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Shear wave velocity profiles of fill dams

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ABSTRACT

The shear stiffness (G_{max}), which is determined from the shear wave velocity (Vs), is an essential parameter in dynamic analyses of fill dams. In this study, Vs profiles were collected and interpreted after comprehensive in situ geophysical seismic surveys of 28 fill dams. The Vs profiles were compared with the empirical formula proposed by Sawada and Takahashi, which was found to overestimate the shear stiffness of a core layer and underestimate that of a shell layer. Regression equations for Vs and G_{max} profiles as functions of effective stress were developed for both the core and shell materials. A regression analysis including the mixed effect model was performed to account for the potential bias of data depending on the material types, survey methods, locations, and repeatability. The presented results will improve the prediction of Vs and the reliability of dynamic analyses of fill dams.

1. Introduction

The seismic safety of large dams under strong excitations is an important issue in terms of dam functionality and their social and economic impacts. The International Commission on Large Dams (ICOLD) has collected statistics on 50,000 large dams, of which approximately 70% are fill dams [1]. Because many fill dams are located in high-seismicity areas and new scientific findings have driven seismic design standards to higher levels, reliable seismic analyses have become increasingly important.

The dynamic analysis of fill dams requires an investigation of the dynamic shear stiffness (G_{max}), which can be determined from the shear wave velocity (Vs) and the density of the soil (ρ) as $G_{max} = \rho\ Vs^2$. Geophysical survey methods are used to obtain the Vs profiles when sufficient funds are available, whereas empirical formulas are often used when field measurements are not available.

Geophysical survey methods can be classified as invasive or non-invasive. Invasive methods, which involve the use of boreholes, include downhole surveys (DHT), crosshole surveys, seismic cone penetration tests (SCPT), and suspension logging. Geophysical seismic wave testing using wave propagation provides estimates of stiffness, damping, and layering characteristics [2]. Non-invasive geophysical survey methods include spectral analysis of surface waves (SASW), multi-channel analysis of surface waves (MASW), harmonic wavelet analysis of waves (HWAW), short-array beamforming (SBF), and seismic reflection surveys. These different survey methods often yield different profiles [3].

In recent engineering practice, in situ Vs profile measurements are preferred to estimate G_{max} [4–7]. DHT, suspension logging, SCPT, and MASW surveying are frequently selected based on cost and time requirements [4–7]. When the field measurements of Vs are not available, the empirical formulas are typically used to determine the shear wave velocity profile [7–12]. However, in dam practice, the use of invasive methods for field measurements of Vs is limited because of the excessive cost and the risk associated with borehole drilling resulting in a potential seepage hazard. Therefore, the available empirical formulas, which are helpful in such cases of lack of adequate data, are limited. Based on this motivation, this study develops empirical formulas for compacted cored fill dams for correlations of Vs (or G_{max}) versus vertical effective stress (σ'_v).

Several studies have provided empirical models to determine Vs for the central core and shell materials. These studies used surface wave seismic surveys of a limited number of fill dams [10–12]. Sawada and Takahashi's empirical formula [4] is widely used to estimate the Vs of fill dams in Japan and Korea when field measurements are unavailable [13,14]. This formula is developed by a limited number of dams using borehole seismic surveys and seismic data analyses of recorded acceleration time histories. Therefore, the application of this formula to different dams requires specific care because the prediction model may range depending on dams, which were not addressed by past studies.

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For instance, the degree of saturation with depth is one factor that may range between dams in the empirical formula. Discrepancies have also been observed between the empirical formula developed in past studies. For example, the model by Kim et al. [10] typically produces greater Vs profiles for the shell layer than for the core layer, while Sawada and Takahashi's [8] formula produces similar trends for both layers. Therefore, it would be beneficial to compare previous empirical formulas with the newly developed model by using recent field measurements.

Correlations between Vs and the penetration resistance have also been proposed [15]. Brandenberg et al. [16], Wair et al. [7], and Kishida and Tsai [17] proposed useful methods for correlating Vs profiles with penetration resistance, using more advanced statistical models. Brandenberg et al. [16] suggested multiple linear regression models by using N and effective overburden stress, and showed that 60% of the total variance of Vs is contributed by the variance between boreholes, indicating the importance of adjusting the correlation models to site-specific conditions. Kishida and Tsai [17] proposed the approach to adjust the Vs correlation models to site-specific conditions based on the conditional probability framework. However, these studies were not specifically intended for compacted-core fill dams, and the use of the correlation requires borehole drilling and penetration tests. Therefore, the development of field-measurement-based empirical correlations of Vs (or G_{max}) versus σ'_v (vertical effective stress) is useful in the analysis of compacted cored fill dams.

In this study, in situ seismic survey data was collected from 28 existing fill dams. Multiple downhole surveys were conducted on the dam crests of 13 earth-core fill dams. The downhole test results were compared with surface wave velocity profiles and profiles obtained using Sawada and Takahashi's empirical formula [8].

This study was based on the four fundamental questions: (1) Are measured Vs profiles obtained for the same dam using different methods consistent or compatible with one another? (2) Are measured Vs profiles consistent with empirically derived profiles? (3) Do Vs profiles measured on a dam crest represent a profile of the core layer exclusively? (4) Can newly developed Vs (or G_{max}) profiles be proposed for each core and shell layer?

As a result, the regression models of Vs and G_{max} profiles were developed for both the core and shell layers. The main features of the newly developed Vs and G_{max} profiles were explored and compared using various seismic survey methods and empirical formulas. More rigorous statistical models (e.g., residual and standard deviation analyses of effective stress-dependent Vs dataset using fixed-effect and mixed-effect models) were introduced for identifying potential bias and uncertainty coming from dams, survey methods, survey locations, and survey repeatability.

2. Dams and geophysical survey procedures

Geophysical surveys were conducted for 28 existing fill dams in Korea. All the dams were built using modern types of construction equipment with fairly good compaction techniques and quality control. Of the 28 dams, 21 were earth-core rock-fill dams (ECRDs) and seven were concrete-faced rock-fill dams (CFRDs). Every ECRD had a central earth core and a granular shell layer. The shell layer was mainly composed of rocks and/or sand and gravel. Such core and shell layers are believed to exhibit significant stiffness contrasts. The CFRDs were composed predominantly of rock-fill and gravel-fill embankments.

Table 1 shows the basic dimensions of the dams, their construction project lengths, the unit weights of the core, and shell layers, and the geophysical survey methods applied. The unit weights of the materials were used in the computation of vertical effective stresses.

Most of the non-invasive geophysical surveys for the ECRDs were conducted on the dam crests to obtain the Vs profiles of the underlying layers. In a few cases, the surveys were performed on the upstream or downstream berms/slopes to measure the Vs profiles of the shell layers. For the CFRD surveys, all the data were used to obtain the Vs profiles of the rock-fill and gravel-fill materials, regardless of the survey location.

Table 1
Basic dimensions and survey methods of the fill dams used in the study.

Dam	Dam type	Project period	H (m)	L (m)	γ_t (kN/m^3)		Survey on dam crest						Survey on shell		
					Core	Shell	DHT	SASW	SBF	MASW	HWAW	Reflection	SASW	MASW	HWAW
GD	ECRD	1985–1989	39.5	292	19	19	O			O					
DB	ECRD	1986–1990	53.5	326	19	19	O			O					
YCN	ECRD	1974–1980	42.0	300	20	20	O			O				O	
AG	ECRD	1968–1971	32.5	223.5	20	20	O			O					
GP	ECRD	2002–2006	35.0	108	19	19	O		O	O		O	O		
WM	ECRD	1985–1994	55.0	407	21	21	O			O				O	
SY	ECRD	1962–1965	46.0	300	20	19	O	O	O	O			O		
DA	ECRD	1968–1969	27.0	318	19	19	O			O					
SA	ECRD	1962–1964	22.0	331	19	19	O			O					
YC	ECRD	1977–1979	24.5	120.0	20	20	O			O					
GC	ECRD	1984–1987	50.0	234.0	20	19	O	O	O	O			O		
SO	ECRD	1974–1978	67.0	437.0	20	18	O			O					
PL	ECRD	2001–2007	37.3	390.5	19	20	O			O					
AD	ECRD	1971–1977	83	612	21	22			O	O			O		O
IH	ECRD	1984–1993	73	515	20	21				O		O			
BR	ECRD	1990–2000	50	291	19	19		O	O	O			O	O	
DC	ECRD	1975–1981	72	495	19	20				O	O				O
JA	ECRD	1984–1992	58	330	18	20		O	O	O					
JAR	ECRD	1984–1996	99.9	562.6	19	19		O	O	O					
SYG	ECRD	1967–1973	123	530	20	20					O				O
HS	ECRD	1990–2002	48.5	205	19	20						O			O
YD	CFRD	1990–2006	70	498	–	20		O	O	O	O				
MY	CFRD	1990–2002	89	535	–	20					O				
DG	CFRD	1999–2005	52	192	–	21				O					
NG	CFRD	1987–2003	34	1126	–	20				O					
BA	CFRD	1990–1996	50	282	–	20				O		O			
ZH	CFRD	1996–2007	53	403	–	21		O	O						
GW	CFRD	2000–2012	45	390	–	21			O						

Note: ECRD = Earth-core rock-fill dam, CFRD = Concrete-face rock-fill dam, γ_t = total unit weight of soil, H = height of dam, L = length of dam.