Applicability of Static and Dynamic Analytical Methods to Structural Evaluation of Flexible Pavements Using FWD Data

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ABSTRACT: We have two methods to evaluate pavement structures by back-calculation based on linear elastic theory using Falling Weight Deflectometer (FWD) data. One is the multi-layer elastic method (static method), in which the peak load and peak surface deflections at sensors extracted from time-historical FWD data are utilized. The other is the dynamic FEM (dynamic method) directly using the time-historical FWD data for analysis. In this study, back-calculations of layer elastic moduli for the structural evaluation were conducted by static and dynamic methods on FWD data at a flexible pavement, which Transportation Research Board (TRB) has uploaded on the website. At the same time, Dynamic Cone Penetorometer (DCP) and Multi-Depth Deflectometer (MDD) were also performed besides FWD test. The modulus of base layer back-calculated by static and dynamic methods is in good agreement with those estimated by DCP. The modulus of subgrade back-calculated by static method was slightly less than that back-calculated by dynamic method or estimated by DCP. On the other hand, the internal displacements calculated by both static and dynamic methods with back-calculated layer modulus were consistent with the measured results by MDD. Therefore, it was demonstrated that both static and dynamic methods would be applicable to predict the pavement response (displacements) in adequate accuracy.

KEY WORDS: FWD, FEM, multi-layer elastic theory, bearing capacity, displacement

1 INTRODUCTION

In the world wide, pavement management system (PMS) is necessary to be implemented in order to keep the condition of pavements well within the budget. FWD is considered as a standard tool to evaluate the bearing capacity of pavements by back-calculated layer elastic moduli. There are two methods to back-calculate the elastic moduli from FWD data; a) static method: the peak values of load and deflections extracted from the time-historical data would be used in the analysis, and b) dynamic method: the time-historical data of load and deflections would be directly utilized for back-calculation (Chatti et al. 2003).

In this paper, FWD data that are uploaded on the website by TRB, are analyzed by both static method based on multi-layered elastic theory and dynamic method based on FEM. On the web site, DCP and MDD data are also uploaded together with FWD data. The elastic modulus estimated by DCP and internal displacements measured by MDD were adopted as the standards to confirm the validity of back-calculation procedures.

2 DATA FOR ANALYSIS

In this study, FWD data collected on State Highway 281 in Texas, USA (Site 3) were applied to investigate applicability of static and dynamic methods to structural evaluation of flexible pavements (TRB committee A2B05). The cross section of pavement in the site is shown in Figure 1(a). FWD test were conducted at four load levels (27, 38, 52, 67 kN) and three drops were carried out for per load level, using DynaTest FWD with a loading plate of a 300 mm in diameter. The six sensors used to measure pavement surface deflections were equipped at distances of 0, 305, 610, 915, 1220, and 1525 mm from the center of loading plate. The temperature in the mid-depth of asphalt layer was of 28 °C during FWD test. A typical time-historical data for the load level 27 kN is shown in Figure 1(b).

As mentioned previously, tests including MDD (Beer et al. 1989) and DCP were also conducted besides FWD test. To recorded the internal vertical displacements induced by FWD, MDD was installed at a distance of 220 mm horizontally from the center of loading plate, and at three depths of 95, 314, and 594 mm beneath the pavement surface, as shown in Figure 1(a). In DCP test, the relationship between the drop times of hammer and the penetration depth was registered from the base layer surface to the depth of 700 mm, after coring asphalt layer near the FWD loading position.

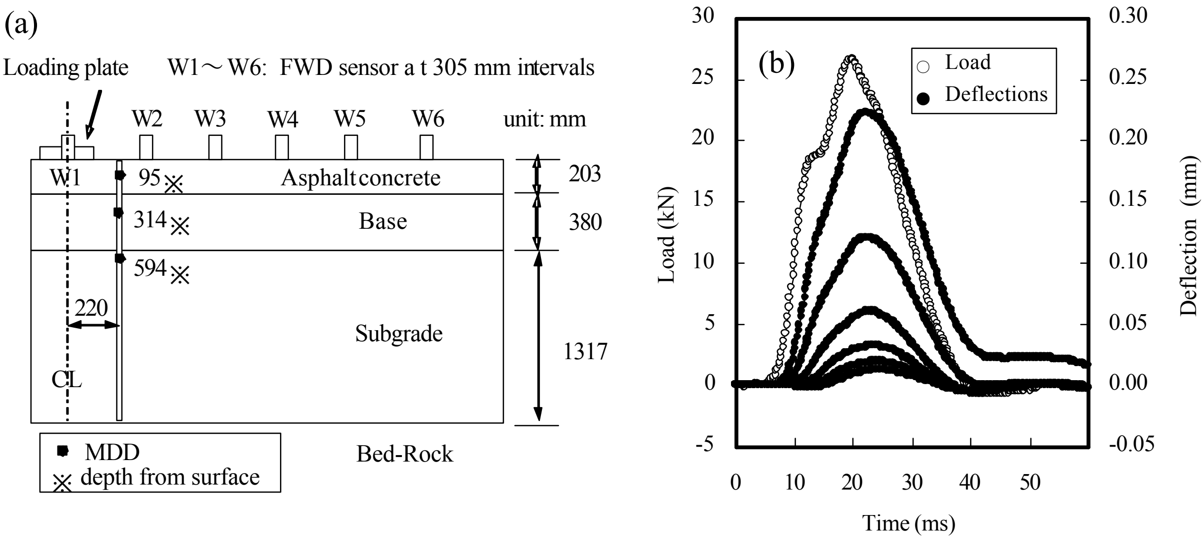

Figure 1: Data for Analysis; (a) cross section of pavement in the site for data collection, (b) typical time-historical FWD data.

3 ANALYTICAL METHODS

Back-calculations of elastic moduli by static and dynamic methods were performed using the extracted peak data and time-historical data from FWD test, respectively. The elastic moduli of base and subgrade were also estimated from DCP tests. In this section, both static and dynamic methods, as well as DCP to estimate elastic moduli of base and subgrade would be explained briefly.

3.1 Static method of back-calculation

The static method uses the peak load and peak deflections extracted from time-historical FWD data to back-calculate the elastic modulus of each layer with multi-layer elastic program, BALM99. Correspondingly, the program, GAMES (Maina and Matsui, 2002), is used for forward analysis. In BALM99, Gauss-Newton method is employed to get the increments of layer moduli in the procedure of back-calculation. The asphalt pavement consists of asphalt concrete (AC), base, subgrade, and bedrock layer. It was modeled as a 2D axisymmetric four-layer system. Initial values of elastic modulus, thickness and Poisson's ratio for each layer were given in Table1. The elastic modulus of bedrock was constant not to be back-calculated.

Table 1: Initial value of elastic modulus, thickness and Poisson's ratio for each layer.

Layer	Elastic modulus (MPa)	Thickness (mm)	Poisson's ratio
AC	6000	203	0.35
Base	300	380	0.35
Subgrade	100	1317	0.40
Bedrock	30000	—	0.25

3.2 Dynamic method of back-calculation

The dynamic method directly utilizes the time-historical FWD data to back-calculate the elastic modulus and damping coefficient of each layer with dynamic FEM program, DBALM (Kanai et al. 1996, Kanai et al. 2000). The pavement profile shown in Figure 1(a) was discretized into axisymmetric isoparametric elements with 8 nodes in each element. The analysis domain has dimensions of 5.0 m wide and 1.9 m deep without bedrock layer, as shown in Figure 2. The boundary conditions are defined as follows: two sides are restrained in x-direction, and the bottom is restrained in both x- and y-directions.

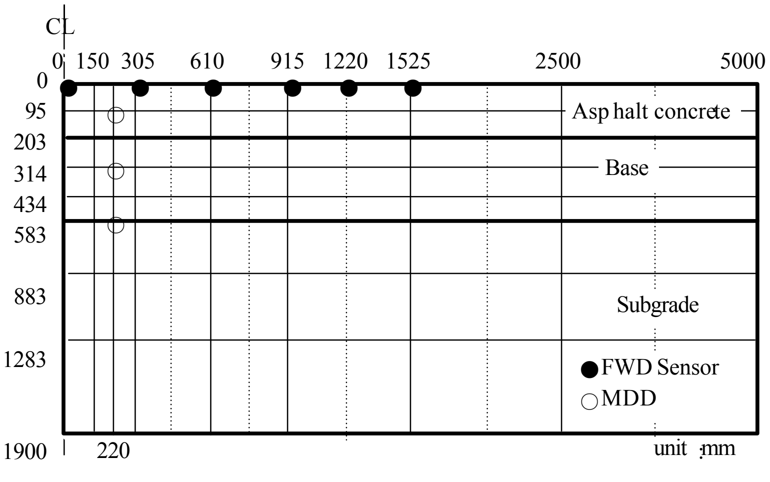

Figure 2: Axisymmetric dynamic FEM model.

In DBALM, a layer damping coefficient **c** is assumed to be proportionally to the layer elastic modulus *E*. When an impulsive force is exerted, the pavement response is calculated from the following equation of motion,

$$\mathbf{M}\frac{\partial^2 \mathbf{z}(t)}{\partial t^2} + \mathbf{C}\frac{\partial \mathbf{z}(t)}{\partial t} + \mathbf{K}\,\mathbf{z}(t) = \mathbf{f}(t) \tag{1}$$

in which **M**, **C** and **K** are mass, damping and stiffness matrices, respectively; $\partial^2\mathbf{z}(t)/\partial t^2$, $\partial\mathbf{z}(t)/\partial t$, $\mathbf{z}(t)$ are acceleration, velocity, and displacement vectors, respectively; $\mathbf{f}(t)$ is load vector.

Since Equation (1) is a large system of 2nd order differential equations, Ritz vector reduction method is introduced to improve computational efficiency. The Gauss-Newton method used in the static method was also adopted to get the increments of parameters in the procedure of back-calculation. A truncated singular value decomposition method is introduced to improve the solution stability in DBALM. The Table 2 shows the parameter values used in the dynamic backcalculation. Layer thickness and Poisson's ratio are same as static one excluding bedrock layer.

Table 2: Parameter values used for dynamic method.

Layer	Initial values		Mass Density (kg/m^3)
	Elastic modulus (MPa)	Damping coefficient (Ns/cm)	
AC	6000	3000	2300
Base	300	150	1900
Subgrade	100	50	1800

3.3 Estimation method of base and subgrade elastic moduli by DCP

The hammer that slides down the steel rod has a height of 575 mm and weight of 8 kg. The cone tip is made of steel with a angled of 30 degrees, and a head of 20 mm in diameter. It penetrates into base and subgrade, subsequently, and the total penetration depths are measured to get average depth per penetration (*DCPI*). Substituting *DCPI* and *CBR* into Equations (2) and (3), it is possible to estimate *CBR* (%) and elastic modulus *E* (MPa), respectively (Powell et al. 1984).

The back-calculated elastic moduli of base and subgrade were compared with those estimated by DCP in order to confirm the applicability of static and dynamic methods.

$$CBR = 292 / DCPI^{1.12} \tag{2}$$

$$E = 17.6 \times CBR^{0.64} \tag{3}$$

where $2 \leqq DCPI \leqq 324, 0.5 \leqq CBR \leqq 100$

4 RESULTS OF ANALYSES

In this section, the results estimated by static and dynamic methods are firstly presented. Secondly, the back-calculated elastic moduli of base and subgrade are compared with those estimated from DCP test. On the other hand, the vertical displacements at the positions of MDD were predicted by static and dynamic forward analysis with back-calculated elastic moduli. And the computed displacements were compared with MDD measurements in order to confirm the applicability of back-calculation procedures, which can be used to evaluate the bearing capacity of pavement.

4.1 Results of static analysis method

The back-calculated elastic moduli by static method are shown in Figure 3(a) for four load levels. From Figure 3(a), it is found that back-calculated elastic moduli slightly change as the load magnitude increases. This might be mainly caused by material non-linearity. However, the variations of elastic moduli induced by load magnitude are not remarkable. Therefore, it might be acceptable to consider that the elastic moduli of AC, base and subgrade are approximately 1250, 210 and 90MPa, respectively in spite of the load level.

The comparison of surface deflections calculated from forward analysis with back-calculated elastic moduli with the measured ones is shown in Figure 3(b). Because the calculated surface deflections are in good agreement with the measured ones for all load levels, it is indicated that the accuracy of the back-calculation procedure is satisfactory.

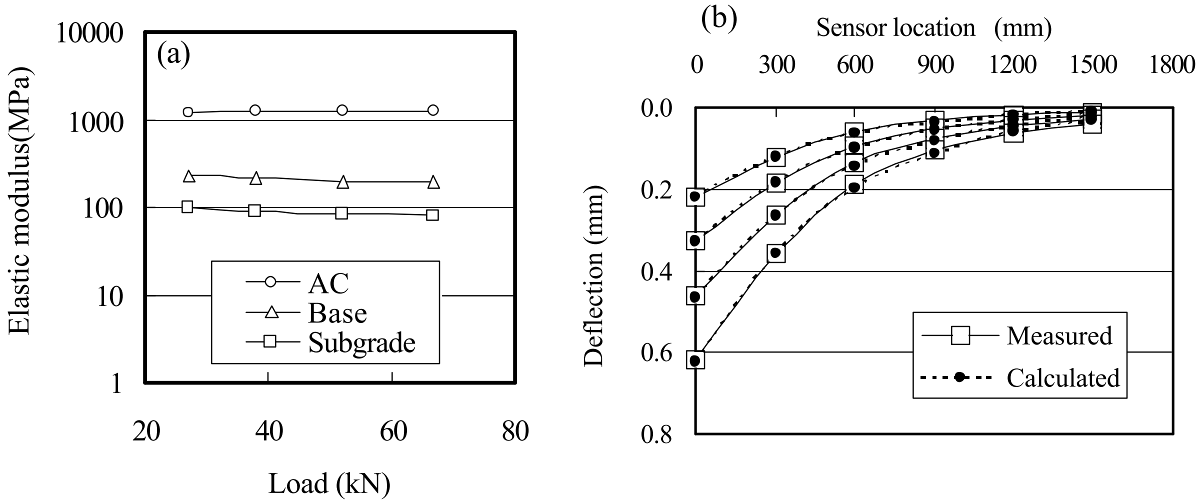

Figure 3: Results of static back-calculation; (a) relationship between load and elastic modulus, (b) comparison of calculated peak deflections with measured ones.

4.2 Results of dynamic analysis method

Before dynamic back-calculation, the relationship between load and the deflection at the center of load plate (D_0) was investigated. From the time-historical data shown in Figure 1(b), the impact load and the corresponding deflection D_0 are depicted at every time step. Their locus illustrated in Figure 4(a) will be obtained for four load levels. The area surrounded by the locus is defined as the dissipated work, which indicates the intensity of energy generated in the pavement by impact load (Killingsworth and Quintas, 1998). To compare the dissipated work at each load level, the dissipated energies calculated from four loci in Figure 4(a) are shown in Figure 4(b) against the load level.

From Figure 4(b), the dissipated energy non-linearly increases with the load level. It is necessary to do further study on the relationship with pavement performance in site. If the dissipated energy is related with fatigue property of pavements, this index could be very useful to evaluate the durability of pavements. Although the dynamic back-calculation procedure using the time-historical FWD data is time-consuming and labor-intensive than the static method, it is worth to focus on the advantage of time-historical data from which the useful information such as the dissipated energy would be gained.

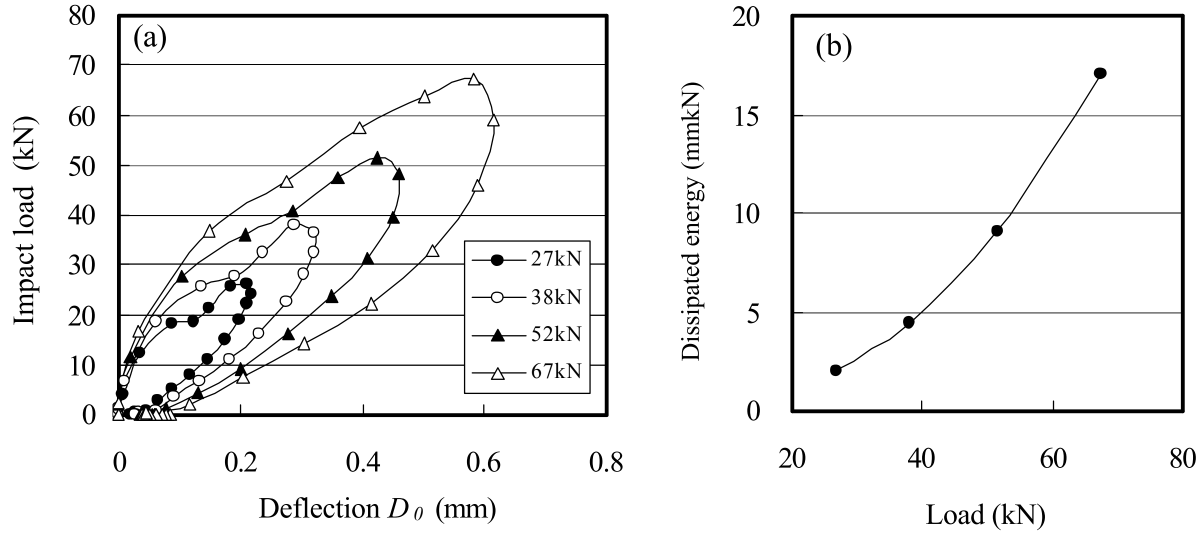

Figure 4: Results of dissipated energy calculation; (a) relationship between deflection D_0 and impact load at the same time, (b) relationship between load level and dissipated energy.

Figure 5(a) shows the back-calculated results by dynamic method. The back-calculated elastic moduli of AC, base and subgrade are approximately 1250, 150 and 160 MPa, respectively. As same as the static method, it is not remarkably recognized for the load level to influence the results of back-calculation due to material non-linearity. Focusing on base and subgrade, the elastic moduli of subgrade are slightly larger than ones of base at all load levels. This trend is characteristic of dynamic method to be different from static method.

Taking the load level of 67 kN, the time-historical deflections calculated with the back-calculated results are compared with the measured ones, as shown in Figure 5(b). From Figure 5(b), the calculated deflections agree very well with the measured ones. It means that the results obtained by dynamic method are acceptable.

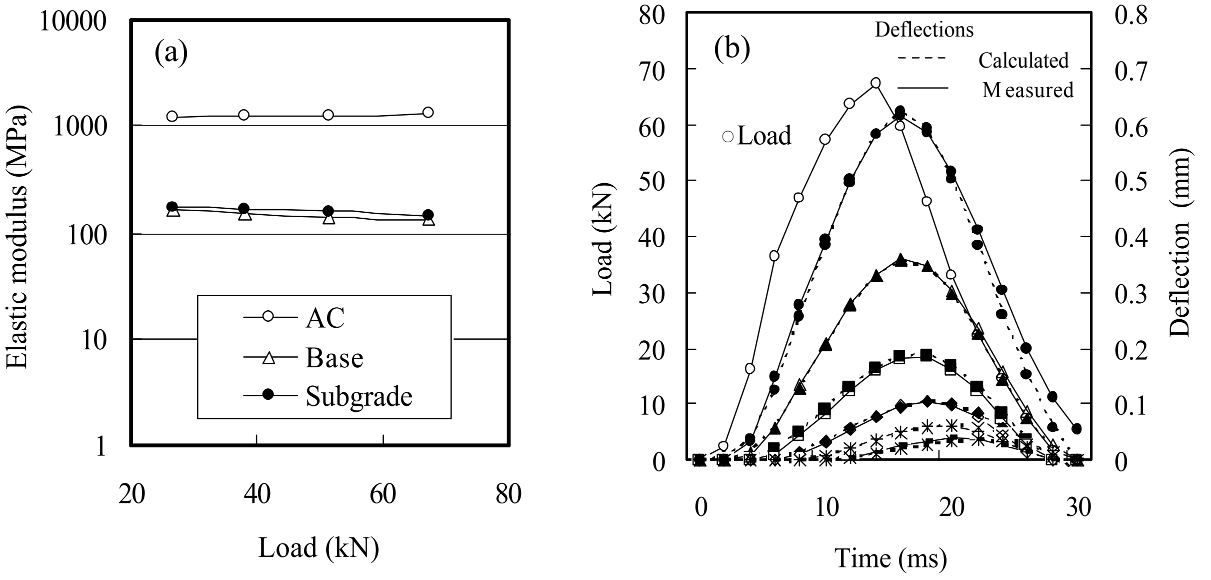

Figure 5: Results of dynamic back-calculation; (a) relationship between load intensity and elastic modulus, (b) comparison of calculated and measured deflections (67 kN).

4.3 Comparison of back-calculated modulus with DCP test

The DCP data were collected for five drops, and the elastic moduli were estimated at approximate depth of 50 mm by Equations (1) and (2), as shown in Figure 6(a) and Figure 6(b), respectively. From Figure 6(b), the elastic moduli of base and subgrade are variable in the direction of depth. Especially, the modulus of subgrade is the largest at the depth from 500 mm to 600 mm, which exceeds the maximum of base.

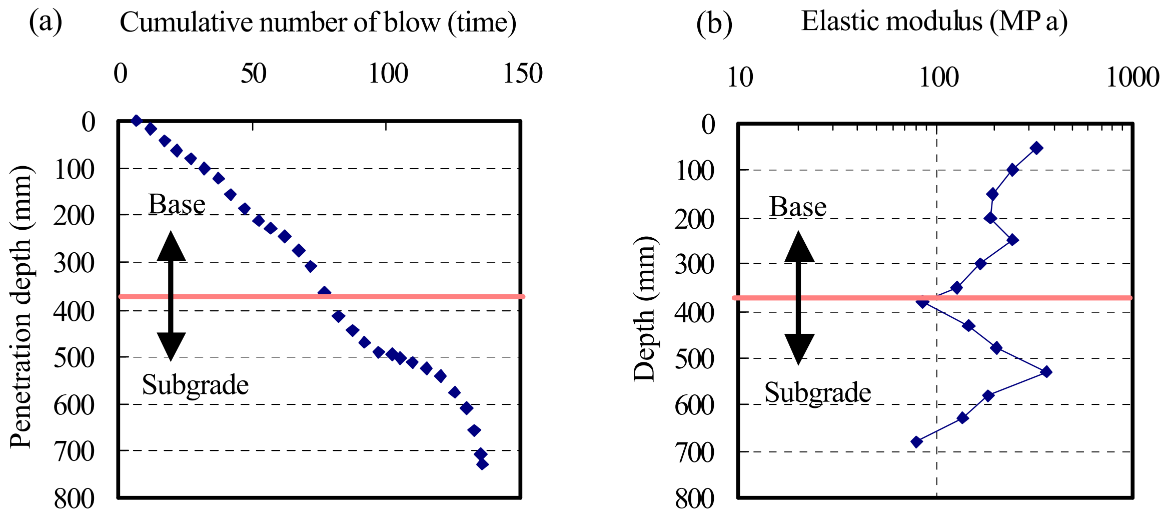

Figure 6: Results of DCP test; (a) relationship between cumulative number of blow and penetration depth, (b) estimated elastic moduli of base and subgrade by DCP.

The elastic moduli back-calculated by static and dynamic methods are compared with ones estimated by DCP, as shown in Figure 7. The back-calculated elastic modulus is the average value of four load levels, and the elastic modulus obtained by DCP is the average of estimated values at some depths for both base and subgrade. Figure 7 also shows the elastic moduli of AC back-calculated by static and dynamic methods to be as a reference.

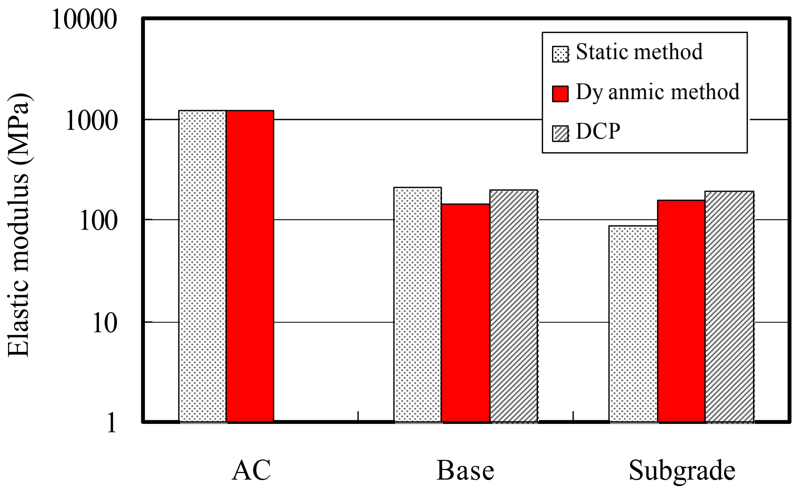

Figure 7: Elastic moduli obtained from back-calculation and DCP.

From Figure 7, it is observed that the elastic moduli back-calculated by static and dynamic methods are identical for AC layer. For the base and subgrade, the elastic moduli of base back-calculated by static and dynamic methods approximately agree with ones estimated by DCP, while the elastic modulus of subgrade back-calculated by static method is slightly less than that obtained by both dynamic method and DCP.

Based on the comparison of back-calculation methods, it is found that the elastic moduli back-calculated by static and dynamic methods are almost same for AC and base. However, they are somewhat different for subgrade.

4.4 Validation of back-calculation results by MDD data

To validate the back-calculation results, the static and dynamic forward analyses were conducted with the back-calculated unknown values obtained by static and dynamic methods to compare the internal vertical displacements and ones measured at the positions of MDD.

On the static method, the comparison of the internal displacements at each load level is shown in Figure 8(a). From Figure 8(a), the displacements calculated by static analysis are in a good agreement with the peak displacements extracted from the displacement-time histories measured by MDD.

On the other hand, the comparison of the internal displacement-time histories at the load level of 67kN is shown in Figure 8(b). From Figure 8(b), the peak displacement calculated is slightly smaller than one measured in subgrade. It is found that there are good agreements between the calculated and the measured internal displacement-time histories at three layers for four level loads. Because the same trend as Figure 8(b) is observed for other load levels, the results back-calculated by dynamic method would be proved to be valid.

Through these considerations, the elastic moduli back-calculated by static method do not perfectly agree with ones by dynamic method. However, it would be possible to predict the pavement responses (internal vertical displacements) with the elastic moduli back-calculated by both static and dynamic methods.

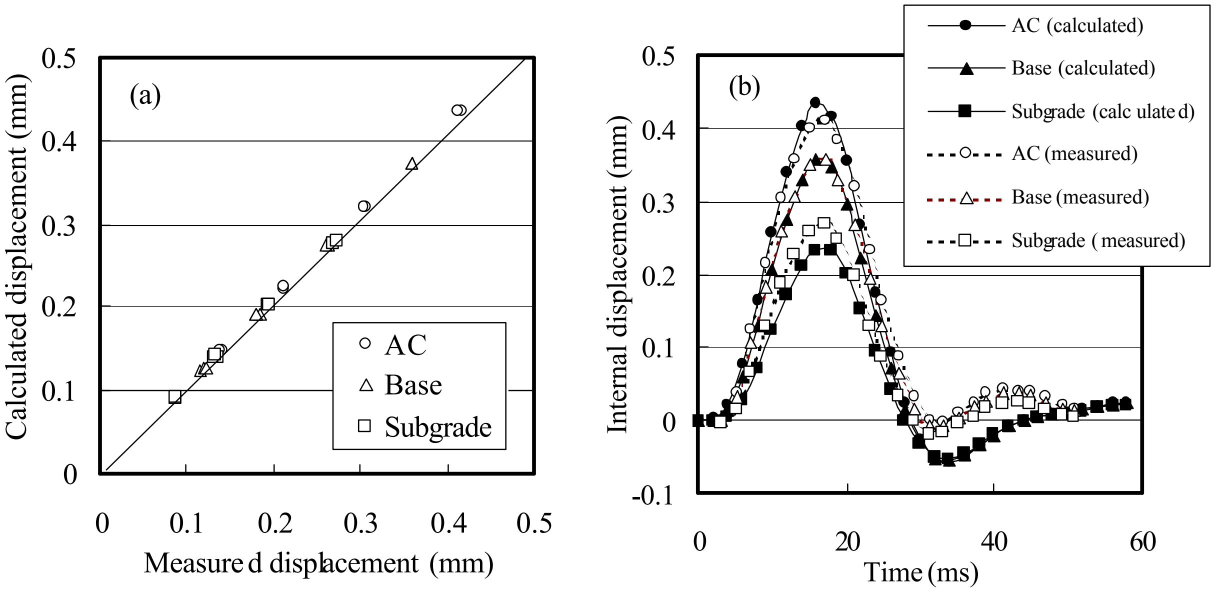

Figure 8: Comparison of the internal displacement between calculation and MDD measurement; (a) static method, and (b) dynamic method (67 kN).

5 CONCLUSIONS

Conclusions in this study are summarized as following:

1. Based on the comparison of back-calculation results, the back-calculated elastic modulus was nearly same by both static and dynamic methods for AC and base, while they were somewhat different for subgrade.
2. When the internal vertical displacements of the pavement were predicted by static and dynamic procedures with the back-calculated elastic moduli, the calculated displacements almost agreed with the measured ones by MDD.
3. From this study, although the elastic moduli back-calculated by static method are not necessarily equal to ones back-calculated by dynamic method, both static and dynamic methods are applicable to predict the responses (internal vertical displacement) and to evaluate the bearing capacity of asphalt pavements.
4. Although the dynamic back-calculation procedure using the displacement-time histories recorded from FWD test is time-consuming and labor-intensive than the static, it gives the useful information such as the dissipated energy, which could be acquired from their data.
5. In order to more certainly verify the applicability of both static and dynamic methods to evaluation of pavement bearing capacity, it is strongly recommended to compare the measured and calculated strain and/or stress, which are utilized for pavement thickness design.

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