

AN EXPERIMENTAL STUDY ON THE SEISMIC BEHAVIOR OF EMBANKMENTS ON PEATY SOFT GROUND THROUGH CENTRIFUGE MODEL TESTS

Takuya EGAWA¹, Satoshi NISHIMOTO², and Kouichi TOMISAWA³

SUMMARY

Although peaty soft ground (simply referred to as peat ground) covers extensive areas of Hokkaido, Japan, embankments constructed on peat ground are considered vulnerable to damage during earthquakes. There have been a few cases, however, in which the seismic behavior of such embankments has been systematically analyzed owing to the lack of observation data. A model embankment on peat ground was therefore constructed, and its seismic behavior was investigated through a series of centrifuge model tests. The test program was arranged for clarifying the effects of the following factors on the seismic behavior of the embankments: (a) thickness of peat ground, (b) height of embankment, and, (c) frequency and acceleration level of the input motion. Main results of this experimental study are summarized as follows:

1) When the frequency of the input motion conformed to the natural frequency of peat ground, lateral deformation and settlement of peat ground progressed due to a high acceleration response in peat ground.

2) Thinner peat ground or higher embankments (larger effective confining pressure on the peat ground) resulted in a high acceleration response in and larger deformation of the peat ground.

3) It was confirmed that the initial shear modulus of peat, obtained from the cyclic triaxial tests by varying effective confining pressure, was dependent on the mean effective principal stress. The above acceleration response characteristics were considered to be dependent on the initial shear modulus of the peat ground.

4) When lower level acceleration of the input motion was applied, the acceleration response rate in peat ground was high, higher level input motion, conversely, resulted in low acceleration response rate in peat ground. It was believed that the acceleration response characteristics were caused by the change of the shear modulus with the shear strain level. The initial shear modulus decreased to approximately 1/3 to 1/10 when the range of shear strain level that occurred in peat ground was 10^{-2} to 10^{-1} , while it nearly kept no change when the shear strain level was less than 10^{-4} .

¹ Researcher, Civil Engineering Research Institute of Hokkaido, Japan. Email: ta-egawa@ceri.go.jp

² Director, Civil Engineering Research Institute of Hokkaido, Japan.

³ Researcher, Civil Engineering Research Institute of Hokkaido, Japan.

INTRODUCTION

No more attention has been paid to seismic design for road embankments, river dykes and other banking structures thus far because these structures usually be considered to be strong to a certain extent during earthquakes. Several large earthquakes that occurred in the 1990s, however, caused serious damage to such banking structures, and weakened their original functions. Today, banking structures have to secure communications, electricity, water supply, gas and other lifeline facilities as essential functions. Under these circumstances, it is needed that banking structures have to strongly resist to earthquakes, and seismic performance of such structures have also been examining [1]. Several major earthquakes that occurred in Hokkaido caused large-scale collapse of banking structures [2~5]. For example, Tokachi-oki Earthquake in 1968 and Kushiro-oki Earthquake in 1993 featured the collapse of river dykes constructed on peat ground and road embankments constructed on swampy or catchment terrains, respectively.

Under such background, studies have been conducting by the authors, aiming at understanding seismic behavior of banking structures during earthquakes, through dynamic centrifuge modeling techniques, and obtaining information concerned with the improvement of seismic performance of such structures. To establish a reasonable seismic design method requires comprehensive understanding of the actual behavior of the peat grounds and embankments during earthquakes. Actual damage cases and reports indicate that embankments constructed on peat ground, which is peculiar to Hokkaido, Japan are vulnerable to damage during earthquakes. There are few cases, however, in which the acceleration response and pore water pressure etc. have been observed. In a recent case study [6, 7] on stability evaluation of earth embankment at swamp terrains where seepage water existed during earthquake, several phenomena could not be properly explained, are supposed as that there was some possibility that peat layers existing at the toe of slopes were involved in the collapse of such embankments.

This paper reports the findings acquired from dynamic centrifuge model tests on the seismic behavior of peat ground and embankments constructed on it for the parameters of thickness of peat ground, height of embankment, and, frequency and acceleration level of the input motion.

CENTRIFUGE MODEL TEST

Model scale and test procedure

In the test, excitation using sine waves was performed at a 50G centrifugal acceleration field (G=9.81 m/sec², gravitational acceleration) by preparing 1/50 scaled peat ground and embankment models in a rigid model container with inner size of 700 mm in width, 350 mm in height and maximum 200 mm in depth. Figure 1 illustrates the configuration and instrumentation of the test model.

Model peat ground

For preparing the peat ground model, a saturated sand layer with a relative density larger than 90% was compacted using Toyoura silica sand with maximum particle size of 425 μ m as the model base ground and also the bottom drainage condition for the model peat ground during consolidation. A composite material of commercially available peat-moss for horticulture purposes, which passed a sieve with 850 μ m opening, and Kaolin clay with a dry weight ratio of 1:1 was then mixed in slurry state with an initial moisture content of approximately 600%, as the model material for the peat ground. The peat ground preparation was followed by self-weight consolidation at a 50G centrifugal acceleration field. During consolidation surcharge loading was applied until the final pressure of 50 kN/m² in three stages to strengthen the peat ground to prevent static destruction after the installation of embankments. Since the coefficient of consolidation in the initial situation was high at around 30000 cm²/day, the primary

consolidation was supposed ended immediately. Surcharge loading was applied for 15 minutes in each stage, including the self-weight consolidation, during which pore water pressure mostly became hydrostatic pressure, at a 50G centrifugal acceleration field and the loading time in the final stage was set as 30 minutes.

Physical properties of model peat ground material were described in comparison with those of the representative peat in Hokkaido [8] in Table 1, and it shows mostly equivalent to those of the representative peat. Figure 2 shows the results of cyclic triaxial tests which were conducted to characterize the dynamic deformation properties of model peat ground by varying effective confining pressure. As shown in this Figure, the initial shear modulus was dependent on the effective confining pressure, i.e. the higher the effective confining pressure, the higher the initial shear modulus. Results of the cyclic triaxial tests for the model peat ground and the calculated values by using the following empirical formula proposed by Noto et al. [9, 10, 11] for estimating dynamic deformation characteristics of peat ground in the Hokkaido area, were also compared, and the validity of the model peat ground material was verified.

Empirical formula for estimating dynamic deformation characteristics of peat is as follows:



Fig. 1 Model configuration and instrumentation

	Table 1	Properties	of the mode	el peat ground	l and typical	peat in 1	Hokkaido J	apan
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Item	Model peat ground	Peat ground in Hokkaido
Particle density $\rho_s(g/cm^3)$	2.07	1.3~2.1
Compression index C _c	3.72	2.6~5.3
Cone index $q_c (kN/m^2)$	103~311	100~300
Moisture content W (%)	211~311	115~1150
Wet density $\rho_t (g/m^3)$	1.04	0.95~1.12

where G: shear modulus (kN/m²), G_0 : initial shear modulus (kN/m²), γ shear strain, γ_r : reference shear strain at $G=G_0/2$, h: damping ratio, h_{max} : maximum damping ratio (=0.23), W_c : moisture content (%), σ_c ': average effective confining pressure (kN/m²).

$$G_0 = 1.37 \times 10^4 W_c^{-0.67} \left(\sigma_c \right)^{0.55}$$
(2)

$$\gamma_r = 7.01 \times 10^{-6} W_c \left(\sigma_c \right)^{0.42}$$
 (3)

Figure 3 shows a comparison between the results of the cyclic triaxial tests and the prediction values according to the above empirical formula. As shown in the figure, as for the test values of the initial shear modulus, the calculated values by using the empirical formula are approximately twice higher. They are identical in terms of the changing trend with the effective confining pressure. The reference shear strain showed no dependency on the effective confining pressure. Nevertheless, it matched the calculated valuess based on the empirical formula. The model peat material that was used for experiments can therefore be considered to have representatives and be reasonable as an experimental model material.



Fig. 2 Test results of cyclic triaxial test for model peat ground



Fig. 3 Comparison between test results and calculated values based on empirical formula

Model embankment

Model embankments were prepared by adjusting the composite material that consisted of Toyoura silica sand and Kaolin clay as the embankment material at a dry weight ratio of 8:2 up to the optimum moisture content and with the degree of compaction Dc=85% and 1:1.0 in the inclination of the slope. The model embankment was compacted in a rigid container with the same inner size as the model container then installed on peat ground where consolidation was completed in a non-disturbing manner. Table 2 shows the physical properties of embankment material and strength parameters at Dc=85% compaction conditions.

In dynamic centrifuge model tests, fluid with N times' viscosity of water (N: model scale ratio) is generally used as pore fluid according to similarity law. In this test, however, attention was mainly focused on earthquake propagation in peat ground rather than other phenomenon such as liquefaction etc, and considering the changes in properties caused by mixing model peat material and viscous fluid such as silicon oil etc., water was used as the pore fluid for both peat ground and embankment.

Test conditions

Table 3 shows the test conditions with the frequencies of input motions. This test program aimed to characterize the impact of changes in effective confining pressure in peat ground, which was caused by the construction of embankments on peat ground, as well as changes in peat ground thickness, on seismic behavior of peat ground and embankments during earthquakes. Taking these purposes into account, the thickness of peat ground and height of embankments were determined as shown in the table. It had been made clear that the acceleration response in peat ground changed depending on the frequency of the input motion and that the input motion with the natural frequency of the model peat ground resulted in larger deformation of the peat ground and embankment in previous experimental studies conducted by Egawa [12]. Therefore, in this test the natural frequencies for different thickness of model peat grounds were used as the input frequencies respectively, which were determined from the preliminary tests.

As the excitation condition of the input acceleration level, approximately 60 gal, 140 gal and 200 gal, were set for the step-up excitation, and the interval time for the next excitation was determined after confirmation that the exceed pore water pressure had dissipated and become hydrostatic pressure.

Particle density	$\rho_{\rm s}({\rm g/cm}^3)$	2.64		
Compaction properties	$\rho_{\rm dmax}$ (g/cm ³)	1.87		
compaction properties	Wopt (%)	11.0		
Wet density	$\rho_t (g/m^3)$	1.77		
Strength parameters at	C' (kN/m ²)	1.96		
Dc=85%	φ' (degree)	26.2		

Table 2 Properties of embankment material

Test case	Thickness of peat	Height of	Effective pressure at the	Frequcency of input		
	ground (m)	embankment (m)	embankment base $\sigma_c'(kN/m^2)$	motion (Hz)		
CASE1	10.0	2.5	35.7	1.2		
CASE2	5.0	2.5	32.3	1.5		
CASE3	2.5	2.5	30.6	1.5		
CASE4	2.5	5.0	59.5	1.5		

Table 3Test conditions

TEST RESULTS AND DISCUSSION

Seismic behavior of peat ground and embankments caused by differences in thickness of peat ground and effective confining pressure in peat ground was examined after analyzing the results of each experiment. Since the wave of the acceleration response is always not symmetric to the time axis, the maximum and minimum values of response acceleration wave were read and the mean value was calculated as the acceleration response level. In addition, measured values for the accelerometer A0 on the surface of base sand ground were regarded as input acceleration in date analysis.

Deformation of peat ground and embankments

As an excitation-induced deformation case of the peat ground and embankment, Figure 4 shows the deformation after the final excitation for CASE1. The deformation of the model may have caused the relative settlement and deformation of embankment, following the settlement and lateral expansion of the central area of the peat ground. Embankments constructed on peat ground showed deformations generally such manner during earthquakes.

Figure 5 shows the relationship between the input acceleration for each case and the accumulate settlement values in the center of embankment crest in prototype scale. Due to differences in thickness of peat ground settlement trends did not show wide disparities when input acceleration level was low, but the thinner the peat thickness, the greater increase in settlement value. At the high level input acceleration stage, the tendency is reversed, i.e. the thicker the peat ground, the higher the settlement value. In CASE4, since high effective confining pressure is applied and the initial shear modulus is considered to be the highest, the settlement trends are higher than other test cases from the first excitation.



Fig. 4 Deformation of the embankment and peat ground after excitation



Fig. 5 Settlement of the embankment crest (L1) versus input acceleration relationship (in prototype scale)

Figure 6 shows the recorded time history for each sensor at the centre line of the model when input acceleration level for CASE1 is approximately 210 gal. The figure confirmed that no major phase lag was recognized in each sensor level and settlement progressed with amplitude. In addition, the acceleration response amplitude significantly magnifies at the central depth of peat ground (A1), and major amplitude changes were not observed in embankment. These tendencies are the same as those for other test cases, and the deformation diagram suggests that compressive settlement of embankment itself is small and peat ground settled in conjunction with the amplitude of the acceleration response.

Acceleration responses in peat ground

Figure 7 shows the comparison of the acceleration response in peat ground for each case, and the data was calculated as the acceleration response rate referring to the input acceleration level. The figure confirmed the magnifying tendency of the acceleration response in peat ground, in particular, in the central depth of peat ground for each test case, despite the fact that there are disparities in the response rate. Differences in magnifying tendencies of the acceleration response in peat ground in each case are prominently observed when the input acceleration level is low (approximately 60 gal). The thinner the peat ground is, the more the acceleration response magnifies. Even if surcharge of embankment applied on peat ground is at the same level in CASE1~3, the different thicknesses of peat ground cause differences in the scope of influence exerted by the surcharge of embankment, and then resulted in different initial shear modulus of the peat ground due to the different effective confining pressure. In addition, the largest acceleration response rate occurred in CASE4, where the effective confining pressure is high and then the initial shear modulus is large. It is thus considered that the acceleration response in peat ground is dependent on the initial shear modulus. Furthermore, when excitation with its increased input acceleration level was accumulated, the acceleration response rate in peat ground showed decreasing tendencies.

Changes in acceleration response characteristics due to different input acceleration level

Figure 7 showed the tendencies of the acceleration response to decrease as the input acceleration level escalated, because the acceleration response rate in peat ground is large when the input acceleration level is low. The next sections aim to clarify the changes in the acceleration response in peat ground, due to differences in the input acceleration level for each test case.

Figure 8 shows the relationships between the input acceleration response of each case, the acceleration response at the central depth of peat ground and the average shear strain that occurred in peat ground. Since there was no major phase lag in the acceleration response time history in the peat ground, as shown in Figure 6, the frequency of the acceleration response is considered to be constant. The aforementioned average shear strain was evaluated by dividing the relative shear displacement response at the central depth of the peat ground to the surface of base sand ground that was calculated by integrating twice the accelerations measured at the respective locations, with the distance between the central depth of peat ground and the surface of the base sand ground.

The figure clearly shows the tendency for the acceleration response in peat ground to decrease by accumulating the excitation with an increased input acceleration. The degree is high in the order of the size of the initial shear modulus in peat ground, except for CASE2. This is considered attributable to the fact that the larger the acceleration response magnification in peat ground, the greater the shear strain that occurs in peat ground.

As shown in Figure 2, according to the result of the cyclic triaxial test for σ_c '=58.8 kN/m², which corresponds to the effective confining pressure on the peat ground in CASE4, the initial shear modulus decreased to approximately 1/10 when the range of shear strain level that occurred in the peat ground of CASE4 was 10⁻¹.



Fig. 6 Time history of the response acceleration and settlement at the center line of the model for CASE1



Fig. 7 Acceleration response rate of the peat ground to the input acceleration at the base ground



(a) Shear strain response versus input acceleration



(b) Acceleration response versus input acceleration

Fig. 8 Relationship between the response acceleration and shear strain at the central level of peat ground and the input acceleration

Accordingly, the result of the cyclic triaxial test for σ_c '=29.4 kN/m², which corresponds to the effective confining pressure in the peat ground in CASE1~4, shows that the initial shear modulus decreased to approximately 1/3 to 1/10 when the range of shear strain level was 10⁻² to 10⁻¹ (see Fig. 2). Therefore, the decline of the acceleration response in peat ground, which is caused by the increased input acceleration level, is attributable to the decline in conformity with the level of shear strain whereby shear modulus of peat ground occurs in ground.

It was considered that the higher effective confining pressure and initial shear modulus a case has, the higher the degree becomes. These relations become compliant with those of lateral deformation and settlement of peat ground, which were caused by excitation.

CONCLUSION

Through the dynamic centrifuge model tests on the seismic behavior of peat ground and banking structures constructed on the peaty soft ground for the parameters of thickness of peat ground, height of embankments, and, frequency and acceleration level of the input motion. The following findings were acquired.

1) In the excitation-induced deformation of peat ground and embankments, relative settlement and deformation of embankments occurred due to the settlement and lateral deformation in the softening of the seismic response of peat ground. The tendency became marked in cases with a large acceleration response in peat ground.

2) The acceleration response in peat ground tends to magnify significantly in the central depth of the ground, and the acceleration response rate depended on the initial shear modulus of the peat ground. Cases with higher effective confining pressure acting on peat ground showed larger response rates.

3) The higher the initial shear modulus of the peat ground, the more prominent the decline of the acceleration response in the peat ground, which is caused by a larger input acceleration response. It is supposed that this was caused by the decrease of the shear modulus of the peat ground in response to the shear strain level induced in the peat ground. It was also considered as the dominant factor for deformation behavior of peat ground and embankments during earthquakes.

REFERENCES

- 1. Japan Road Association "Guidelines for Road Earth Works–Slope Works." Slope Stability Works, pp.173-180, 1999.
- 2. Development and Civil Engineering Experiment Station of Hokkaido "Damage Investigation Report on the 1968 Tokachi-oki Earthquake." Development and Civil Engineering Experiment Station Report No. 49, pp.9-24, 1968.
- 3. Civil Engineering Research Institute of Hokkaido "Damage Investigation Report on the 1993 Kushiro-oki Earthquake." Civil Engineering Research Institute Report No. 100, pp.13-40, 1993.
- 4. Civil Engineering Research Institute of Hokkaido "Damage Investigation Report on the 1993 Hokkaido Nanse-oki Earthquake." Civil Engineering Research Institute Report No. 101, pp.21-40, 1994.
- 5. Civil Engineering Research Institute of Hokkaido "Damage Investigation Report on the 1994 Hokkaido Toho-oki Earthquake." Civil Engineering Research Institute Report No.108, pp7-24, 1995.

- 6. Takuya Egawa, Junichi Nishikawa, Hirochika Hayashi "Dynamic Centrifugal Model Experiment concerning the Stability of Road Embankments during Earthquakes." Proc. of the 26th JSCE Earthquake Engineering Symposium, pp.689-692, 2001.
- 7. Takuya Egawa, Junichi Nishikawa, Hirochika Hayashi "Stability Evaluation of Road Embankments to be Affected by Seepage Water during Earthquakes." Civil Engineering Research Institute Report No.582, pp.20-26, 2001.
- 8. Civil Engineering Research Institute of Hokkaido "Manual for Countermeasure Works for Peaty Soft Ground." Hokkaido Development Engineering Center, pp.1-6, 2002.
- 9. Shigeyuki Noto, Moriaki Kumagai "Experimental Research on Dynamic Deformation Characteristics of Peat (a)." Development and Civil Engineering Experiment Station Report No.393, pp.12-21, 1986.
- 10. Shigeyuki Noto, Yasuhiko Kajiya "Experimental Research on Dynamic Deformation Characteristics of Peat (b)." Development and Civil Engineering Experiment Station Report No.406, pp.14-24, 1987.
- 11. Yasuhiko Kajiya, Shigeyuki Noto "Experimental Research on Dynamic Deformation Characteristics of Peat (c), Seismic Response Characteristics of Peat Ground." Development and Civil Engineering Experiment Station Report No.418, pp.1-9, 1988.
- 12. Takuya Egawa, Junichi Nishikawa, Hirochika Hayashi "Centrifuge Model Test concerning Seismic Behavior of Peaty Soft Ground on which Embankments were Constructed." Proc. of the 11th Japan Earthquake Engineering Symposium, pp.959-962, 2002.