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SEISMIC RISK EVALUATION OF IRRIGATION TANKS: A CASE STUDY IN IBIGAWA-CHO, GIFU PREFECTURE, JAPAN

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ABSTRACT: Landslides are one of earth's most serious types of natural disasters and they are often induced by earthquakes. Predicting the approximate landslide displacements caused by earthquakes is helpful for assessing earthquake hazards and for designing slopes to withstand future seismic shaking. In this research, the authors firstly focus on obtaining the residual strength parameters and the peak strength parameters by multistage procedure with the Bromhead ring shear apparatus, which are used in the slope stability analysis. The maximum vertical settlement (MVS) of a slope is determined by the Newmark method using representative data from three earthquakes, i.e., Great Hanshin Earthquake, Chuetsu Earthquake and Iwate-Miyagi Nairiku Earthquake. It is experimentally demonstrated that the MVS is very large in both Tanigumi Pond and Sugo Pond. Once a great earthquake occurs, the progressive failure phenomenon appears and people living in the area will be in danger. The results presented in this paper can be applied to future landslide hazard assessments and used to promote reconstruction efforts by the government in the affected areas and for future disaster prevention and mitigation.

Keywords: Residual strength parameters; Bromhead ring shear apparatus; Multistage procedure; Earthquake; Newmark method

1. INTRODUCTION

Landslides which cause the loss of human life and the damage to the social economy are always attracted a lot of concerning in modern society. The majority of infrastructural damage and loss of life is ascribed to landslides brought about by great earthquakes. In Japan, there are more than 200 thousand irrigation tanks, many of which were built up to 200 years ago. In addition, due to destructive earthquakes that occur frequently, the sliding phenomenon has been affecting many of these tanks. Once a landslide occurs, it will cause great damage to the economy and people's lives. Moreover, even for the irrigation tanks which do not fail, relative movement takes place in the embankments and the tanks will fail more easily when the next large earthquake strikes. Many scientists [1], [2] have made comparisons between the Newmark method and other methods for slope stability analyses, and have concluded that the Newmark method is better for practical use. In this paper, multistage procedure is applied to getting the residual strength parameters and peak strength parameters by Bromhead ring shear apparatus, which are utilized in the slope stability analysis with the great earthquake data. This paper could provide a seismic risk evaluation of irrigation tanks for the local government from the viewpoint of the MVS by the Newmark method.

2. STUDY AREA AND METHODOLOGY

2.1 Study Area

The samples were taken from Tanigumi Pond and Sugo Pond. Both ponds are located in Ibigawa-cho, Gifu Prefecture, and both irrigation tanks are of the homogeneous type. The dimensions of the tanks are listed in Table 1.

Table 1 Dimensions of irrigation tanks

	Tanigumi Pond	Sugo Pond
Height (m)	12.8	10.0
Crest width (m)	3.2-3.7	4.1
Full water level (m)	10.23	8.01
Water storage capacity (m^3)	37,400	20,000
Saturated unit weight (kN/m^3)	20.7	20.7
Specific density (g/cm^3)	2.63	2.61
Soil type	SF*	F*

*SF: Fine-grained soil mixed sand; F: Fine soil (The Japanese Unified Soil Classification System)

2.2 Methodology

2.2.1 Bromhead ring shear test procedure

Compared with the direct shear apparatus, the main advantage of the torsional ring shear apparatus is that it shears the soil continuously in one direction for any magnitude of displacement. This allows for the full orientation of the clay particles parallel to the direction of shear and the development of a true residual strength condition [3]. To determine the shear strength parameters (residual frictional angle $\emptyset_r$, cohesion C_r in a residual strength situation, peak frictional angle $\emptyset_p$ and cohesion C_p under a peak strength situation), among the multiplicity of ring shear apparatuses reported by scientists [4], [5], the Bromhead ring shear apparatus developed by Bromhead is becoming widely used due to its simplicity in operation, its reasonable cost and its availability compared to previous models. Stark and Eid [6] also showed that the drained residual strength values measured with the Bromhead apparatus are in excellent agreement with the back-calculated values for landslides at Warden Point in the United Kingdom and at a site in Southern California.

At present, there are four main test procedures for measuring the drained residual strength of cohesive soils with the Bromhead ring shear apparatus. These procedures are termed single stage, pre-shearing, multistage and the proposed “flush” procedure. Full descriptions of these procedures can be found in Stark and Vettel [3]. In this research, the multistage procedure is used to obtain the residual strength parameters. The advantage of using multistage procedure is that the residual strength line (left part in Figs.1-4) could be obtained in one day. It can save more time than using other procedures. The main factor affecting the residual strength measured with the Bromhead ring shear apparatus is the magnitude of wall friction that develops along the inner and outer circumferences of the specimen. The farther the top porous stone settles into the specimen container, the more wall friction that develops on the shear plane and the higher the measured residual strength. If the total settlement of the top platen is less than 0.75 mm, the increase in shear stress with continued displacement should not be significant. During the experiment, if the total settlement is over 0.75 mm, the sample has to be recompressed.

In this research, the rate of 0.072 deg/min is selected as the shear displacement rate.

The calculation is performed as follows:

Since the torque arms produce torsion forces F_1 and F_2 , shear resistance τ , induced by torsion moment *M*, is calculated as follows:

$$M = \int_{R_1}^{R_2} r(2\pi r\tau dr) \tag{1}$$

where R_1 is the inside sample radius and R_2 is the outside sample radius.

$$M = 2\pi\tau(R_2^3 - R_1^3)/3 \tag{2}$$

$$\tau = 3M/\{2\pi(R_2^3 - R_1^3)\} \tag{3}$$

$$M = (F_1 + F_2)L/2 \tag{4}$$

$$\tau = 3(F_1 + F_2)L/\{4\pi(R_2^3 - R_1^3)\} \tag{5}$$

where *L* is the distance between the proving rings.

The average displacement, *D*, is calculated as follows:

$$D = R\omega t\,(\pi/180) \tag{6}$$

$$R = (R_1 + R_2)/2 \tag{7}$$

where ω is the rate of displacement (deg/min) and *t* is the time in minutes.

$$D = (R_1 + R_2)\pi\omega t/360 \tag{8}$$

2.2.2 Slope stability analysis

It is possible to determine the amount of slope settlement in a short time because only a few parameters are required for the calculation when using the Newmark method. Many scientists prefer to use the Newmark method when designing irrigation tanks or conducting risk evaluations for irrigation tanks because of this advantage.

The Newmark method [7] is a method for determining the residual displacement on the arc slope surface, for example, on the slope surface of irrigation tanks, and for judging whether the amount of residual displacement falls within the allowable range or not.

The slip circle is determined by the Newmark method when the safety factor of the circular arc is minimized. The movement equation for the mass above the arc is described from D'Alembert's principle, as follows:

$$-J\ddot{\theta} + M_{DW} + k_h M_{DK} - M_{RW} + k_h M_{RK} - M_{RC} = 0 \tag{9}$$

$$J = \sum(J_G + W R_G^2/g) \tag{10}$$

where θ is the rotation angle, J is the moment of inertia, M_{DW} is the sliding moment coming from the self-weight, M_{DK} is the sliding moment coming from the earthquake’s inertial force, M_{RW} is the resistant moment coming from the self-weight, M_{RK} is the resistant moment coming from the earthquake resistance force, M_{RC} is the resistant moment coming from cohesion and k_h is the horizontal seismic intensity. J_G is the polar moment of inertia around the center of gravity, *W* is the weight of the slice, R_G is the distance between the slice’s center of gravity and the center of the arc and g is the acceleration of gravity.

When an earthquake strikes, the equation for safety factor F_s on the arc's sliding surface is

$$F_s = M_R/M_D = (M_{RW} + M_{RC} - k_h M_{RK})/(M_{DW} + k_h M_{DK}) \quad (11)$$

where M_R is the resistant moment and M_D is the sliding moment.

Yield seismic intensity k_y is obtained from horizontal seismic intensity k_h when the condition F_s=1 is met, and the following equation can be obtained:

$$k_y = (M_{RW} + M_{RC} - M_{DW})/(M_{DK} + M_{RK}) \quad (12)$$

When Eq. (12) is substituted into Eq. (9),

$$\ddot{\theta} = (k_h - k_y)(M_{DK} + M_{RK})/J \quad (13)$$

Based on the observed acceleration waveform, residual rotation angle θ can be calculated with a numerical integration which starts from a point exceeding yield seismic intensity k_y . The integration of rotational acceleration $\ddot{\theta}$ is calculated until rotational speed $\dot{\theta}$ becomes 0.

By successive integrations, rotation angle θ can be obtained. Residual displacement S, residual rotation angle θ and arc radius R are related as seen in the equation below:

$$S = R\theta \quad (14)$$

A seismic risk evaluation of an irrigation tank is analyzed by the Newmark method with representative data from three earthquakes, i.e., Great Hanshin Earthquake, Chuetsu Earthquake and Iwate-Miyagi Nairiku Earthquake. To analyze the seismic components, the NS and EW components are taken into consideration. "1" and "-1" refer to different directions. In detail, the "NS, 1" component means that the direction of acceleration is to the north. Conversely, the "NS, -1" component means that the direction of acceleration is to the south. Similarly, the "EW, 1" component means that the direction of acceleration is to the east. The "EW, -1" component means the direction of acceleration is to the west. For every earthquake, data from many stations are acquired. In this study, data from Kobe Station are used for the Great Hanshin Earthquake, data from Ojiya Station are used for the Chuetsu Earthquake and data from Kurihara Station are used for the Iwate-Miyagi Nairiku Earthquake. The data are shown in Figure 6 and can be downloaded from the Japan Meteorological Agency webpage [8].

In addition, the crest width in Tanigumi Pond varies from 3.2 m to 3.7 m. The safety of an irrigation tank increases as the crest width increases. Therefore, the authors will analyze the slope using a crest width of 3.7 m, and try to find out how much the MVS will be from the viewpoint of safety.

3. RESULTS

3.1 Residual Strength Parameters

In Figs. 1-4, the residual strength has been reached for each sample by multistage procedure. The shear strength envelope is shown on the right side of every figure; it is obtained from the data which could be obtained in one day for each sample on the left side. Except for the Tanigumi Pond saturated sample, it can also be noticed that the deformation to peak strength is significantly small. The peak strength is reached at a shear displacement of less than 5 mm, while the residual strength is reached at a shear displacement of nearly 30 to 40 mm. In Table 2, it is seen that the residual frictional angle and the cohesion of the unsaturated (US) samples from Tanigumi Pond and Sugo Pond are all lower than those of the saturated (S) samples.

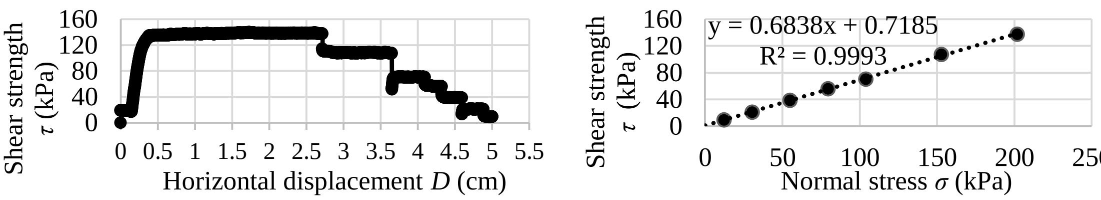


Fig.1 Shear strength vs. horizontal displacement and shear strength envelope in Tanigumi Pond soil (S)

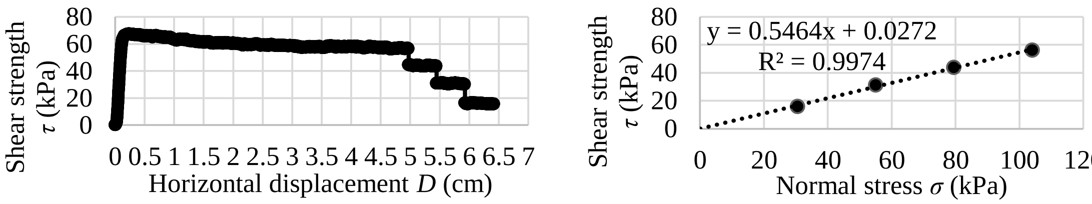


Fig.2 Shear strength vs. horizontal displacement and shear strength envelope in Tanigumi Pond soil (US)

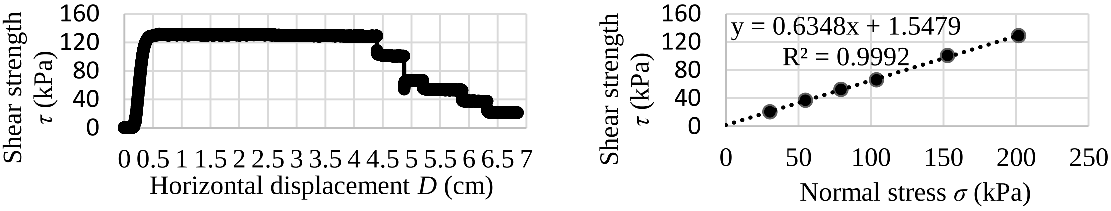


Fig.3 Shear strength vs. horizontal displacement and shear strength envelope in Sugo Pond soil (S)

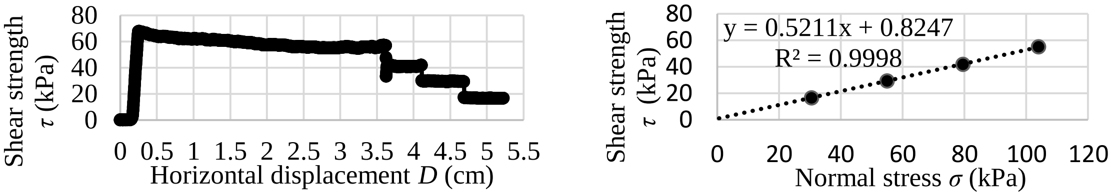


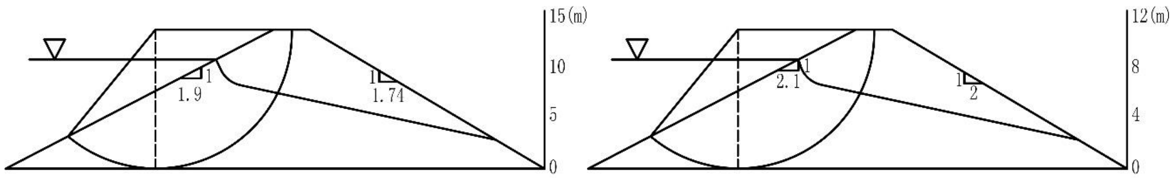
Fig.4 Shear strength vs. horizontal displacement and shear strength envelope in Sugo Pond soil (US)

Table 2 Results of Bromhead ring shear tests

	Tanigumi Pond		Sugo Pond	
Water condition	S	US	S	US
ϕ_r (°)	34.4	28.7	32.4	27.5
C_r (kPa)	0.7	0	1.5	0.8
ϕ_p (°)	36	36	32.5	31.7
C_p (kPa)	13	13	2.1	4.0

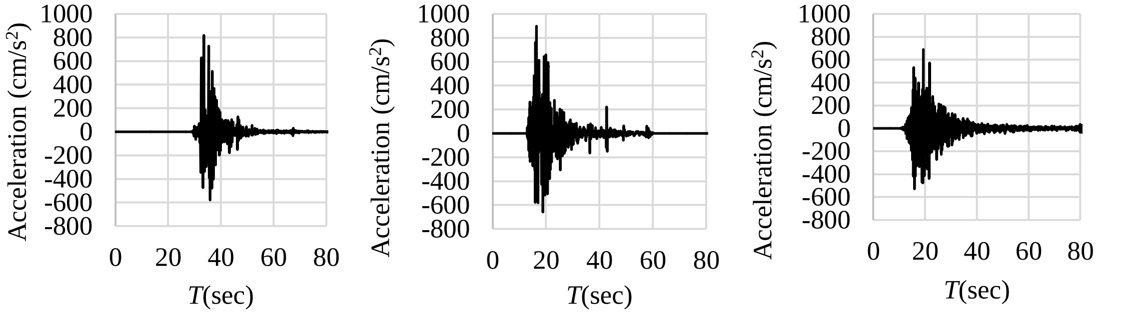
3.2 Slope Stability Analysis

Figure 5 shows a schematic diagram of the irrigation tanks and slip circles. In the slope stability analysis results, only the representative figures for the MVS are input here for the earthquake data for each irrigation tank shown in Table 3 and Figs. 6-7. It is clear that in Tanigumi Pond, the MVS for the Great Hanshin Earthquake is obtained at 86.1 cm in the south direction; the MVS for the Chuetsu Earthquake is obtained at 88.2 cm in the west direction; the MVS for the Iwate-Miyagi Nairiku Earthquake is obtained at 31.5 cm in the east direction. Similarly, in Sugo Pond, the MVS for the Great Hanshin Earthquake is obtained at 62.3 cm in the south direction; the MVS for the Chuetsu Earthquake is obtained at 59.8 cm in the west direction; the MVS for the Iwate-Miyagi Nairiku Earthquake is obtained at 22.3 cm in the east direction. It is found that the MVS of each irrigation tank obtained with the Newmark method is very large when a great earthquake strikes.



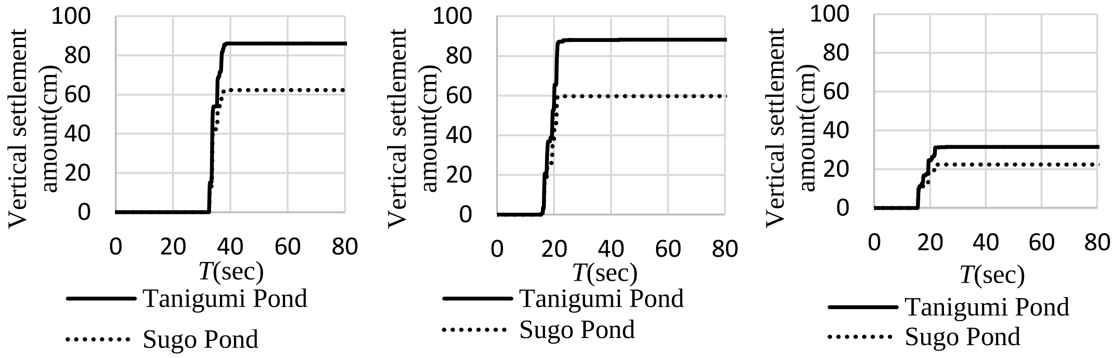
(a) Tanigumi Pond (a) Sugo Pond

Fig.5 Schematic diagram of irrigation tanks and slip circles



(a) Great Hanshin Earthquake (NS) (b) Chuetsu Earthquake (EW) (c) Iwate-Miyagi Nairiku Earthquake (EW)

Fig.6 Input acceleration



(a) Great Hanshin Earthquake (NS) (b) Chuetsu Earthquake (EW) (c) Iwate-Miyagi Nairiku Earthquake (EW)

Fig.7 Vertical settlement amount by Newmark method

Table 3 Results of slope stability analyses for each earthquake type

	Yield seismic coefficient k_y		Safety factor F_s	Safety factor F_{se}*	Seismic component	Earthquake type	MVS S (cm)
Tanigumi Pond	Peak strength k_{yp}	Residual strength k_y			NS,-1	Great Hanshin Earthquake	86.1
	0.42	0.17	2.80	1.79	EW,-1	Chuetsu Earthquake	88.2
					EW,1	Iwate-Miyagi Nairiku Earthquake	31.5
Sugo Pond	0.31	0.21	2.44	1.17	NS,-1	Great Hanshin Earthquake	62.3
					EW,-1	Chuetsu Earthquake	59.8
					EW,1	Iwate-Miyagi Nairiku Earthquake	22.3

* F_{se} is the safety factor when k equals to 0.15.

4. DISCUSSION

4.1 Residual Strength

Many scientists agree that both the residual frictional angle and the cohesion will decrease with an increasing water content in common soil. However, it is found that the residual strength parameters (residual frictional angle and cohesion) of saturated samples are higher than those of unsaturated samples in each soil from Tanigumi Pond or Sugo Pond. The difference in soil texture may perhaps come from the irrigation tank and the degree of compaction during the ring shear tests. Future work should be done to illuminate this relationship.

4.2 Slope Stability Analysis

There are many soil settlement or subsidence failures in the world [9], [10]. As for the permissible amount of displacement for a high embankment, no clear permissible range has yet been established. Tokida *et al*. [11] took the Chuetsu Earthquake and the Iwate-Miyagi Nairiku Earthquake as references and presented evaluation criteria for the seismic performance of road embankments. Their rank classification has four stages. In rank 1, if the MVS is less than 2 cm, safety can be ensured and it is feasible for cars and people to pass. In rank 2, if the MVS is more than 2 cm and less than 25 cm, the slope surface does not appear on the roadway portion as it will stop on the shoulder. It would not be good to travel along the road, but it is relatively easy to ensure safety. In rank 3, if the MVS is more than 25 cm and less than 50 cm, and the slope surface appears on the road, it is somewhat difficult to ensure safety. In rank 4, if the MVS is more than 50 cm, it is difficult to perform emergency restoration and the road must be closed.

Therefore, from the data on slope stability analyses for Tanigumi Pond and Sugo Pond, the MVS for every tank has been obtained as more than 20 cm when a great earthquake occurs. In some cases, the MVS is even more than 50 cm, which means the safety of the irrigation tank cannot be ensured.

In addition, for Tanigumi Pond, the height from the crest to the full water level is 2.57 m, but when a great earthquake strikes, the MVS is about 90 cm. And for Sugo Pond, the height from the crest to the full water level is only 1.99 m, but when a great earthquake strikes, the MVS is more than 60 cm, which is more dangerous.

5. CONCLUSIONS

In this study, multistage procedure is used to obtain the residual strength parameters and peak strength parameters by Bromhead ring shear apparatus, which are used in slope stability analysis with the great earthquake data. Besides that, residual strength line could be acquired with each sample only in one day when the multistage procedure was used.

Based on the above study, the following conclusions have been obtained:

(1) The peak strength can be reached at a shear displacement of less than 5 mm. The residual strength is reached at a shear displacement of nearly 30 to 40 mm.

(2) The amounts of vertical settlement obtained from slope stability analyses using the Newmark method are very large in both Tanigumi Pond and Sugo Pond. When a great earthquake strikes, the situation will be dangerous for all irrigation tanks and for the people who live in the area if the progressive failure phenomenon appears.

The results could be applied to future landslide hazard assessments and used to promote reconstruction efforts in the affected areas. In fact, many people live in the downstream area around Tanigumi Pond. Therefore, Tanigumi Pond has been under repair. On the other hand, few people live in the downstream area around Sugo Pond. Thus, no repair work has been carried out there. However, when the stability and the controllability of the stream are taken into consideration, it is recommended that repair work be done as soon as possible.

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