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Comparison of shear wave velocities evaluated in the core zone of an existing fill dam by field and laboratory tests

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ABSTRACT

The objective of this study is to compare shear wave velocities evaluated by laboratory and field tests in the core zone of an existing fill dam, and to verify the applicability of empirical methods by comparing the shear wave velocities evaluated by empirical methods with those evaluated by experimental methods. In this study, boring and sampling were conducted at the Yeongcheon dam in Korea. Laboratory tests on the core samples were carried out and field tests such as borehole surveys and seismic methods were conducted to evaluate the shear wave velocity. The results obtained by laboratory and field tests were compared. Furthermore, the results obtained by these experimental methods were compared with those obtained by empirical methods. The shear wave velocity determined by the seismic methods was, to a limited extent, lower than that determined by the borehole surveys at shallow depths of less than 15 m, but was predicted to be similar at depths deeper than 15 m. The results of the two kinds of laboratory tests were almost similar to each other but both the results were 10–20% lower than those obtained by the seismic methods. The results obtained by the empirical method based on the field tests and the measured in-situ records were similar to the field test results. On the other hand, the results obtained by the empirical method using the basic properties of sample cores were similar to the laboratory test results.

1. Introduction

1.1. Background and previous studies

Historically, various methods have been employed to evaluate the seismic stability of earth fill dams, such as the pseudo-static sliding surface method, which was typically adopted and regarded as a conservative method. Currently, dynamic numerical analysis is more widely used, because the pseudo-static method cannot appropriately assess the magnitude of earthquakes and certain technical conditions.

For the evaluation of the dynamic behavior of earth fill dams using numerical analysis, it is a prerequisite to determine reasonable input parameters related to the dam materials. The major input parameters used in dynamic deformation analysis are the shear modulus and the damping ratio of the dam materials. Of these two parameters, the shear modulus is closely related to deformation, and in particular, the maximum shear modulus, G_{max} (the modulus below 10^{-3}% of strain level), is considered to be the most important factor [1]. If the shear wave velocity of the ground, V_s is obtained, G_{max} can then be calculated using Eq. (1).

$$G_{max} = \rho V_s^2 \tag{1}$$

where ρ is the density of the material.

Experimental methods to evaluate the shear wave velocity of core materials in a dam are laboratory tests and field tests. The laboratory tests include the resonant column test [2], the bender element test [3], the cyclic triaxial test [4], and others. There are two types of field tests for evaluating the shear wave velocity of dam core materials: methods using boreholes [5,6], such as the down-hole test, the cross-hole test, and suspension PS logging; and seismic methods that do not require boreholes, such as SASW (Spectral Analysis of Surface Waves) [7,8], MASW (Multi-channel Analysis of Surface Waves) [9–11], HWAW (Harmonic Wavelet Analysis of Waves) [12], refraction surveys, and reflection surveys [5].

Studies have been carried out to obtain the shear wave velocities of several dam core materials using one or two field tests and to present the shear wave velocity of the dam core material [13–15]. Furthermore, studies have also been carried out on the evaluation of the shear wave velocities of core materials by conducting different laboratory tests on different core materials [16–19]. In addition, although the target core materials are different, a comparison of the shear wave velocities obtained by field tests with those obtained by laboratory tests was carried out [20]. However, except in the case where the shear wave velocities obtained by the down-hole test were compared with those obtained by

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Table 1
Velocity distribution formulae (Sawada & Takahashi [23]).

Depth (m)	Shear wave velocity in core zone, V_S (m/s)	
	Lower bound	Upper bound
0–5	$V_s = 210$	
5–30	$V_s = 140\ z^{0.34}$	$V_s = 180\ z^{0.35}$
30-		

the cyclic triaxial test [21], there are very few studies in which the shear wave velocities obtained by various field tests were compared with those obtained by various laboratory tests for the same in-situ core material.

In 1970, Hardin and Drnevich [22] presented factors affecting the shear modulus of core materials and recommended the empirical Eq., Eq. (2) by which the maximum shear modulus could be calculated. In Eq. (2), the mean principal effective stress, σ_m' can be determined by a static numerical analysis and the rest of the input parameters can be determined from the results of soil physical characteristic tests such as a moisture content test, liquid limit test, plastic limit test, and the specific gravity test.

$$G_{max} = 14760 \times \frac{(2.973 - e)^2}{1 + e}(OCR)^a(\sigma_m')^{\frac{1}{2}} \tag{2}$$

where G_{max} is the maximum shear modulus in psf, e is void ratio, OCR is over consolidation ratio, a is a parameter that depends on the plasticity index of the soil, and σ_m' is the mean principal effective stress in psf.

In 1975, Sawada and Takahashi [23] recommended empirical formulae (shown in Table 1) for obtaining shear wave velocities in the core zone. These formulae were based on the results of analyses on elastic wave velocities measured from boreholes and the results of analyses of seismograph records, which were measured at different depths within the core zone at the Kinsenyama dam (95 m in height), the Shimokotori dam (107 m in height), and the Niikappu dam (103 m in height) in Japan. At present, because of insufficient data on the dynamic core zone properties of dams, shear wave velocities, which are needed to determine the maximum shear moduli for dynamic analyses, are frequently estimated by the empirical method of Sawada and Takahashi in Korea.

However, because these formulae are based on seismograph records observed at Japanese dams and results of field tests conducted at Japanese dams, which are mostly very large, the formulae need to be verified before they can be applied to dams in other countries, or to mid-to-small dams. Furthermore, as shown in Table 1, the gap between the lower and the upper bound values of the shear wave velocity with depth when the empirical formulae are used is very large, and therefore, evaluations of the shear wave velocity could be arbitrary [13].

1.2. Research scope and objective

In this study, boring and sampling were conducted at the Yeongcheon dam in Korea. Laboratory tests, such as the resonant column test and bender element test, and field tests such as the cross-hole test, MASW, and reflection surveys were carried out on the core materials to evaluate the shear wave velocity. The results obtained by laboratory tests and field tests were compared with each other. Furthermore, the results obtained by these experimental methods were compared with those obtained by the empirical methods.

The objective of this study is to compare shear wave velocities evaluated by laboratory and field tests in the core zone of a fill dam, and to verify the applicability of empirical methods from comparisons of the shear wave velocity evaluated by empirical methods with those evaluated by experimental methods.

Table 2
Basic information about the Yeongcheon dam.

Type	Center-cored rockfill	Altitude of crest	EL. 162.0 m
Height	42 m	Length of crest	300 m
Volume	960,000 m^3	Width of crest	10 m

2. Test outline and basic properties of core materials

2.1. Test outline

Basic information about the Yeongcheon dam is given in Table 2 and a cross section of the dam is shown in Fig. 1. Fig. 2 shows the boreholes and sampling locations, survey path, and the summary of field tests. Table 3 shows the summaries of laboratory and field tests carried out at the Yeongcheon dam. Two boreholes were located at a distance of about 130 m from the left-side abutment and the distance between the two boreholes (BH-1 and BH-2) was 8 m. Because the dam body water level was built at about an 18 m depth from the dam crest due to the reservoir water level, and the depths of BH-1 borehole and BH-2 borehole were limited to 21.45 m and 21.0 m, respectively, to prevent disturbing the stabilized core zone by the boring. Density logging [24] was carried out in two boreholes and undisturbed core samples for laboratory tests were taken from each borehole. The cross-hole test was conducted using boreholes BH-1 and BH-2. MASW and reflection surveys were conducted at the crest of the dam in the longitudinal direction of dam axis.

2.2. Basic properties of core materials

2.2.1. Density logging

To obtain the density profile with depth in the core zone, density logging was carried out in two boreholes located at the middle of the dam crest. The density logging data was obtained by applying the gamma-gamma density logging method [24] using the physical logging system of Robertson Geologging Ltd., England. The depths of density logging conducted in the BH-1 and BH-2 boreholes were 17.6 m and 17.7 m, respectively. The measured densities were substituted into Eq. (1) and used to transform the maximum shear modulus and the shear wave velocity each other. Furthermore, they were used to calculate the void ratio, e, which is a major input parameter of Eq. (2); the procedure by which 'e' is determined is presented in 2.2.2.

Fig. 3 shows density profiles, determined by density logging, of the BH-1 and BH-2 boreholes. From the figure, the densities of the core materials in BH-1 and BH-2 are 2050–2240 kg/m^3 and 1940–2220 kg/m^3, respectively and thus the total average is about 2100 kg/m^3.

2.2.2. Results of basic property test on core materials

Table 4 shows the basic properties of the core materials of the Yeongcheon dam. Based on the results shown in Table 4, the core materials were classified as "CL" i.e. "lean clay", according to the Unified Soil Classification System. The test results shown in Table 4 present the characteristics of core materials and are further used to calculate the void ratio, e, shown in Eq. (2) (the empirical equation of Hardin and Drnevich).

Eq. (3) [25] is useful for solving problems involving soil three-phase relationship.

$$G_s w = Se \tag{3}$$

where G_s is the specific gravity of core soil solids, w is moisture content, and S is degree of saturation.

G_s and w were obtained from the test results, which are shown in Table 4. The dry density of core materials, ρ_d can be calculated using the equation $\rho_d = \rho_t/(1 + w)$ because the density of core soils, ρ_t is obtained from the density logging. Therefore, the void ratio, e can be