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Technical Note

Identification method for travel time based on the time domain technique in bender element tests on sandy and clayey soils

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Abstract

Based on the bender element (BE) international parallel tests, conducted from 2003 to 2005 using Toyoura sand, a standard test method for BE tests was proposed by Yamashita et al. (2009). The proposed method showed that any of the different identification methods would give a comparable travel time if the frequency of the transmitted wave were approximately equal to the frequency of the received wave. The proposed test method, however, did not show any specific procedure for choosing the input frequencies or for calculating the travel time. In the present study, therefore, with reference to the results from several previous studies on BE testing, a conditional expression for determining the input frequency and a calculation formula for the travel time have been defined, and BE testing using 13 different sandy and clayey soils has been conducted. After the testing, it was confirmed that the testing method is able to determine the shear wave velocity of sandy and clayey soils having widely different stiffnesses. Furthermore, the study has found that a reevaluation of the International Parallel Test results using this method has resulted in less variation as compared to the results from the reevaluation by Yamashita et al. (2009). This method is recommended in the "Method for laboratory measurement of shear wave velocity of soils by bender element test" standardized by the Japanese Geotechnical Society (JGS) in 2011 (Japanese Geotechnical Society, 2011).

Keywords: Bender element test; Travel time; Time domain method; Clayey soil; Sandy soil (**IGC:** D6/D8)

1. Introduction

The bender element (BE) test is an inexpensive method that enables the simplified determination of shear wave velocity V_S for geomaterials (Shirley and Hampton, 1978; Dyvik and Madshus, 1985). For this reason, an increasing number of existing test apparatuses, such as oedometers, shear boxes, and triaxial apparatuses, are equipped with BEs, by which V_S measurements are incrementally made during testing. However, no standardized test methods have been put into place, making it difficult to objectively compare V_S measurements from different laboratories due to their lack of reliability. This problem was acknowledged by the technical committee, TC29 (currently TC101), of the International Society of Soil Mechanics and Geotechnical Engineering, one of their missions being to optimize and internationally standardize the laboratory test apparatuses and/or methods for evaluating the deformation characteristics of geomaterials. In order to address this problem, the domestic TC29 group of the Japanese Geotechnical Society (TC29-JGS) has led the effort for international parallel tests conducted using the BE and has used the results of these tests to publicize a proposed standard test method (Yamashita et al., 2009). The proposed test method demonstrates that any of the “start-to-start” (S.S.), “peak-to-peak” (P.P.), or “cross

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correlation" (C.C.) methods will produce a comparable travel time if the frequency of the transmitted wave is made approximately equal to the frequency of the received wave. However, the proposed test method does not show how input frequencies are specifically chosen or how the travel time is specifically calculated. In addition, the proposed test method is based on the results of BE tests conducted only with Toyoura sand, resulting in uncertainty about whether or not the proposed test method, if applied to other sandy and clayey soils, would yield proper results.

To address such uncertainty, BE tests were conducted in this study on 13 different sandy and clayey soils, thereby making improvements to the test methods proposed by the TC29-JGS to properly identify the travel time from a wide range of sandy and clayey soils.

2. Test apparatuses and specimens

The tests described here, separate from the international parallel tests, were performed using four different triaxial apparatuses equipped with BEs installed in the cap and pedestal. Two specimens, one having a diameter and height of 70 mm and the other having a diameter of 50 mm and a height of 100 mm, were used in each of the test apparatuses. Both of the BEs used in the experiment were of a bimorph type consisting of PZT (lead zirconate titanate, $Pb(Zr.Ti)O_3$) and were coated with resin for the purposes of insulating and waterproofing.

As shown in Fig. 1, all of the test apparatuses were configured in such a manner that the transmitter BE was subjected to a voltage with the tips of the transmitter/receiver BEs closely attached to each other. When the directions in which the BEs initially moved coincided with each other, the polarities of the transmitting/receiving voltages were aligned with each other (Kuwano et al., 1999; Yamashita et al., 2009). Then, the delay time Δt_d of the entire measurement apparatus was measured. All apparatuses had a negligibly small delay time Δt_d, which was regarded as zero. In these apparatuses, the proportion of the total insertion length of the BEs to the height of the specimen ranged from 8% to 20%. The effect of the ratio of the insertion length on

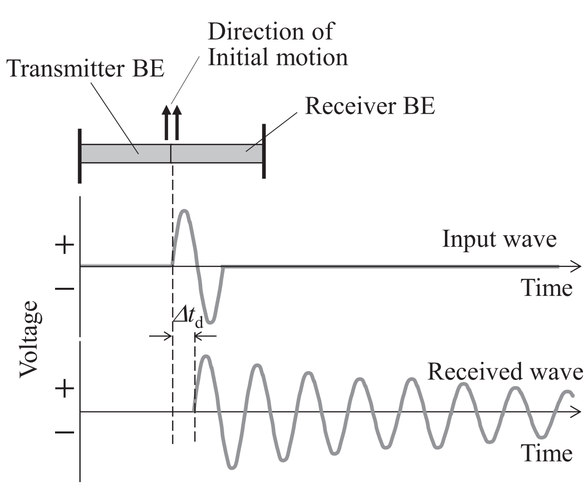

Fig. 1. Methods for checking the direction of initial motion of BE and measuring the delay time of the entire apparatus.

the measured shear wave velocity has been determined to be minimal (Yamashita et al., 2009).

Table 1 summarizes the physical properties of the 13 different sandy and clayey soils used in this study along with the BE test conditions. Considering the test results submitted from the international parallel tests, only the results of the BE tests on Toyoura sand (TS), obtained by transmitting a sine wave of one wavelength to the cylindrical specimens (e.g., triaxial or resonant column tests), were applied. Cement-Treated Dredged Soils A and B (CA, CB) are specimens that were formed by mixing a clayey soil retrieved from the Port of Kobe and from off the Sea of Okhotsk, respectively, with cement and air foam, and then curing them in a plastic mold with a diameter of 5 cm and a height of 10 cm (Kataoka et al., 2013). Table 1 lists the physical properties of the base soils. Glass Beads A (GA) and Glass Beads B (GB), having particle sizes of 2 mm and 0.4 mm, respectively, were commercially available, and specimens were made by the air pluviation method. Kussharo Volcanic Soil (KV), Inagi Sand (IS), Toryo Weathered Volcanic Soil (TW), Ebetsu Organic Clay (EO), and Ebetsu Peat (EP) are specimens that were made by reconstituting a naturally deposited soil through the use of the air pluviation method, compaction, and reconsolidation (Yamashita et al., 2005; Ogino et al., 2010; Kawaguchi et al., 2013). Chiba Sand (CS), Pisa Clay (PC), and Mexico Clay (MC) are intact soil specimens that were obtained from thin-walled sampling tubes (Lo Presti et al., 2003; Hayashi et al., 2011). For the case of MC, BE tests were conducted on two specimens retrieved from different depths.

Fig. 2 shows the grain size distribution curves for soils other than MC, EO, and EP (Hayashi et al., 2011; Ogino et al., 2010), on which grain size tests could not be performed. GA and GB are pertinent to the grain size distribution curves of the base soils. The figure shows that sandy and clayey soils, having a wide range of grain size distributions, were subjected to BE tests.

3. Methodology

In the BE tests, elastic shear modulus G was calculated from the following formula using wet density ρ_t and the shear wave velocity:

$$G = \rho_t \cdot V_S^2 = \rho_t \cdot \left(\frac{L}{\Delta t}\right)^2, \quad (1)$$

where L is the travel distance and Δt is the travel time. Most of the laboratories participating in the international parallel tests define the value "L" as the distance between the tips of the BEs (tip-to-tip distance); this definition has gained international consensus (Dyvik and Madshus, 1985; Viggiani and Atkinson, 1995). Methods for identifying Δt include the T.D. method, known as the time domain technique and using temporal axes, and the F.D. method, known as the frequency domain technique and using frequency axes. Examples of the T.D. method include the start-to-start (S.S.), peak-to-peak (P.P.), and cross-correlation (C.C.) methods, as shown in Fig. 3(e.g., Viggiani and Atkinson, 1995; Jovičić et al., 1996; Kawaguchi et al., 2001; Yamashita et al., 2009). The S.S. method treats