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Data processing of downhole records in embankment dams to extract insitu modulus reduction curves

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ABSTRACT: Dynamic properties of compacted earth core materials are difficult to measure in the laboratory because of sampling difficulties and the inclusion of larger-size particles. Significant uncertainties exist in selecting the modulus reduction curves of earth core materials in seismic design practice. This study reviews the acceleration time series recorded at multiple earthfill dams in Japan. The study describes the data processing methodology to extract the apparent shear wave velocities between downhole sensors during strong shaking by calculating the wave travel time. The study also describes the calculation of transient shear strains from the difference in displacement time series between sensors by double-integrating filtered acceleration time series. By combing these apparent shear wave velocities and shear strains between sensors, the insitu modulus reduction curves are extracted for earthfill central core materials for selected dams. The results are compared to the empirical models of modulus reduction curves for dam materials.

1 DOWNHOLE TIME SERIES IN EMBANKMENT DAMS

1.1 *Overview*

Aratozawa Rockfill Dam was shaken by the 2008 M6.9 Iwate–Miyagi Nairiku Earthquake. During the earthquake event, the dam experienced minor visible damages, however the shaking caused a severe landslide at the adjacent mountain slope (Kayen et al. 2008). Fujinuma Earthfill Dam was shaken by the 2011 M9.1 Tohoku Earthquake. The dam deformed considerably due to the earthquake's strong shaking and long duration, which caused the reservoir to overtop the dam crest and led to the breaching of the dam (Harder et al. 2011). Therefore, the seismic vulnerability of embankment dams is an important issue in Japan. However, predicting the dynamic response of embankment dams is uncertain, due to the difficulties associated with selecting representative dynamic properties of embankment materials. An example is the uncertainty associated with estimating shear-wave velocities for dam core materials (Park and Kishida 2018a). Also, laboratory-based dynamic tests on sampled embankment materials are often limited (Park and Kishida 2018b). Therefore, modulus reduction curves are generally not obtained from laboratory testing; hence in practice, these properties are determined based on empirical relations.

Recently, downhole seismic arrays have been installed from the foundation to the crest in embankment dams in Japan. A large database has been released by the Japan Commission on Large Dams (JCOLD, 2014) containing acceleration times series recorded at dam crests, dam foundations, and adjacent abutments. Ohmachi and Tahara (2011) and Mogi et al. (2015) showed the usefulness of monitoring embankment dams using downhole arrays by showing how the reduction of wave velocities during the shaking related to the internal damage of embankment dams. By following the past studies, this study also shows modulus reduction data during strong shaking by using the downhole acceleration time series at the foundation and crest from the JCOLD (2014) database. For the apparent V_s, the cross-correlation method (CCM) (Elgamal et al. 1995) and the normalized input–output method (NIOM) (Haddadi and Kawakami 1998) are used. The amplitudes of γ are also calculated from the displacement time series from two sensors by double-integrating the acceleration time series. Representative modulus reduction data are extracted for the embankment core materials by using the apparent V_s and the amplitudes of γ between sensors. These data are compared with empirical models from past studies that are based on the numerical simulation to fit the observed dam responses (Cao et al. 2010, Feng et al. 2010), laboratory test results of dam core materials (Park and Kishida 2018b), and inferred from the downhole time series (Ohmachi and Tahara 2011). The data processing methodology used to calculate the apparent V_s and γ is described in the next section.

1.2 *Data processing methodology*

The JCOLD database includes 191 pairs of three-component downhole time series from 51 embankment dams. These time series have recording stations at the dam foundations and crest, and several stations also record at the middle of the embankment core. From the entire database, nine dams were selected for analysis. Table 1 presents the 27 analyzed acceleration time series from the 9 dams and the earthquakes' names, moment magnitude (**M**), and epicentral distances (R_{epi}). Figure 1a shows the flowchart of the data processing methodology used in this study. Two-component horizontal acceleration time series were analyzed from dam

Table 1. Earthquake catalog for downhole records analyses

Record ID	Dam Name	Year/Month/Date	Earthquake Name	M
1	Aikawa	2003/05/26	South Sanriku	7.1
2	Aikawa	2011/03/11	Tohoku	9.1
3	Aratozawa	1996/08/11	Akita-ken Nairiku Nanbu	5.9
4	Aratozawa	1996/08/11	Miyagi-ken Hokubu	5.7
5	Aratozawa	1996/08/11	Miyagi-ken Hokubu As	4.4
6	Aratozawa	2003/05/26	South Sanriku	7.1
7	Aratozawa	2008/06/14	Iwate-Miyagi Nairiku	6.9
8	Aratozawa	2011/03/11	Tohoku	9.1
9	Aratozawa	2011/04/07	Miyagi Offshore	7.1
10	Hokkawa	2011/03/11	Tohoku	9.1
11	Nishounai	1994/12/28	Sanriku Haruka-oki	7.7
12	Kassa	2004/10/23	Niigata Chuetsu	6.6
13	Kassa	2007/07/16	Niigataken Chuetsu-oki	6.6
14	Kassa	2011/03/12	North Nagano	6.3
15	Kejyonuma	2003/05/26	South Sanriku	7.1
16	Kejyonuma	2005/08/16	Miyagi Earthquake	7.2
17	Kejyonuma	2008/06/14	Iwate-Miyagi Nairiku	6.9
18	Kejyonuma	2011/03/11	Tohoku	9.1
19	Kejyonuma	2011/04/07	Miyagi Offshore	7.1
20	Shichikashuku	2005/08/16	Miyagi Earthquake	7.2
21	Shichikashuku	2011/03/11	Tohoku	9.1
22	Shichikashuku	2011/04/07	Miyagi Offshore	7.1
23	Tadami	2004/10/23	Niigata Chuetsu	6.6
24	Tadami	2004/10/23	Niigata Chuetsu As	5.8
25	Tadami	2004/10/27	Niigata Chuetsu As	5.9
26	Tarumizu	2008/06/14	Iwate-Miyagi Nairiku	6.9
27	Tarumizu	2011/04/07	Miyagi Offshore	7.1

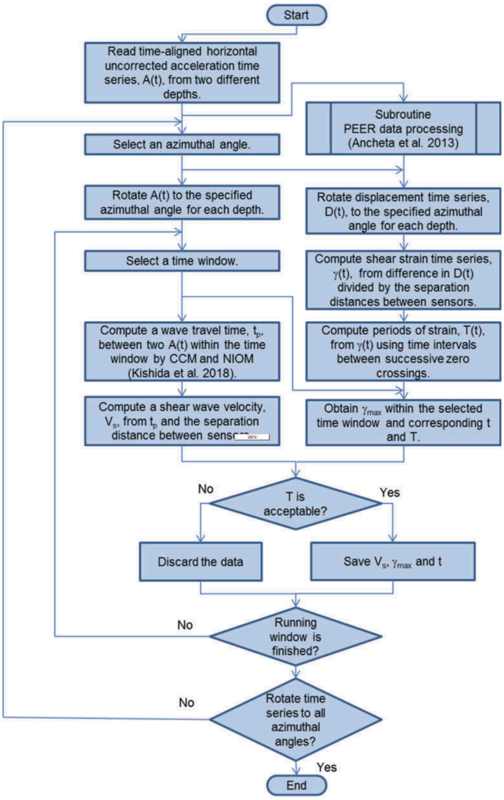

Figure 1a. Data processing flowchart.

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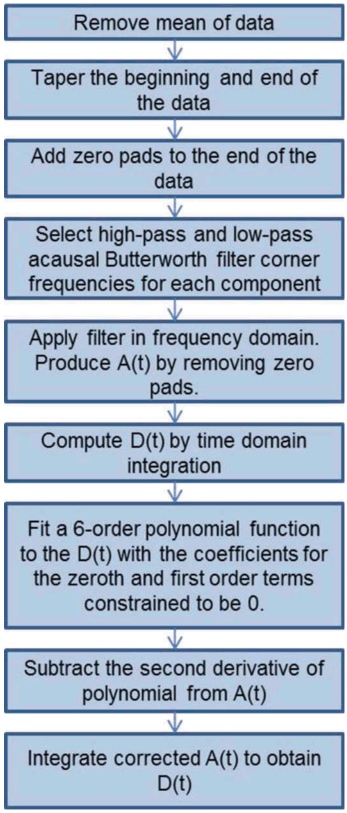

Figure 1b. PEER data processing method to compute displacement time series (Ancheta et al. 2013).

foundation and crests. These time series were rotated to the specified azimuthal angles by following the approach of Boore (2010). V_s travel times between the foundation and crest sensors were calculated by CCM and NIOM following past studies (Elgamal et al. 1995, Haddadi and Kawakami 1998, Kishida et al. 2018). The time windows for analysis were shifted along the time series (i.e., running window). Figure 1b presents the methodology utilized to compute displacement time series by applying filters and baseline corrections by the Pacific Earthquake Engineering Research Center (Chiou et al. 2008, Ancheta et al. 2013, Kishida et al. 2016). The displacement time series was then obtained by double-integrating the baseline-corrected acceleration time series. The time series of γ was calculated by dividing the difference in displacement time series between sensors by a separation distance. Variations in apparent V_s and γ amplitude were obtained during strong shaking by using these approaches.

2 ANALYSIS RESULTS

2.1 *Apparent shear wave velocities and shear strain*

Figure 2 shows the recorded time series at the Kejyonuma Dam crest during the 2008 Iwate–Miyagi Nairiku Earthquake. The PGAs were 0.37 and 0.22 g at stream and dam-axis directions, respectively. Figures 3a and 3b show the variations in apparent V_s and γ and the acceleration time series from 5 s to 40 s, respectively. The time series presented in Figure 3b corresponds to the windowed time series in the stream direction in Figure 2. The figure shows

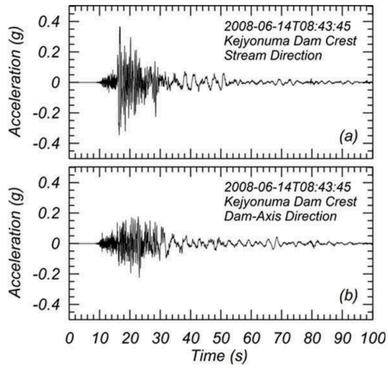

Figure 2. Examples of recorded time series at Kejyonuma Dam

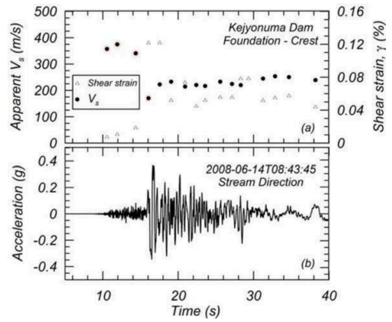

Figure 3. Variation in apparent V_s with time at Kejyonuma Dam between foundations and crests

that apparent V_s decreased and γ increased when the peak acceleration was observed at 16 s. However, these properties increased and decreased gradually as time elapsed after strong shaking.

2.2 *Insitu modulus reduction data*

Shear modulus data extracted from the downhole time series were compared with the laboratory test results. The data were extracted only when the γ amplitude is the maximum compared with the prior strains and the development of pore-water pressure limited before the loading. For example, the data points in Figure 3 with red circles satisfy this condition. The developed excess pore water pressure at t =16 s is considered negligible based on the authors' judgment because the V_s at the previous time window (i.e., t = 14.3 s) did not show any drop compared with the initial values.

Figures 4a and 4b present a comparison between the normalized modulus reduction data for Kejyonuma Dam and Aratozawa Dam, respectively, and the results of the empirical models by Cao et al. (2010), Feng et al. (2010), Ohmachi and Tahara (2011) and Park and Kishida (2018b). The results by Cao et al. (2010) and Feng et al. (2010) are based on the numerical analyses by fitting the dam responses to the observations. The results by Ohmachi and Tahara (2011) were extracted from the downhole time series at Aratozawa Dam as similar to this study. The model by Park and Kishida (2018b) is based on the laboratory experiments from undisturbed dam core samples. The figure shows that the extracted normalized modulus data were different for Kejyonuma and Aratozawa Dams and show dam-dependent characteristics. The inclusion and exclusion of usable/unusable data also provided a different picture and matched the empirical models differently. Therefore, deciding to include or exclude data,

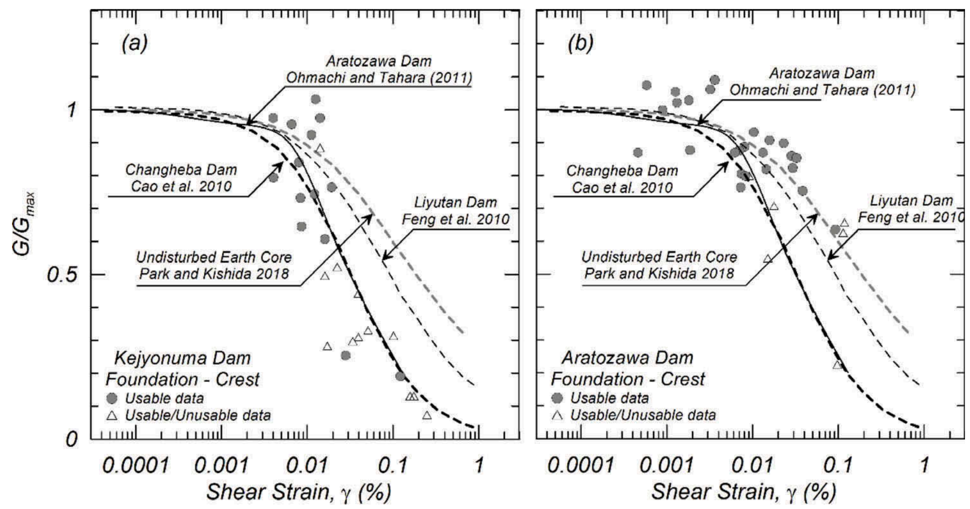

Figure 4. Comparison of G/G_{max} data from downhole records at with empirical curves from the past studies (a) Kejyonuma Dam, (b) Aratozawa Dam.

that are deemed unusable via pore pressure development, requires engineering judgment in accordance with the design objectives.

3 SUMMARY

This study reviewed 27 downhole recordings at nine embankment dams in Japan from 1987 to 2011 to extract the dynamic properties of core materials. The earthquake magnitude and epicentral distance of these recordings ranged from 4.4 to 9.1 and from 15 km to 595 km, respectively. Apparent V_s was computed through running windows between downhole sensors from the wave travel times and separation distances. The wave travel times were obtained with NIOM. Apparent γ time series were computed from the difference in the displacement time series and the separation distances between sensors after double-integrating the processed acceleration time series. The analysis showed that the apparent V_s decreased and γ increased when the peak acceleration was observed. However, these properties increased and decreased gradually as time elapsed after strong shaking. These observations indicate that the instrumentations of downhole arrays are useful and promising in observing the potential degradation of embankment dams by strong shaking, especially when the undisturbed sampling is impossible due to the inclusion of large-size particles in dam embankments.

The apparent V_s and γ were extracted based on the potential influence of excess pore-water pressure. Then, insitu G/G_{max} and G data were calculated with the assumed unit weight. These G/G_{max} data were compared with results of empirical models for compacted dam materials from previous studies. Comparison showed that insitu G/G_{max} data range widely dependent on the dam; hence, the best-fitted empirical model also differs for each dam. Large uncertainties in insitu G/G_{max} data were also observed. These observations show the importance of adjusting the estimated insitu G curves by using insitu observations with their uncertainties.

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