

タイトル	An Improvement Approach for Portable FWD
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引用	北海学園大学工学部研究報告(38): 1-11
発行日	2011-02-14

An Improvement Approach for Portable FWD

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Abstract

The stiffness of subgrades of roads plays a major role in the structural stability of pavement structures. It has been regarded that the values of stiffness determined by using Portable FWDs is larger than that determined by Plate Bearing Test devices for loading plates of the same size and the same peak value of deflection. The focus of this study is on the investigation of the factors influencing this difference. A rubber plate and a torus-shaped iron plate combining a contact pressure measurement device were developed as a part of this study. The important conclusions and findings of this study are the distribution of contact pressure on the rubber plate was not affected by the torus-shaped iron plate, but it was dependent on the loading condition such as static loading or dynamic loading and it was found that the damping of gravel is related to a substantial part of increase in the conversion coefficient due to the use of the PFWD/PBT device from static and dynamic FEM analyses.

1. Instruction

The stiffness of subgrades of roads plays an important role in the structural stability of pavement structures. The recent developments in portable FWD (PFWD), which is similar to LWD and can be used under dynamic loading conditions, have made it possible to directly measure the stiffness of pavement structures during the construction itself. Deflectometer-type devices are dynamic nondestructive testing tools and are commonly utilized in the in-situ characterization of pavement systems. During testing, an impact load is applied on the pavement surface using these devices, and the induced pavement surface motion is monitored. Multiple versions of these devices have been tested in Japan, U.S., and Europe and used for quality control during construction. PFWD and LWD vary depending on the manufacturing company and the country of development and production ; however, except for the positioning of sensors (acceleration sensors or geophone sensors), their basic mechanical operation remains almost the same. These devices consist of three parts : (a) a base with a loading plate, a load cell, and a displacement sensor and associated elements, (b) a loading weight, and (c) rubber buffers and a guidance rod. Users have the option of selecting loading plates of different di-

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ameters : 100mm, 200mm, or 300mm. An acceleration sensor or a geophone sensor is mounted at the center of the loading plate to measure the surface displacement. A data acquisition system is used to assess the stiffness of the ground by monitoring the surface settlement under the plate and the contact stress.

In Europe and U.S., most of the PFWDs or LWDs are developed on the basis of Boussinesq's elastic theory, and the assumption of stress distribution is used to calculate the elastic modulus from the measured contact stress and peak deflection under the loading plate. In Japan, the stiffness parameter of subgrades is estimated using K_{30} that is determined from a plate-bearing test (PBT). The K value is utilized by introducing the elastic stiffness modulus in the simple elastic theory ; this elastic stiffness modulus is defined by the contact pressure p ($p = P/A$, where P = force applied on the loading plate (N) ; A = area of the loading plate (mm^2), and d = deflection of the loading plate (mm ; $d=1.25\text{mm}$ for a loading plate of diameter 30 cm)). Although the PBT is widely used in Japan, it is increasingly being replaced by PFWD tests because the latter is easier. The subgrade benchmark value K_{PFWD} , determined by using PFWD, is estimated from the contact pressure and the deflection of the PFWD loading plate. Since the PFWD loading conditions affect the stiffness evaluation, a conversion coefficient is required for K_{30} (Kamiura 2000). Equation (1) is obtained by statistical analysis.

$$K_{30} = \frac{K_{\text{PFWD}}}{\gamma} \quad (1)$$

Where, γ (conversion coefficient), $\gamma=1$ (clay), $\gamma=1.5$ (sand), $\gamma=2$ (gravel)

The conversion coefficients for typical examples of soils such as clay, sand, and gravel have been estimated (JSCE2002). Equation (1) implies that the loading force measured by using a PFWD is larger than that measured by a PBT device for loading plates of the same size and the same peak value of deflection. On the basis of this, we obtain equation (2).

$$P_{\text{static}} = \frac{P_{\text{dynamic}}}{\gamma} \quad (2)$$

where P_{static} = peak value of load applied using the PBT device and P_{dynamic} = peak value of load applied using the PFWD.

Some trials have been carried out to study the factors affecting the conversion coefficient. Hirakawa (2008) took particular note of the deflection velocity of the loading plate in his study since dynamic loading affects the contact stress.

2. Focus of this study

The contact pressure between the loading plate and the ground surface depends on the pressure dis-

tribution on the loading plate and the stress distribution of the subgrade. The significant differences in the peak vertical stress observed at shallow depths in different soils can be explained by the presence of different contact stress distributions between a rigid plate and clay or sand soil (Bell 2004). Terzaghi (1943) theorized that the contact stress distribution between a rigid plate and the soil depends on the soil type. He suggested that the stress distribution of a rigid circular plate has an inverse parabolic profile. Equation (3) is derived from Terzaghi's elastic theory.

$$E_s = \frac{S \cdot (1 - \nu^2) \cdot F}{\pi \cdot a \cdot d} \quad (3)$$

where E_s = gravel modulus (MPa), S = stress distribution factor (–), F = peak value of load (N), a = radius of the loading plate (mm), and ν = Poisson's ratio (–).

The magnitude of S depends on the stress distribution under the rigid plate with respect to that of the underlying medium. According to Boussinesq, $S = \pi/2$ for a rigid plate and $S = 2$ for a flexible plate for a uniform stress distribution (Gurp 2000). In practice, a plate can be neither completely rigid nor perfectly flexible. Therefore, the average of the two values, 1.8, would be a good approximation (George 2006).

Then, if the peak value of load is considered to be independent of the loading time in Terzaghi's elastic theory, the gravel modulus estimated using equation (3) is found to be independent of the loading condition (dynamic loading or static loading). However, the peak value of load is found to be dependent on the loading condition from equation (2). Therefore, two concepts are proposed according to dependence of the peak value of load on the loading condition.

We consider that the peak value of load is dependent on the loading condition. In this study, we focus on the investigation of the factors affecting the conversion coefficient in equation (1).

3. Test equipment

3.1 Rubber plate

It was discussed in the previous section that dynamic loading force measured by a PFWD is larger than the static loading force measured by a PBT for loading plates of the same size and the same peak value of deflection for a gravel subgrade. It is important to study the quasi-velocity of the loading plate deflection since dynamic loading affects the contact stress. In this study, a natural rubber plate (*Figure 1*) is introduced during the determination of the quasi-velocity of the loading plate deflection under dynamic loading by using a PFWD and under static loading by using a PBT. This rubber plate has an international rubber hardness degree of 70 and its length, width, thickness, and weight are 1m, 1m, 0.3m, and 700kN, respectively.

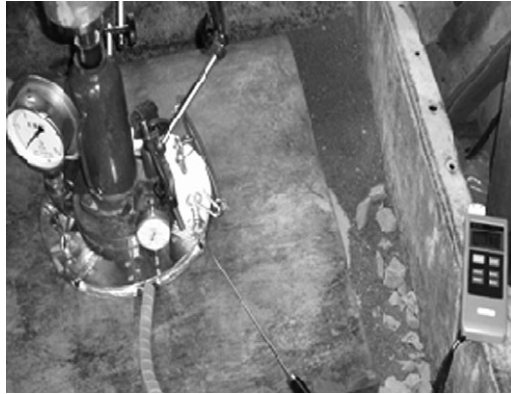


Fig. 1 Rubber Plate

3.2 Gravel subgrade test pit

The loading tests were performed in the gravel subgrade test pit. The water content, wet density, and dry density of the gravel were 2%, 1.65g/cm^3 , and 1.3g/cm^3 , respectively. The length, width, and depth of the gravel subgrade test pit were $1.5\text{m} \times 1.5\text{m} \times 1\text{m}$. The layer of the gravel soil in the pit was made uniform by using a vibration exciter.

3.3 Torus-shaped iron plate

When a load is applied on the ground soil, the soil layer gets deformed by the well-known Prandtl mechanism, as shown in *Figure 2*. A circular loading plate forms a boundary for the continuous displacement field beneath the plate. The shear distribution in this boundary can be divided into three zones. These regions undergo shearing and deformations compatibly and continuously with no relative sliding of their boundaries. Consequently, the gravel subgrade beneath the wedge is forced downwards and outwards, with plastic bulging taking place within the regions. The gravel around the loading plate is displaced away from the plate, and shear forces propagate outward from the apex of the wedge, as shown by the dashed line in *Figure 2*. Terzaghi's elastic theory cannot explain this plastic

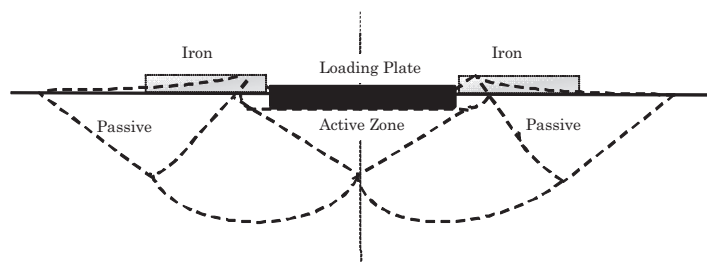


Fig. 2 Prandtl mechanism in soil deformation

bulging taking place close to the edge of the loading plate. A torus-shaped iron plate (*Figure 3*) is introduced to inhibit the transfer of plastic bulging near the edge of the loading plate. The inner and outer diameters of the torus-shaped iron plate shown in *Figure 3* are 30cm and 70cm, respectively. This plate is 3-cm thick and weighs 300N.

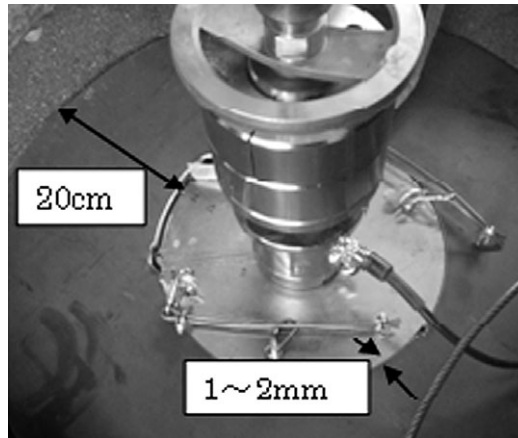


Fig. 3 Torus shaped iron plate

3.4 Contact pressure measurement device and loading devices

The contact pressure distribution on the loading plate was estimated by using 10 pressure sensors with a maximum capacity of 500kPa placed on the contact surface of the loading plate, as shown in *Figure 4*. The PFWD used in this study is shown in *Figure 2* ; a PFWD is used in this study because it is easy to use it for the estimation of the in-situ bearing capacity of subgrades. Since it weighs only 15kg, it is portable as compared to PBT devices ; PBT devices are normally equipped with a 300-mm

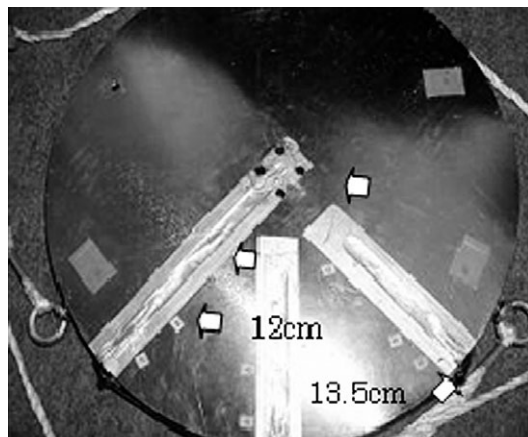


Fig. 4 Contact pressure measurement device

circular loading plate and a 50–kN hydraulic jack (*Figure 1*).

3.5 Vertical stress measurement system

A stress measurement system with geostatic stress sensors (diameter : 100mm, thickness : 20mm, maximum capacity : 200kPa) was used to monitor the behavior of stress distribution in an in–situ test pit. These sensors were located at depths of 10cm, 20cm, 30cm, 40cm, and 50cm. The positions of the measuring devices are shown in *Figure 5*. No sensors were overlapped in a vertical direction to inhabit an upper gauge acting on the other lower gauges.

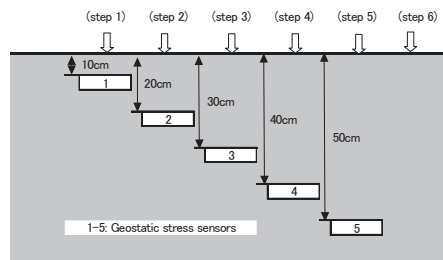


Fig. 5 Location of Geostatic stress sensors

4. Test results

4.1 Contact pressure

4.1.1 Rubber plate

A rubber plate, made of a uniform and viscoelastic material, was introduced in the loading tests. The contact pressure values measured using the conventional method (hereafter, called as the N method) and the method using the torus–shaped iron plate (hereafter, called as the T method) were compared. Moreover, two types of loading devices (PBT device and PFWD) were used for the estimation of stiffness. *Figures 6* and *7* show that there is no marked difference between the results of the N method and the T method. However, it has been confirmed that most of the contact pressure values measured by the PFWD are higher than those measured by the PBT device. The mean loading weight applied using the PFWD is almost twice that applied using the PBT device. This indicates that the distribution of contact pressure is unaffected by the torus–shaped iron plate. However, it is affected by the loading condition such as static loading or dynamic loading.

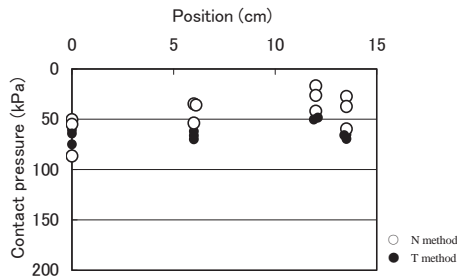


Fig. 6 Contact pressure distribution in rubber plate using PBT

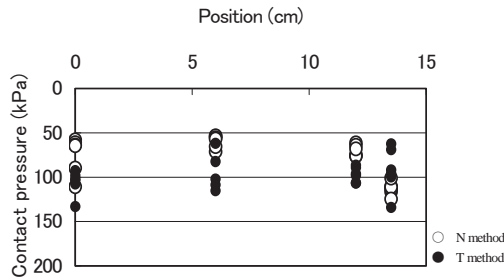


Fig. 7 Contact pressure distribution in rubber plate using PFWD

4.1.2 Gravel subgrade

The loading tests using the PBT device and PFWD were performed in the gravel subgrade test pit described in the previous section. As shown in *Figure 8*, in the N method, the contact pressure decreases with increasing distance from the center. In the T method, the contact pressure decreases with increasing distance from the center up to 12cm and increases beyond this point. On the other hand, *Figure 9* shows a completely different behavior. In the N method, the contact pressure remains relatively constant from the center to a distance of 6cm. However, in the T method, the contact pressure is maximum at 6cm. These results indicate that the torus-shaped iron plate is effective in distributing

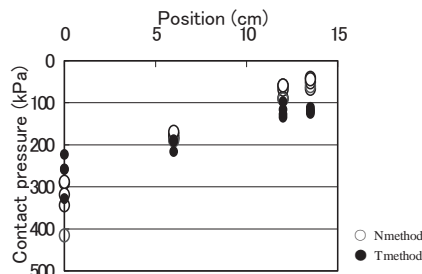


Fig. 8 Contact pressure distribution in Gravel subgrade using PBT

contact pressure inside the loading plate near its edge.

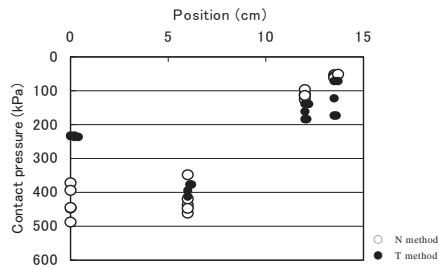


Fig. 9 Contact pressure distribution in Gravel subgrade using PFWD

4.2 Reaction force

As described previously, contact pressure decreases with increasing distance from the center by the use of the PBT device and PFWD. Since it is assumed that the reaction force remains the same along concentric circles, it is important to investigate the main area over which reaction forces are acting for summing the reaction forces over the entire surface.

Figure 10 presents the results of the loading tests performed by using the PBT device. This figure shows the relationship between the reaction force per unit length along the radial direction and the position on the gravel subgrade.

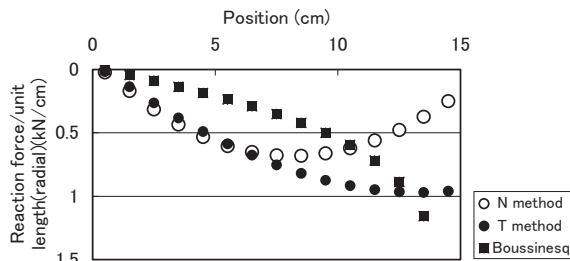


Fig. 10 Distribution of reaction force per unit length in Gravel subgrade using PBT

Interestingly, it was found that the reaction forces at distances below 7cm from the center were almost the same in the N method and the T method. Further, as the distance from the center increased above 7 cm, the reaction force in the N method reduced, while that in the T method increased.

On the other hand, the reaction forces calculated using Boussinesq's elastic theory were almost similar to those calculated using the T method. This implies that the torus-shaped iron plate is effective in inhibiting the transfer of plastic bulging near the edge of the loading plate.

Figure 11 shows the results of the loading tests performed by using the PFWD. The conditions in

this figure are the same as those in *Figure 9*. It was found that the reaction forces at distances below 9 cm were almost the same in the N method and T method. At distances greater than 9cm, the reaction force using the N method reduced, while that using the T method increased. The reaction force increases progressively near the edge of the loading plate. This implies that the torus-shaped iron plate is effective in inhibiting the transfer of plastic bulging near the edge of the loading plate.

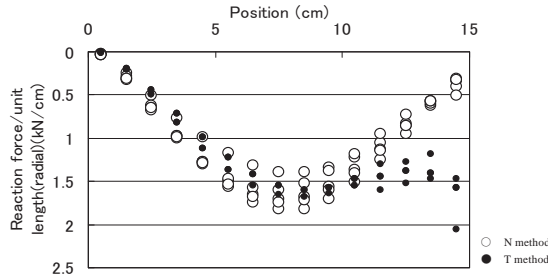


Fig. 11 Distribution of reaction force par unitlength in Gravel subgrade using PFWD

4.3 Increase in conversion coefficient by use of PFWD/PBT device

One of the objectives of this study is to investigate the factors that affect the conversion coefficient determined by using a PFWD/PBT device. *Table 1* shows the conversion coefficients determined using the PFWD/PBT device, the rubber plate, and the gravel subgrade. The results show that the conversion coefficient decreases by nearly 15% by the use of the torus-shaped iron plate. This indicates that the rate of increase in the conversion coefficient defined by the loading force ratio PFWD/PBT was 15% that deal with the plastic bulging near the edge of loading plate.

Table 1 Conversion coefficient by PFWD/PBT

	Rubber Plate	Gravel subgrade
N method	8.1	2.2
T method	8.1	1.9

5. FEM analysis of viscoelasticity of gravel subgrade

There are two approaches to backcalculate the layer moduli from the PFWD data : a static method that uses peak values of both loading and surface deflection and a dynamic method that uses time histories of loading and surface deflection. The dynamic method is usually used to examine the viscoelasticity of soils. The FEM used in this study was developed to analyze time-domain viscoelastic issues (Dong2003). A two-dimensional axisymmetric model was developed for a homogeneous linear

elastic half-space.

In this theory, the following equation is adopted :

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) = \mathbf{F}(t) \quad (4)$$

$$\ddot{\mathbf{u}}(0) = \mathbf{0} \quad \dot{\mathbf{u}}(0) = \mathbf{0}$$

where \mathbf{M} , \mathbf{C} , and \mathbf{K} denote the mass, damping, and stiffness matrixes, respectively ; $\ddot{\mathbf{u}}(t)$, $\dot{\mathbf{u}}(t)$, and $\mathbf{u}(t)$ denote acceleration, velocity, and displacement variables, respectively ; and $\mathbf{F}(t)$ denotes a loading vector. In the finite element analysis under dynamic loading conditions, the relation between the load and the loading time for the PFWD was used for defining the force vector $\mathbf{F}(t)$.

The relationship between the results of the vertical stress distribution measurement and the FEM analysis is shown in *Figure 12*. It is observed that the results of FEM analysis and the tests using the PFWD are in a fairly good agreement under the dynamic loading condition. Similarly, under the static loading condition, the results of the FEM analysis and the PBT are in a good agreement. *Table 2* shows the characteristic data used in the FEM analysis. It is found that damping coefficient in the case of the PFWD is more than twice that in the case of the PBT device. It can be said that the damping of gravel is related to a substantial part of increase in the conversion coefficient by the use of the PFWD/PBT device.

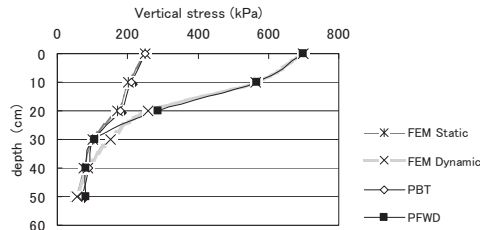


Fig. 12 Vertical stress dispersion measurements and the FEM analysis results

Table 2 Sample table

	Elastic modulus (MPa)	Poison ratio	Damping coefficient (kNs/m)
Plate Bearing Test	85.3	0.30	0.04
PFWD	170.5	0.30	0.09

6. Summary and Conclusions

The performance and service life of pavements depend on the stiffness of the subgrades used. The stiffness of subgrades of roads plays a major role in the structural stability of pavement structures.

The recent developments in PFWDs have made it possible to directly measure the stiffness of pavement structures during the construction itself. It has been regarded that the values of stiffness determined by using PFWDs is larger than that determined by PBT devices for loading plates of the same size and the same peak value of deflection. The focus of this study is on the investigation of the factors influencing this difference.

Two new devices combining a contact pressure measurement device were developed as a part of this study. One of the devices was a rubber plate that is regarding to quasi-velocities since the dynamic loading affects the contact stress. The other was a torus-shaped iron plate that was introduced to inhibit the transfer of plastic bulging near the edge of the loading plate.

The important conclusions and findings of this study are listed below :

- The distribution of contact pressure on the rubber plate was not affected by the torus-shaped iron plate, but it was dependent on the loading condition such as static loading or dynamic loading.
- The torus-shaped iron plate was effective in distributing contact pressure inside the loading plate, near its edge,
- The rate of increase in the conversion coefficient defined by the loading force ratio PFWD/PBT was 15% that deal with the plastic bulging near the edge of loading plate.
- From static and dynamic FEM analyses, it was found that the damping of gravel is related to a substantial part of increase in the conversion coefficient due to the use of the PFWD/PBT device.

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