Application of dynamic and static cone penetrometer for characterization of railway substructure

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ABSTRACT

The excessive loading generated from the train may cause the subgrade failure in the railway. Subsequently, the failure of subgrade leads to the change in the geometry of the rail. This paper represents the application of a dynamic and static cone penetrometer (DSCP) to evaluate the strength in the railway substructure. The DSCP, which consists of an outer pipe and an inner cone, is designed for the penetration into the ballast and subgrade, respectively. For the ballast, the outer pipe mounted with an accelerometer and four strain gauges is used to estimate the energy transferred into the head of pipe. During the penetration of the outer pipe, dynamic cone penetration indexes (DCPI) are recorded and can be corrected with the transferred energy. To evaluate the soil strength in the subgrade, the inner cone, which is mounted with four strain gauges, is used. For the field application of the DSCP, the dynamic and static cone penetration tests are performed at two positions. The results show that the corrected DCPI with the transferred energy is independent on the impact system. Furthermore, in the subgrade, the inner cone of the DSCP provides the soil strength profile with a high resolution, in terms of the cone tip resistance. This study suggests that the dynamic and static cone penetrometer may be effectively used for the characterization of the substructure in the railway.

Keywords: cone penetrometer, DCPI, cone tip resistance, subsurface characterization, railway substructure

1 INTRODUCTION

The substructure of railway track system is composed of the ballast, the sub-ballast, and the subgrade. In general, the substructure provides resistance to the forces by traffic loading, but sometime it has potential problems, such as the ballast deterioration and the progressive shear failure.

To investigate the railway substructure, several testing methods have been proposed (Brough et al. 2003; Brough et al. 2006). First, trial pit excavation is a conventional method for the examination of the condition of ballast and subgrade, but it may affect the stability of the railway. Automatic ballast sampler is also an effective method to investigate the substructure profile. However, the boring process of automatic ballast sampler may cause the disturbance of sample. Dynamic cone penetration test (DCPT) has been performed to evaluate the strength of subsoil under the road pavement (Kleyn and Savage 1982; Siekmeier et al. 2000; Mohammadi et al. 2008). DCP index obtained from the DCPT has low reliability with resilient stiffness. In contrast, portable falling weight deflectometer (PFWD) as a nondestructive testing method is widely used to estimate the resilient stiffness of subgrade. However, the application of the PFWD is limited to the uneven surface, which causes the inaccurate measurement of deflection (Nazzal et al. 2007). To produce the continuous profile of the substructure, ground penetrating radar (GPR) has been applied for the railway, although any engineering properties can be not obtained (Sussmann et al. 2003; Al-Qadi et al. 2010).

This paper presents the application of the dynamic and static cone penetrometer (DSCP) to investigate the variation of strength in the railway substructure. The DSCP, which is composed of an outer pipe and an inner cone, is used for dynamic and static penetration tests, respectively. The design of the DSCP is followed by the static calibration and dynamic response. In the end, field tests are discussed.

2 DYNAMIC AND STATIC CONE PENETROMETER (DSCP)

The dynamic and static cone penetrometer (DSCP)
consists of an outer pipe and an inner cone. The outer pipe of the DSCP has the outer diameter of 24 mm and the inner diameter of 15 mm, as shown in Fig. 1. The tip diameter of the inner cone \(D_{\text{tip}} = 20\) mm was designed greater than the inner diameter of the outer pipe to reduce the friction of sleeve. A guide for hammer is connected on the head of the outer pipe as shown in Fig. 1(a). Fig. 1(b) shows that, at the head of the outer pipe, an accelerometer and four strain gauges are installed for measuring the transferred energy. In the inner cone as shown in Fig. 1(c), four strain gauges configured with full-bridge circuit are installed for measuring the cone tip resistance. The strain gauges and accelerometer are connected with the data acquisition system, as reported by Byun et al. (2015).

![Fig. 1. Schematic drawing of the DSCP: (a) assembled; (b) outer pipe; (c) inner cone.](image)

3 CALIBRATION

3.1 Force

The strain gauges installed at the pipe head were used for measuring the forces detected at each position. To obtain a relationship between the force and the output voltage, a force calibration was carried out. From the calibration, the linear relationship between the applied force and the measured output voltage from the strain gauges was established with a high reliability (greater than determinant coefficient of 0.99).

3.2 Velocity

To evaluate the transferred energy into the pipe head, the accelerometer and the strain gauges installed at the pipe head were used. First, velocity is obtained from the integration of acceleration, and then the velocity is multiplied by the impedance of the outer pipe \(Z\), in order to be expressed in terms of force.

To match the velocity with the force measured by the strain gauges, the dynamic response in free resistance condition was investigated by impacting the outer pipe in the air [see the details in Byun et al. (2015)]. Fig. 2 shows the force and velocity measured at the pipe head. Before 2.97 ms, the force measured by the strain gauges is identical to the velocity. After 2.97 ms, the peak velocity is almost twice the peak force. During the multi-reflection of the compressional wave, the force and velocity are attenuated. It should be noted that the time of 2.97 ms corresponds to first arrival time of the reflection wave from the end of the outer pipe.

![Fig. 2. Dynamic responses of an accelerometer and strain gauges installed at the outer pipe.](image)

4 FIELD TESTS

4.1 Procedure

The procedures of the dynamic and static penetration tests for application of the DSCP are described as follows:

1) The DSCP is located in the hole of the guide plates, and then connected with the hammer and the guide rod, as shown in Fig. 3(a). For the dynamic penetration, the DSCP is driven by dropping the hammer.
2) When the tip of the DSCP arrives at the subgrade, the electric motor system is substituted for the guide plates and hammer. Also, the electric motor system for the static penetration plays a role of the reaction frame.
3) After the zero loading state of the DSCP is confirmed by extracting the DSCP, the inner cone is pushed into the subgrade as shown in Fig. 3(b). The penetration rate of 1 mm/sec is kept during the static penetration.
4.2 Dynamic penetration results

The dynamic cone penetration tests at two positions (1 and 2) in the railway were carried out by using the DSCP. In the DCP tests, the blow counts at each depth were recorded as DCP index (DCPI). Fig. 4 shows the DCPI results measured up to the penetration depth of 602 mm at position 1. The DCPI profile is plotted from the depth of 120 mm, considering the seating drops.

From the force and velocity measured at the pipe head, the transferred energy was calculated by using F-V integration (ASTM D4633). In the field tests, the energy ratios of the transferred energy to the potential hammer energy were plotted in Fig. 4. In two dynamic cone penetration tests, the average energy ratio approximately corresponded to 50%.

To exclude the effect of the transferred energy on the DCPI, the DCPI was corrected by the transferred energy. The corrected DCPI (CDCPI) with the transferred energy was expressed as follows.

\[
CDCPI = DCPI \times \frac{E_{50\%}}{E_{measured}} \tag{1}
\]

where \(E_{50\%}\) is half of potential energy for the hammer and \(E_{measured}\) is the energy directly measured at each blow. The CDCPI along the penetration depth is plotted in Fig. 4. The variation of CDCPI is almost similar to that of DCPI, but the value of CDCPI is independent on the impact system.

4.3 Static penetration results

After the dynamic penetration, the static cone penetration tests were carried out at two positions (1 and 2). The inner cone of the DSCP was pushed from 650 to 1140 mm, and the profiles of the cone tip resistance are shown in Fig. 5. The cone tip resistance in the whole depth remains at approximately 5.0 MPa. The sharp increase of cone tip resistance between the depth of 850 mm and 950 mm coincided at two positions.

\[
\begin{array}{c}
\text{Penetration depth [mm]} \\
\text{Cone tip resistance [MPa]}
\end{array}
\]

Fig. 5. Results obtained at position 1 in the dynamic cone penetration test.
In the whole depth, the profiles of the CDCPI and cone tip resistance are plotted in Fig. 6. The results of dynamic and static cone penetration tests performed at two positions confirmed the repeatability of the DSCP. Namely, the profiles of the CDCPI and cone tip resistance were almost same at two positions. Eventually, the DSCP may be a more reliable in-situ testing method to characterize the variation of soil strength in the railway substructure.

5 CONCLUSIONS

The dynamic and static cone penetrometer (DSCP) was used to evaluate the condition of railway substructures. The DSCP, which is composed of an outer pipe and an inner cone, can penetrate the ballast and subgrade by the dynamic and static methods, respectively. The outer pipe included an accelerometer and four strain gauges for the evaluation of the transferred energy and, in the inner cone, four strain gauges were installed for detection of the cone tip resistance. Before the field application of the DSCP, the calibrations for estimation of the force and velocity were conducted by using the strain gauges and accelerometer. The field tests of the DSCP were performed in a railway. The corrected dynamic cone penetration index (CDCPI) determined from the dynamic cone penetration index and the transferred energy represented the variation of in-situ strength in ballast, which is independent on the impact system. In the field tests, the DSCP produced the repeatable profiles of the CDCPI and the cone tip resistance. The DSCP may be an effectively useful method for the evaluation of the in-situ strength in the railway substructure.

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