Seismic behavior and numerical simulation of a small-sized earth-fill with bentonite sheet observed in shaking table test

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ABSTRACT

Recently, a bentonite sheet is often employed in deteriorated earth-fill dams for preventing water leakage. However, it is concerned that a slipping type of failure may occur at the boundary between the bentonite sheet and the fill material in the event of seismic attack. In this paper, seismic behavior of a small-sized earth fill model inside which a bentonite sheet was mantled was examined in shaking table test, and it was simulated by numerical analysis. It is manifested in the shaking table test that a shallow slip surface developed in the fill above the bentonite sheet, and no harmful deformation was observed along the bentonite sheet when subjected to seismic motion, noting also that the shallow failure was successfully simulated by pseudo static limit equilibrium analysis. In addition, it was confirmed that the seismic response of the model earth-fill was unaffected by the existence of bentonite sheet as examined by FEM seismic numerical simulations.

Keywords: earth-fill, bentonite sheet, shaking table test, numerical analysis

1 INTRODUCTION

A large number of small-sized earth-fill dams were severely damaged in the preceding events of the 1995 Hyogo-ken Nanbu Earthquake(Fujii et al. 2002), the 2007 Noto Peninsula Earthquake(Mohri et al. 2008) and the 2011 Great East-Japan Earthquake(Hori et al. 2012). It has been pointed out that the damaged earth-fill dams were neither well compacted nor waterproofing(Tanaka et al. 2014). In Hyogo Prefecture, a bentonite sheet having an outstanding waterproofing ability has been used in small-sized earth-fills for improving earthquake resistant. However, it is a concern that a slip type of failure may take place at the boundary of soil and bentonite sheet when the fill is subjected to seismic motion. Accordingly, it is an urgent demand to examine the behavior of a small-sized earth-fill with bentonite sheet against earthquake attack. In this paper, seismic behavior of a small-sized earth fill model inside which a bentonite sheet was mantled was examined in shaking table test. In addition, the seismic behavior was simulated by numerical analysis.

2 OUTLINE

2.1 Shaking table test

A well-graded soil from an earth-fill dam having the mean diameter, \(D_0=0.35\)mm was mixed with poorly graded clean sand with \(D_0=0.3\)mm was employed in the shaking table test, noting that the \(D_0\) of the mixed soil was 1.7mm. The model fill was prepared by compacting the soil to the degree of compaction ranging from 80% to 85%. More details of the shaking table test are described by Tajima et al. (2016).

![Fig. 1. Two cases of shaking table test.](image-url)
Figure 1 shows a couple of shaking table tests performed in this study. Case 1 refers to the test without bentonite sheet, whereas Case 2 with a bentonite sheet mounted in the fill. Figure 2 shows the structure of bentonite sheet employed in this study.

2.2 Numerical simulation

In order to examine the seismic behavior of a small-sized earth-fill with and without the bentonite sheet, 2D-FEM time-history analysis as well as pseudo static limit equilibrium analysis are carried out for the two cases shown in Fig.1.

At first, an eigenvalue analysis using the computer program Plaxis 2D was carried out to find the natural frequencies of vibration of the earth-fill. In the analysis, the soil was modeled as linear elastic. The base of the earth-fill was fixed both in horizontal and vertical directions, whereas the right side is fixed only in horizontal direction. A plastic analysis has been performed in first phase with a static force ($q_p=100kN/m$) acting laterally at the top of left corner of the crest. In the next phase, the free vibration analysis was carried out over the period of 2 seconds after reducing the static force. The time history of horizontal displacement at the top of slope is obtained. Based on this result, the natural frequency was obtained by the corresponding Fourier transform plot.

Second, time history seismic response analysis was carried out by using Plaxis 2D. In this analysis, a sine wave (the frequency, $f=5Hz$) horizontal acceleration data was applied at the base boundary for 8 sec in match with the dynamic motion applied in the shaking table test (Fig 3). The viscous boundaries were used to absorb the stress increments at the boundaries, which may be brought about by the reflected wave of dynamic loading in the base as well as the side boundary of the model. After the plastic analysis for setting the initial stresses of soil model, the dynamic analysis has been performed. The material properties used in this analysis are listed in Table 1.

![Figure 2. Bentonite sheet employed.](image)

![Figure 3. Base input accelerations (sine wave).](image)

A pseudo static limit equilibrium analysis was performed along the circular slip by following the modified Fellenius slice method to compare failure shapes and the factor of safety in COSTANA program. The groundwater condition was not considered. The bentonite sheet was modeled as a solid element, noting that the parameters used in the pseudo static analysis are summarized in Table 1.

### Table 1. Material properties.

|                | Frame | Embankment slope | Bentonite sheet |
|----------------|-------|------------------|-----------------|
| Model          | Linear elastic | Mohr-coulomb     | Mohr-coulomb    |
| $γ_t$ (kN/m$^3$) | 20.0  | 18.5             | 16.0            |
| $γ_{sat}$ (kN/m$^3$) | 21.0  | 19.0             | 18.0            |
| $E$ (kN/m$^2$)  | 100,000 | 5,000            | 15,000          |
| $ν$             | 0.20  | 0.34             | 0.35            |
| $c$ (kPa)       | -     | 0.5              | 15              |
| $φ$ (°)         | -     | 38               | 28              |

Fig. 4. Result of shaking table test (Case 1).

Fig. 5. Results of shaking table test (Case 2).
In summary, there observed no failure along the bentonite sheet, implying the sheet was not a weak layer in the shaking table test. Since compacting the soil on the soft bentonite sheet is not easy, it may be surmised that the degree of compaction of soil adjacent to the sheet was relatively low, which in turn may have brought about the progressive type of failure observed in case 2.

4 DISCUSSION ON NUMERICAL ANALYSIS

4.1 Eigenvalue analysis

The eigenvalue analysis was performed to find out the natural frequency of the model. Figure 6 shows time history of horizontal displacement during the free vibration analysis. Figures 7 and 8 show the results of Fourier transform plot from the time history of horizontal displacement. It was manifested that there observed no difference in terms of the natural frequency for these two cases with and without bentonite sheet. It should be noted that the natural frequency of both cases was approximately 20 Hz.

| Width (m) | Case | Input acceleration (gal) |
|-----------|------|--------------------------|
|           | max. response | top of slope | 1 | 611.50 | 990.64 |
|           | Acceleration  | toe of slope  | 2 | 612.84 | 1017.43 |
|           | ampl. ratio   | top of slope  | 1 | 1.02  | 0.99 |
|           |              | toe of slope  | 2 | 1.02  | 1.02 |

4.2 FEM dynamic response analysis

The time history FEM seismic response analysis was performed in order to examine the response characteristics between the 2 cases. Figures 9 and 10 show time history horizontal response acceleration at the top as well as the toe of slope (0~2sec). The maximum response acceleration, together with the amplification ratio (response acceleration / input acceleration) is summarized in Table 2.

Fig. 9. Horizontal acceleration at the top of slope (0~2sec).

Fig. 10. Horizontal acceleration at the toe of slope (0~2sec).

In this numerical simulation of the small-sized earth-fill in shaking table test, it is verified that the bentonite sheet does not affect the seismic response characteristics. In addition, it should be mentioned that the effect of amplification is insignificant for both the cases. Figures 11 and 12 show the contours of horizontal response acceleration at the instant when the maximum acceleration occurred (t=1.86 s).

Fig. 11. Contours of horizontal response acceleration (Case 1).
4.3 Slope stability analysis

A pseudo static limit equilibrium analysis was carried out to find out the influence of bentonite sheet on the shape of failure surface as well as the factor of safety. In this analysis, seismic coefficient \((k_h)\) varied 0.15, 0.3, 0.6 and 1.0. Table 3 shows the results showing no difference at all for both the cases. Similar to the result of shaking table test, there was no sliding at boundary of ground and bentonite sheet, since the slip surface formed well above the bentonite sheet. Figures 13 and 14 show circular sliding surfaces in the case of \(k_h=0.6\).

![Fig. 12. Contours of horizontal response acceleration (Case 2).](image)

Table 3. Factor of safety.

| Case | Lateral seismic coefficient |
|------|-----------------------------|
| 1    | 1.54 1.19 0.76 0.46         |
| 2    | 1.54 1.19 0.77 0.46         |

![Fig. 13. Circular sliding surface in case 1 (k\(h\)=0.6).](image)

![Fig. 14. Circular sliding surface in case 2 (k\(h\)=0.6).](image)

5 CONCLUDING REMARKS

Seismic behavior of a small-sized earth-fill with bentonite sheet was examined by performing shaking table test, and the results were interpreted by numerical simulation. Despite of a concern for the bentonite sheet acting as a weak layer, there observed no failure along the bentonite sheet when the small-sized earth-fill model was subjected to seismic motion. It was confirmed by pseudo static limit equilibrium analysis. The results of time history FEM seismic numerical simulations exhibited that seismic behaviors; i.e., the natural frequency and response characteristic, were unaffected by the bentonite sheet.

Bearing in mind that these remarks refer to qualitative study by using small-scaled shaking table test without considering ground water condition, the mock up tests, together with numerical simulations are planed in near future.

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