked up by outer receivers were used to examine the transient elastic wave.

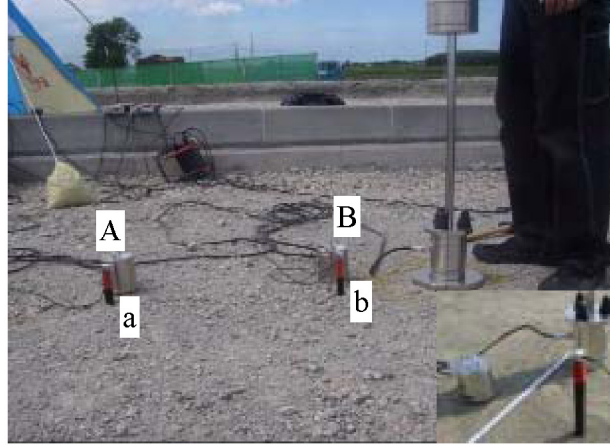


Figure 6: Outer receivers (A and B) and Sticks (a and b).

In an homogeneous isotropic half space with mass density  $\rho$ , and Poisson's ratio  $\nu$ , the corresponding longitudinal wave velocity  $V_s$  is defined with the elastic modulus  $E$  or shear modulus  $G$  of base layer as follows.

$$V_s = \frac{L}{t_L} \quad (3)$$

$$G = \rho V_s^2 \quad (4)$$

$$E = 2(1+\nu)G \quad (5)$$

The outer accelerometers (A and B) of pFWD and the receivers (a and b) with acceleration sensors at the tip of sticks are shown in Figure 6. The specification of the acceleration sensor is as follows: The capacity is 1000m/sec<sup>2</sup> acquisition of temperature compensated digital acceleration data of 0.2 Hz -700 Hz. At an interval of 20cm, the distance between the receivers B and A changes from 30cm to 110cm. The acceleration receivers at the tip of sticks were embedded into the base layer at a depth of 20cm. The distance between the sticks b and a changes from 30cm to 110cm at an interval of 20cm. Here, the time difference means transiting time from the receiver A to B or from the receiver a and b. The outer receiver (A or B) was used to record the surface deflections on the base layer. And the acceleration sensors at the tip of sticks (a or b) were used to measure the accelerations.

Figure 7 shows the results of FFT analysis for receiver A. It could be said that the peaks were classified in the range under100Hz, and the others were from 100Hz to 200Hz.

Although the distance from the source to the receiver A and B varies, the peaks of power spectrum shown in Figure 7 appear at the same frequencies. Comparing Figure 8 with 7, it is noted that the peaks are observed in almost the same frequencies. It could be said that the elastic wave spread horizontally and vertically with the same power spectrum-frequency conditions.

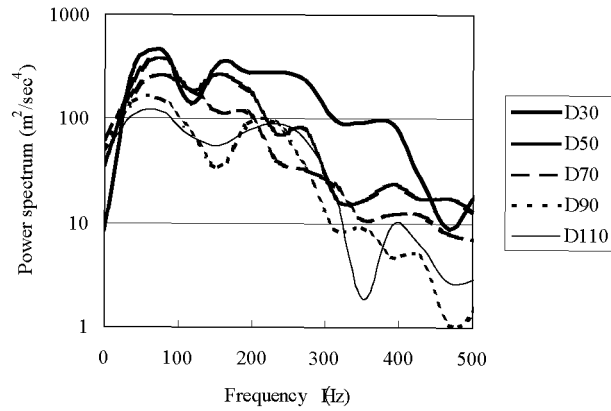


Figure 7: FFT analysis-The receiver A of pFWD.

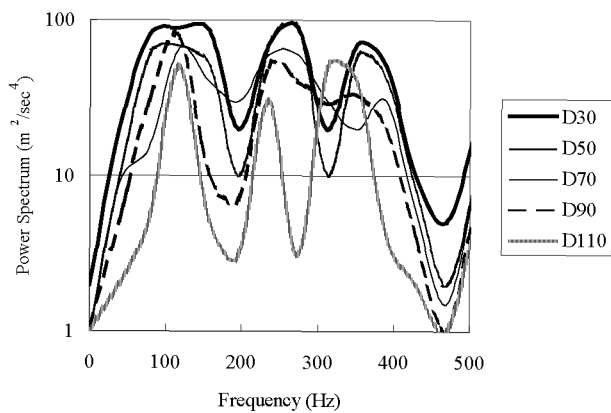


Figure 8: FFT analysis –The receiver a with acceleration sensor.

## 6 DYNAMIC ANALYSIS IN FINITE ELEMENT METHOD

The dynamic finite element (FE) analysis was applied to predict the spread of elastic wave in the base layer from pFWD impact loading. The method can be used to calculate the response of the multi-layered elastic systems with non-proportional damping using Ritz vectors (Dong, 2003). For dynamic analysis of full time history, a computer program developed was used to predict the surface deflection on the base layer.

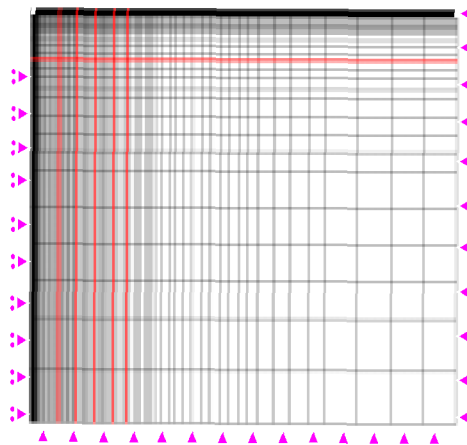


Figure 9: FEM mesh and boundary conditions.

The finite elements mesh consists of 2333 nodes, 738 elements with 8-nodes axisymmetric element, as shown in Figure 9. Total horizontal length is 6m and vertical depth is 6m. The dynamic FE analysis using the load history of pFWD was carried out to obtain the surface deflections.

It is particularly interesting to see how well the calculated deflection on the surface of the base layer fits the measured deflection. Two different pulse shapes are plotted, as shown in Figure 10. One is a deflection curve from dynamic FE analysis using only the loading history of pFWD. The other is a deflection data measured by a sensor of pFWD at an interval of 30cm.

It could be said that calculated curve fairly fits the measured one from the beginning to the peak of the curve.

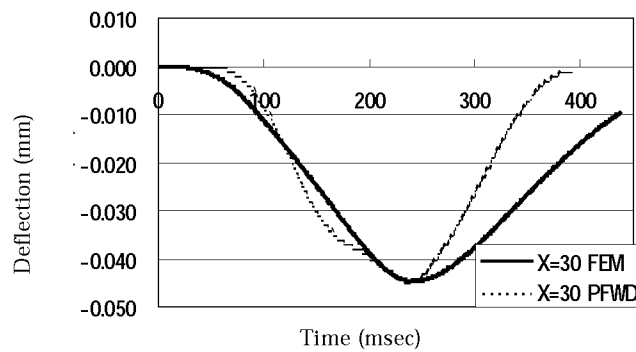


Figure 10: Comparison of measured and predicted deflection.

Figure 11 depicts the results of FFT analysis for the acceleration from dynamic FE analysis. It could be said that the peaks were classified in the range under 100Hz, and the others were from 100Hz to 200Hz. The similar trends can be found in Figure 7 or Figure 8. This fact indicates that the dynamic FE analysis is fairly satisfactory with the deflection history of field tests using FWDs.

Figure 12 illustrates comparisons between the predicted and measured velocities at a depth of 20cm in the base layer. It can be seen that the predicted velocity histories by dynamic FE analysis gave almost same values to those measured in the tested field.

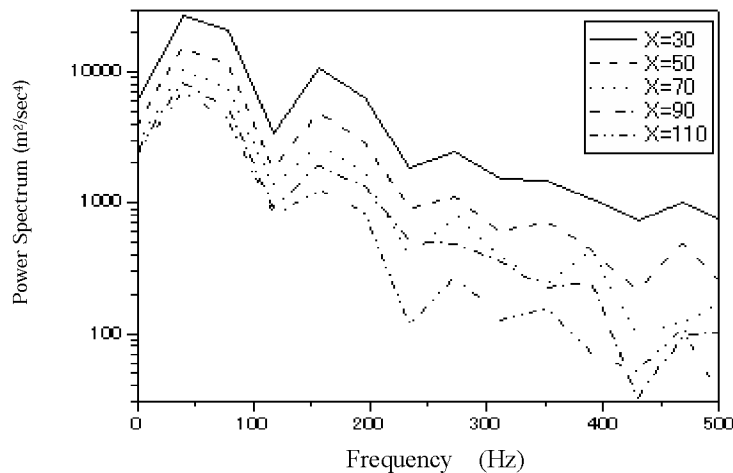


Figure 11: FFT analysis for predicted acceleration.

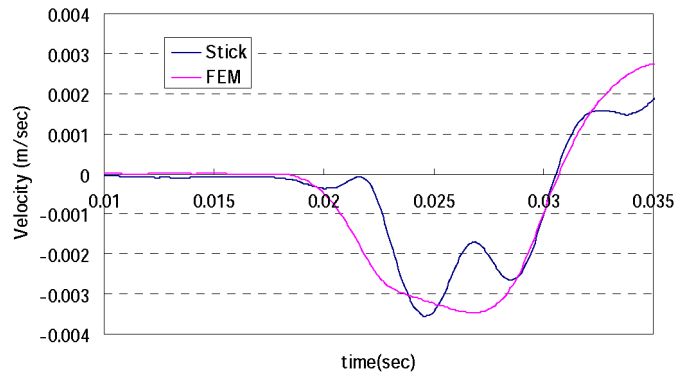


Figure 12: Comparison of predicted and measured velocity histories on stick at the depth of 20cm.

## 7 STIFFNESS EVALUATIONS

The results obtained from the three methods for evaluating stiffness were shown in Figure 13. In the figure, 30-50 means the distance from the center of first to second receiver of pFWD or sticks. The remaining has the same meanings.

- Using the elastic wave measurement on the surface, the values of stiffness in the base layer were calculated with formula (3), (4) and (5) by varying the distance from 30cm to 110cm for two receivers of pFWD.
- Using the elastic wave measurement at a depth of 20cm, the values of stiffness were calculated by the same formula used in (a) for the sticks with acceleration sensors.
- Using the deflections measured by pFWD, the values of stiffness were evaluated with help of dynamic FEM back-calculation.

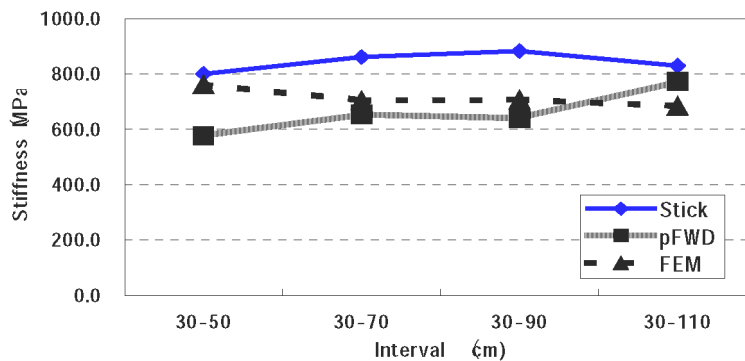


Figure 13: Comparison of stiffness values estimated with measured data (stick and pFWD) and predicted with FEM.

It is quite interesting to compare the stiffness shown in Figure 13 with Figure 4. The values of stiffness shown in Figure 4 were evaluated using quasi-static back-calculation program, and they are consistently lower than all values shown in Figure 13. The ratio is of 1 to 7 or 8.

Figure 14 shows the relationship between the stiffness (Elastic modulus) and strain from the results of FWD, HFWD (that is one kind of the pFWD devices) and tri-axial compression tests (Kamiura, 2000). In this Figure, S.G means the sandy gravel, and V.C.S means volcanic cohesive soil. The material of base layer used in this study belongs to the category of S.G.



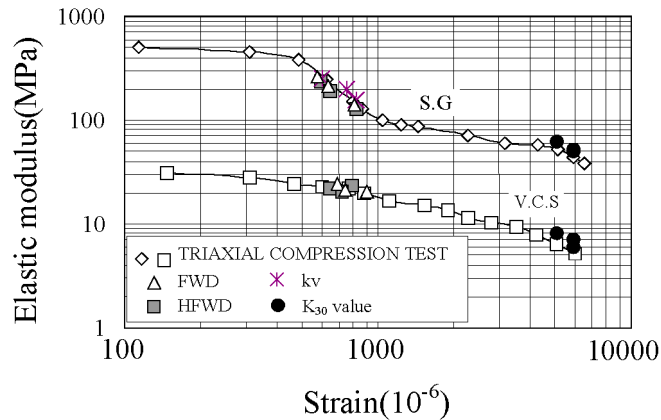


Figure 14: The relationship between strain and elastic modulus (Kamiura, 2000).

In a common sense, the strain generated in the elastic wave tests is nearly  $10^{-4}$  to  $10^{-5}$  (Richart, 1970). The value of elastic modulus shown in Figure 14 is nearly 500MPa corresponding to the strain level in the elastic wave tests. And it is nearly 80-90MPa corresponding to the strain level in the pFWD tests. Considering the ratio of (pFWD) to (elastics wave test) in the stiffness to be nearly 1 to 6 in Figure 14, it could be said that the values of stiffness in Figure 13 is acceptable.

## 8 CONCLUSION

This paper describes the stiffness estimation methods for the base layer of asphalt pavements using quasi-static back-calculation, dynamic back-calculation and transit elastic wave measurement system. A FWD device and two types of pFWD were used to estimate the stiffness of base layer of asphalt pavement.

The conclusions are as follows:

- The elastic stiffness of base layer could be estimated by one of FWD ( FWD or pFWD device) through introducing Power Factor of loading.
- In FFT analysis, the frequency of peak value in a standard type and a large type of pFWD devices are very much similar to those conducted by FWD.
- It is observed that the elastic wave spreads horizontally and vertically with the power spectrum-frequency conditions.
- It is confirmed that the values of stiffness in elastic wave tests and dynamic back-calculation analysis are acceptable corresponding to the strain level.

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