Seismic analysis based on results of the laboratory shaking table tests for the dam-model

Masakazu Matsuura[1,a], Hiroyuki Ieda[1,b], Hidekazu Tagashira[2,c], Seiichi Sato[3,d]

[1]*Head Office, NTC Consultants Co.,Ltd., Japan, Nagoya, Japan*

[2]*Division of Facilities and Geotechnical Engineering, National Institute for Rural Engineering, Nagoya, Japan*

[3]*Domestic Consulting Operations, Nippon Koei Co., Ltd., Japan, Tokyo, Japan*

[a]m.matsuura@ntc-c.co.jp

[b]h.ieda@ntc-c.co.jp

[c]tagataga@affrc.go.jp

[d]a5016@n-koei.co.jp

ABSTRACT

As Japan frequently suffers large earthquakes, a safety collation of performance against earthquake for aged fill-dams is an urgent issue. But an application of technique to maintain high resistance to earthquake based on results of quantitative analysis is limited. First we have taken one step of arranging examples which analyzed conditions and problems about present design techniques for earthquake-resistance. The series of the example of the seismic-stability analysis for the fill-dams is shown in this paper, in which reduction of undrained strength in saturated zone, liquefaction of dam body and foundation and the non-linear property of loose dam body were taken into account. Then we introduce the results for the shaking table tests, which we can demonstrate and inspect the applicability of examination methods for earthquake-resistance. In the tests, six cases using silica sand were carried out on the 1G field of a small dam with many sensors and centrifugal force field of 60G corresponding to an actual dam height. Three cases of the tests were conducted in the seepage condition. The response acceleration, the settlement and the deformation for the tests were investigated. And we present consideration about diagnosis and its procedure to support a rational and appropriate evaluation.

1. INTRODUCTION

Many small-scale dams have been constructed and maintained in Japan for irrigation of rice paddies since ancient times.

For the construction of small-scale fill dams, soil materials available nearby dam site were utilized to reduce a construction cost. Technologies to ensure structural integrity and water-shielding function of such small-scale dams on soft ground have been developed in government-academia-industry partnership. The solution of these issues has facilitated the dam construction significantly.

Development of measures to protect structures from earthquake damage is an important technical issue in Japan where strong earthquakes occur frequently across the entire country. Possibilities of subsidence and deformation of dams and reduction in strength of embankment materials are serious concerns when an earthfill dam is to be constructed on soft ground. Therefore, the development of a rational method to evaluate the seismic performance of the earthfill dams is urgently required.

The 2011 Tohoku Earthquake caused not only cracking and rupture in the crests and subsidence and deformation at the embankments of some of these small-scale earthfill dams, but also disastrous failure.

Responding this background, we summarize the current state of seismic performance evaluation and discuss the validity of analysis methods by reproducing the behavior that led to the dam failure in this paper. We also present examples of the results of dynamic response analyses using different strain dependence models of rigidity and damping factor for the quantitative evaluation of the dam safety

Because the results of the above-mentioned analyses show that use of different input conditions and analysis parameters produces significantly different outputs, we addressed this issue by conducting a shaking table test with hypothetical models to elucidate the sensitivity of the input conditions with the reproduction results. Then, we examined the results of the test and the re-productivity of various analysis methods for the further improvement of the analysis technology.

We consider that this study, including the results of the shaking table test developed as a new technology in a government-industry partnership that aims at improving the analysis accuracy in future, will help develop technologies to improve the seismic performance of the small-scale earthfill dams.

2. EVALUATION OF SEISMIC PERFORMANCE OF EARTHFILL DAMS AT PRESENT IN JAPAN

The studies on seismic design methods and the revision of the design standards for the structures resistant to large-scale ground motion have been conducted in Japan since the occurrence of the 1995 Kobe Earthquake (Mw 6.9).

The Ministry of Land, Infrastructure, Transport and Tourism published the “Guidelines for Seismic Performance Evaluation of Dams during Large Earthquakes (Draft)” in March 2005. The guidelines provide stipulation concerning the seismic performance of a dam against strongest possible ground motion conceivable at the dam site concerned at present and in future (level-2 ground motion). The stipulation requires a dam to have seismic resistance “to maintain reservoir water even when a main body suffers damage and to limit such damage to a repairable extent”.

The guidelines establish the principles that the seismic performance of an earthfill dam shall be evaluated by dynamic response analysis based on an equivalent linear method and that the plastic deformation of dam-body obtained by above analysis should be confirmed to be enough small so as to avoid causing overflow of water from the reservoir.

Since the 2011 Tohoku Earthquake (Mw 9.0), attention has been paid to the instability of old earthfill dams constructed a long time ago and the verification of the seismic performance of numerous earthfill dams has become a pressing task.

An investigation of the earthfill dams which failed in this earthquake has concluded that the earthquake ground motion lasting for a long time reduced the strength of the loosely-compacted, and saturated sandy embankment of the dams and this reduction in strength resulted in the slip failure of the embankments causing dam failure. Therefore, an analysis is necessary to be considered the reduction in the strength of the earth material to evaluate the seismic performance about old earthfill dams which may have small degree of embankment compaction.

3. NEW APPROACHES TO SEISMIC PERFORMANCE EVALUATION

3.1 Newmark's Method that Incorporates Soil Strength Reduction by Undrained Cyclic Loading

The 2011 Tohoku Earthquake damaged many earthfill dams including A Dam (constructed between 1937 and 1949 with an embankment height of 18.5 m). The earthquake motion caused slip failure of the dam embankment and a huge amount of water flowing down from the reservoir killed eight people downstream of the dam.

A study (Tanaka et.al. 2013) about the causes of A Dam failure found that:

- As a whole the compaction degree of the embankment material was lower than modern construction standards
- The inconsistency in the embankment materials and the degree of the compaction might have contributed to occurrence of the slip; and
- The strength of the sandy material used in the upper part of the embankment was reduced when strong and long earthquake motion was applied.

A detailed study was conducted using Newmark's Method that incorporates the effects of the reduction in the strength of the embankment material by ground motion (modified Newmark -D method) to reproduce the above-mentioned process that led to embankment failure(Tanaka et.al. 2013).

The modified Newmark-D method (Duttine et al. 2015) is that to estimate the reduction in the strength of the embankment material over time by undrained cyclic loading into the calculation of slip displacement by Newmark's method.

The slip deformation of the embankment by the earthquake was applying the estimation from response acceleration on the presumed circular slip surface in the simulation with the modified Newmark-D method. The estimated slip displacement was 2.60 m (which corresponded to subsidence of 2.0 m at the dam crest) in this analysis. This estimate is consistent with the observation that confirmed the slip displacement of several meters at actual failure of the dam.(Tanaka et.al. 2013).

Meanwhile, A Dam was designed as a central core rockfill dam (Figure 1) in its reconstruction project.The degree of compaction was controlled at 95 % (EC=100%) or above for the dam embankment so that the strength of the embankment materials would not be reduced.

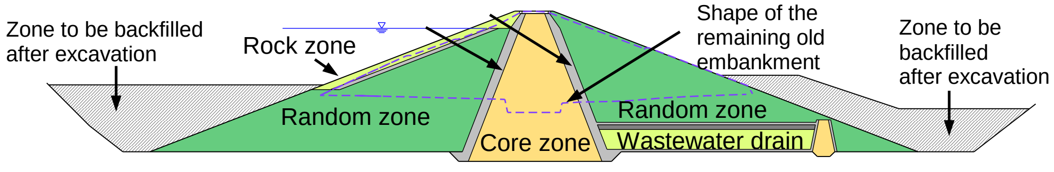

Figure 1. Standard cross-section of the reconstructed dam

We evaluated the seismic performance of the reconstructed dam against the estimated ground motion at the time of the earthquake by conducting an analysis of its cross-section with the modified Newmark-D method.

The seismic waveform estimated from the waveform observed near the dam was used for the analysis (Figure 2).

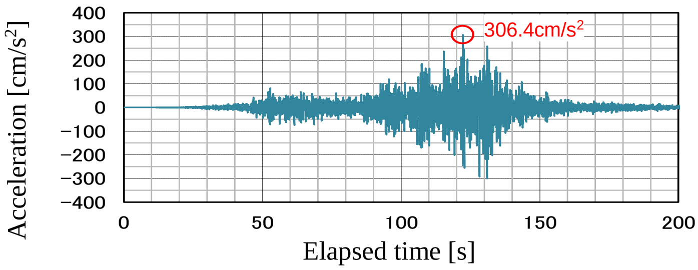

Figure 2. Input seismic waveform

We set the analysis parameters of each zone as shown in Table 2 using the results of the material tests. We elucidated the characteristics of the soil strength reduction of the embankment materials from the results of the cyclic and the monotonous loading tests. The strength reduction of the core material of a test model is shown in Figure 3. The unit weights and the shear strength of the reconstruct embankment materials are larger than those of old embankment.

Table 1. Parameters of analysis

Item			Main materials of the reconstructed embankment		Embankment material of the old embankment
			Core material	Random material	Embankment material in the upper part
Unit weight	Wet unit weight	(kN/m³)	19.7	21.1	16.8
	Saturated wet weight	(kN/m³)	20.1	21.3	18.3
Linear parameter	Cohesion: C	(kN/m³)	95.7	75.2	9.5
	Internal friction angle: φ	(°)	16.8	21.8	15.7
	Initial shear modulus: G_0	(MN/m²)	110	313	46
	Dynamic Poisson's ratio: ν	—	0.450	0.450	0.450
	Maximum damping constant: hmax		19.200	19.200	0.286

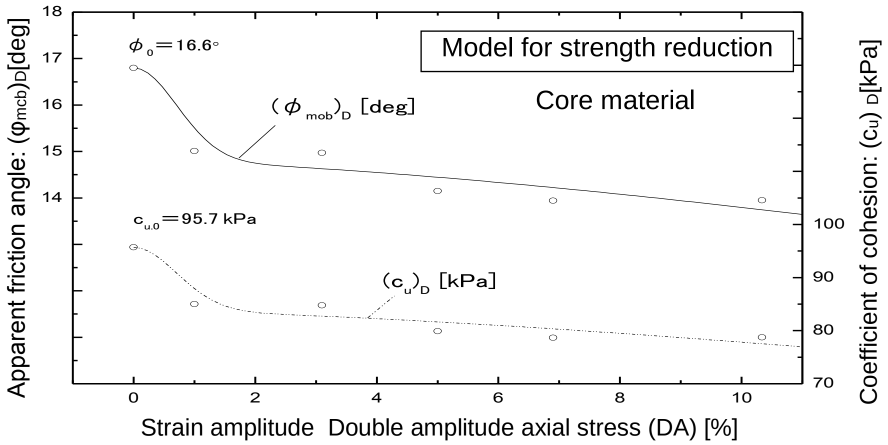

Figure 3. Strength reduction of the core material of a test model

Although the analysis with above-mentioned conditions presented the reduction in the strength of the embankment and the yield of seismic intensity on the circular slip surface by the ground motion, the amount of the slip deformation was 0 (Figure 4). The result implied that the stability of the embankment had been markedly improved in the reconstruction.

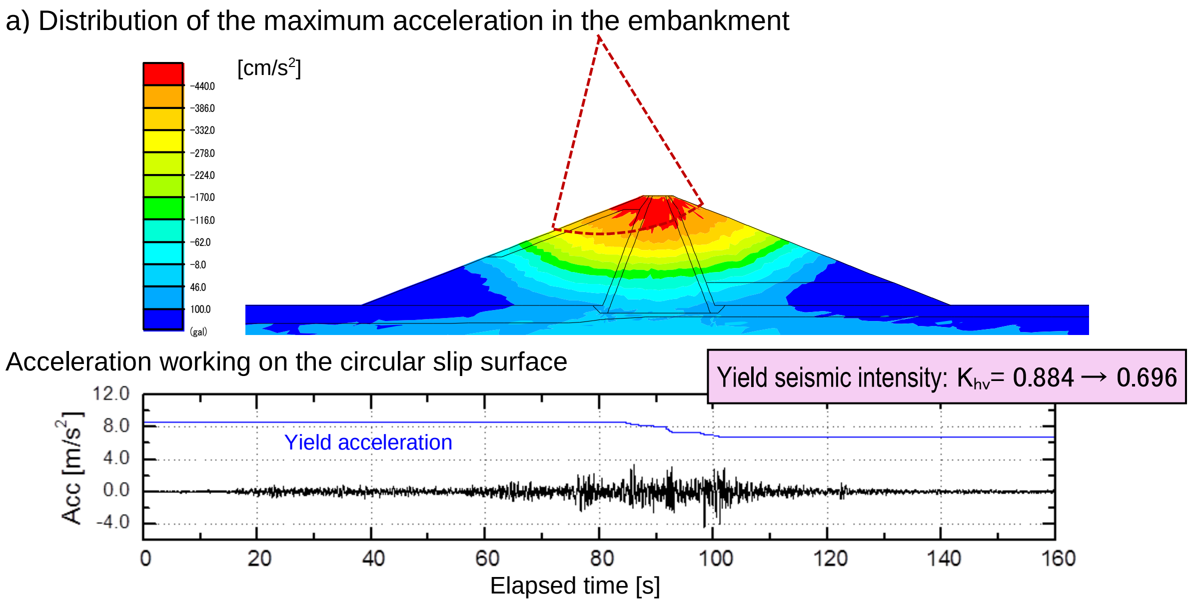

Figure 4. Downstream view of Example Dam

3.2 Effect of Strain Dependence Models of Rigidity and Damping Factor on Equivalent Linear Method

Dynamic response analysis by the equivalent linear method using an Hardin-Drnevich model(H-D model), which has been widely used as a model of strain dependence in rigidity and damping factor (dynamic deformation properties), is believed to reproduce the dynamic deformation properties observed in tests relatively well up to approx. 0.1 % of shear strain. The strain-stress relationship in the H-D model, however, is defined as symmetrical curves from the point of at the standard strain. Therefore, value of shear modulus G significantly reduces from point passing 0.1% of the shear strain in the deformation range and the model tends to produce excessive strain and damping ratio there.

Then, analysis with an H-D model cases in which large ground motion is applied to the embankment of an earthfill dam that has relatively low rigidity may reveal the concentration of shear strain. This may lead a significant reduction in rigidity and increase in damping in the lower and middle parts of the embankment and extremely small amplification of the seismic wave to the dam crest. We describe the case study on B Dam in the following (Figure 5) as an example of such a case:

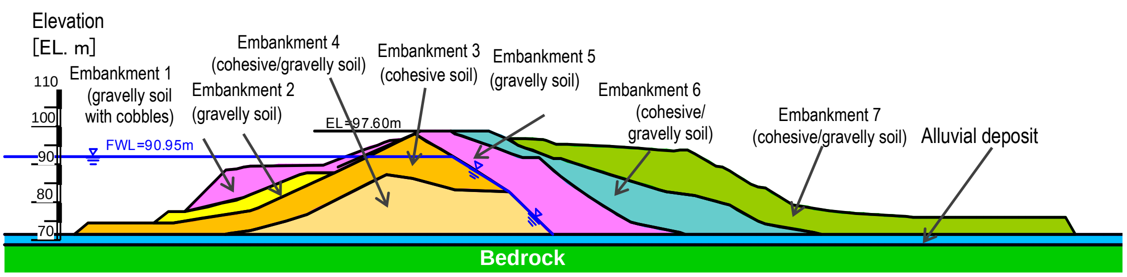

Figure 5. Analysis model (B Dam)

Figure 7 shows the results of the dynamic response analysis with the equivalent linear method at a case in which the nonlinear characteristics of the embankment materials were approximated with a H-D model (Figure 6).

When ground motion does not cause failure of an embankment, the response acceleration at its crest is usually larger than that at the base. However, the strain of less than 5 %, which would not cause embankment failure, created concentration of area of large shear strain between the crest and the mid-section of the embankment and the response acceleration at the crest was slightly smaller than that at the base in this analysis.

Therefore, we used a Generalized Hyperbolic Model (GHE mode) in Figure 6 that could be used to reproduce the situation where the strain was large (10 %). Then, as shown in H-D model at Figure 8, the concentration of the shear stress was alleviated in the lower to the mid-sections of the embankment. and the normal increase of the acceleration from the bottom to the crest was observed in the analysis.

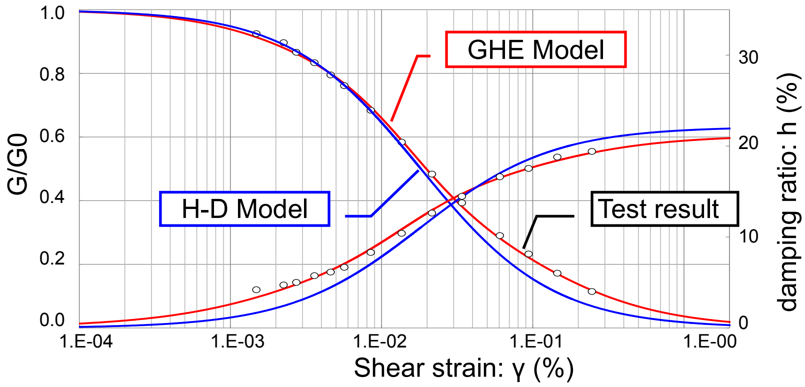

Figure 6. Dynamic deformation characteristics of embankment material approximated by H-D and GHE models (G_0 indicates the values of G when γ is 10^{-6})

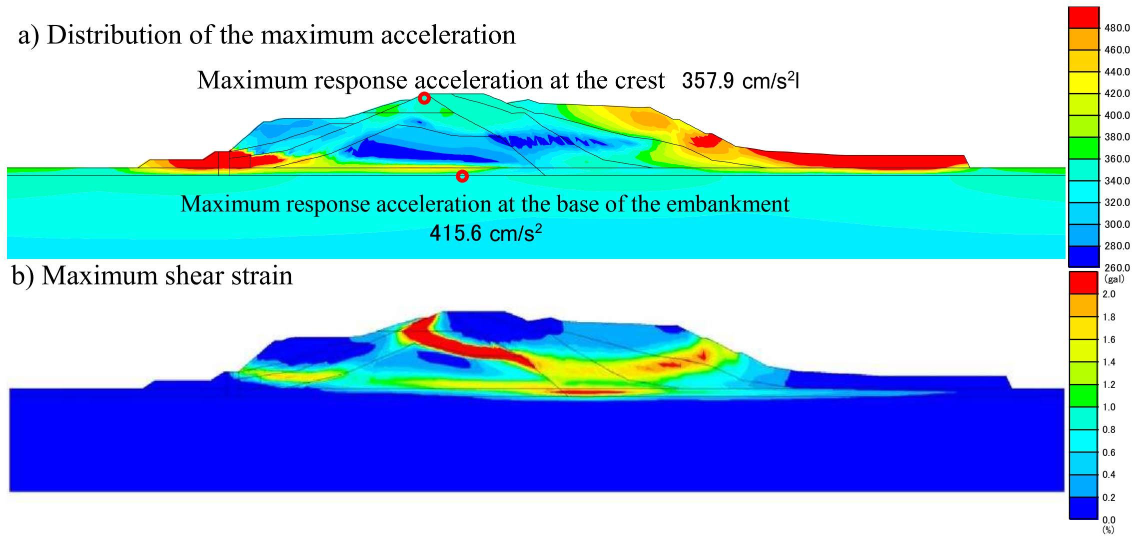

Figure 7. Result of the dynamic analysis with a H-D model

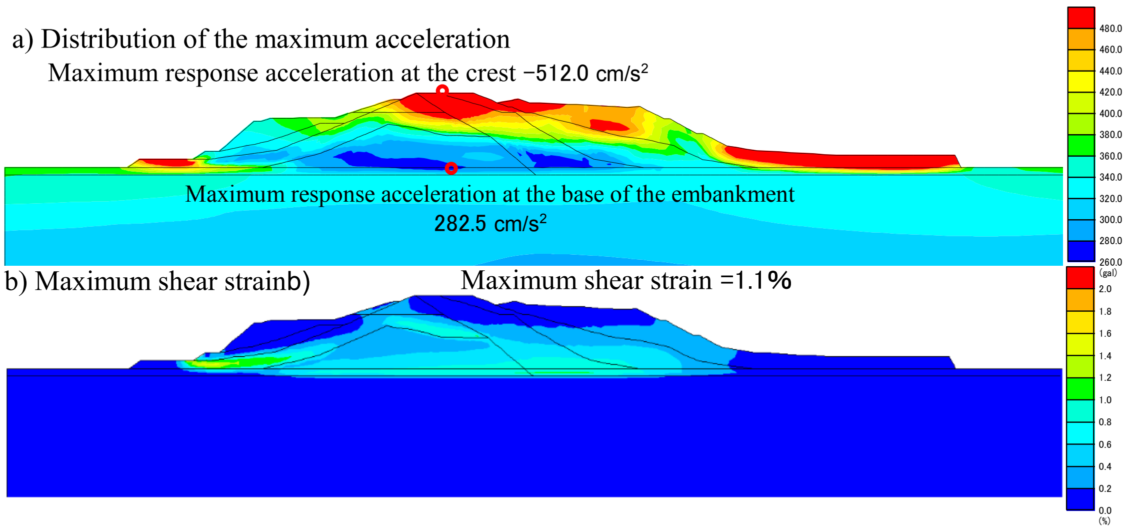

Figure 8. Result of the dynamic analysis with a GHE model

4. SHAKING TABLE TESTS THAT REPRODUCES BEHAVIOR OF EARTHFILL DAMS

4.1 Basic Policy

Various methods ,which include a simple evaluation method based on the seismic coefficient method and non-linear response analysis taking into account failure of the dam embankment, have been developed for the seismic design of earthfill dams. However, the indicators for setting the application limits of these methods and the quantitative evaluations of the results on the analysis are not sufficiently developed. This insufficiency has been a major obstacle to the evaluation of seismic performance of irrigation reservoirs with regard to the level-1 and level-2 ground motion. And it has been also a major factor for the difficulty in evaluating the need and the effect for the measures against earthquakes.

Therefore, we developed a shaking table test to elucidate behavior of dams at the time of earthquake in detail and to reproduce their typical behavior.

We also propose a method to use the results of the shaking table test developed in this study to facilitate verification of various seismic performance evaluation methods.

4.2 Condition Settings for Shaking Table Test

In order to represent the characteristics of the standard behavior of dams at the time of an earthquake shaking table tests were conducted for the control model which applies for verification of seismic analysis method with the specification described in the Table 2.

We tested a “1G (gravity) model which was smaller than reality to measure detail behavior of the entire model embankment, and a 60G (centrifuge) model which enabled reproduction about behavior of dam with a scale close to reality in a centrifugal (60G) field. We conducted the shaking table test on a total six cases with different water level and density conditions.

Table 2. Specifications and conditions of shaking table test conducted as control model

Structure type	Homogenous earth embankment for verification of most basic behavior
Model materials	Sand (silica sand) of a homogenous grain size is used because 1) The use of homogenous sand enables observation of crack formations and slip surfaces 2) The use of homogenous sand makes it relatively easy to control the moisture content and homogenize the density of the embankment when models are created 3) Earthfill dams constructed with sandy embankment material have a high damage rate.
Seepage	The conditions without the reservoir (dry) and with reservoir (seepage) are assumed.
Density condition	Two different density conditions (loose and dense compaction) are set to compare the behavior of the model embankments under these conditions. 1) The reduction in the strength of loosely-compacted saturated material with a low degree of compaction is a problem (as seen in the case of failure of Lake Fujinuma embankment). 2) The relative densities of loose and dense compaction are set at Dr = 65.2(Loose) and Dr = 95(Dense), respectively.
Test cases	The 1G and 60G (centrifuge) models described below are designed (a total of six cases). The 1G and 60G system used belong to the National Institute for Rural Engineering and the Research and Development center of Nippon Koei Co. Ltd., Japan, respectively.

4.3 Results of Shaking Table Test

Table 3. shows the behavior of the embankment model in each shaking table test. Cracks, subsidence and slip failures of the embankment model were observed with different densities and water-level conditions. Figures 9 and 10 show a summary of the results of typical 1G and 60G model tests, respectively.

Table 3. Summary of results of each shaking table test

Case	Confining model	Seepage	Density	Characteristics of behavior (type of failure)		
				Final displacement (subsidence at crest)	Acceleration at time of failure	Type (mode) of failure [1)]
1G-01-D-L	1G model	Dry	Loose	5 cm	600 gal	I II III IV
1G-02-S-L		Seepage	Loose	3 cm	300 gal	I II III IV
60G-01-D-L	60G (centrifuge) model	Dry	Loose	100 cm	600 gal	I II III IV
60G-02-D-D			Dense	95 cm	600 gal	I II III IV
60G-03-S-L		Seepage	Loose	66 cm	500 gal	I II III IV
60G-04-S-D			Dense	41 cm	500 gal	I I II III

1) I.Crack, II.Subsidence, III.Surface slip, IV.Deep slip

4.4 Examples of Reproduced Results of Shaking Table Test

We reproduced the behavior of the embankment model in each shaking table test by the Newmark-D method (detailed method). The subsidence at the crest observed in the test and the subsidence observed in the analysis are compared in Table 4.

Results in Table 5 shows the evaluation of the capacity to reproduce the behaviors at the shaking table test comparing several dynamic response analysis methods. Even though the calculation was conducted under the same basic conditions with the same soil constants, same models and same boundary conditions, each analysis programs gave different displacement values. We consider that this difference was partly due to the each setting of the different program-specific parameter for the non-linear models of the materials.

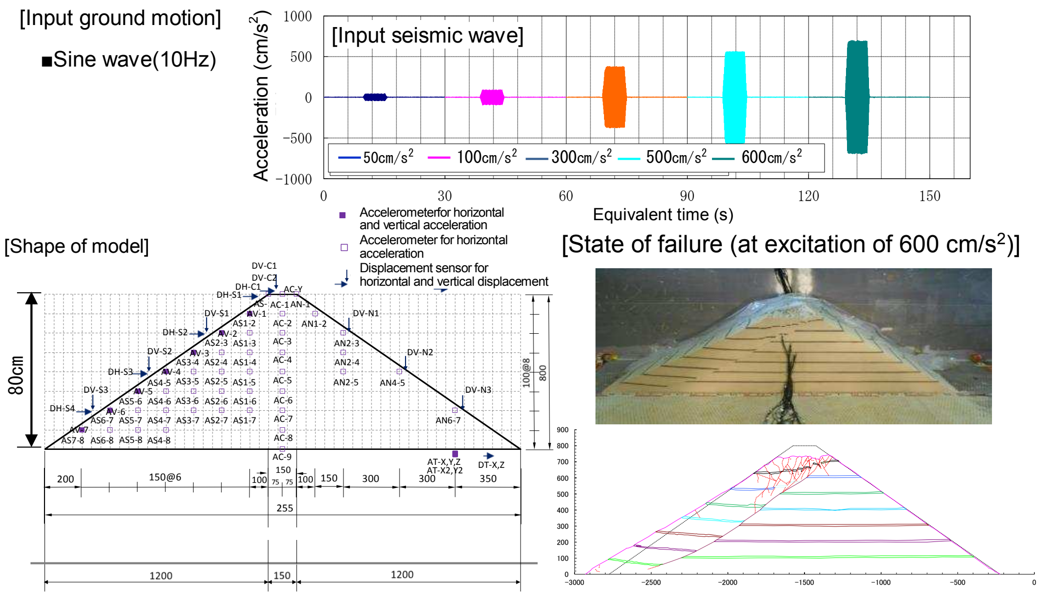

Figure 9. Results of 1G model test [Dr = 65.2 % (loose), dry: Case 1G-01-D-L]

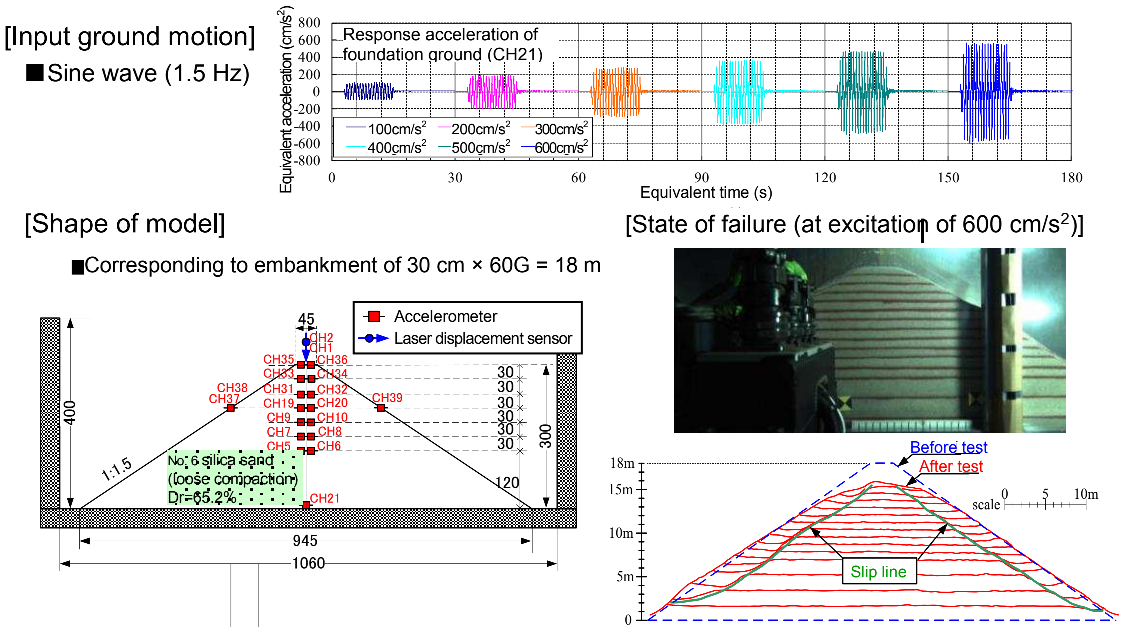

Figure 10. Results of 60G (centrifuge) model test [Dr = 65.2 % (loose), dry: Case 60G-01-S-L]

Table 4. Results of analysis of reproducibility by Newmark method

60G (centrifuge) model [seepage, loose(60G-03-S-L)]	Settlement at crest (cm)	
	Observed value	Analysis result
300 cm/s²	38.9(38.9)	45.2(45.2)
400 cm/s²	49.1(88.0)	95.0(140.2)
500 cm/s² (at time of failure)	66.1(154.1)	160.4(300.6)

Table 5. Results of reproducibility evaluation by various analysis programs for 1G model test [Dr = 65.2 % (loose), Seepage: Case 1G-02-S-L, Input waveform 300gal]

Method	Program	Settlement at crest (observed value:2.90cm)
Equivalent linear analysis	(1)	0.00cm
Sequential non-linear analysis	(2)～(5)	14.50cm, 3.67cm, 0.00cm, 0.06cm, respectively

4.5 Use of Results of Shaking Table Test

Based on the shaking test methodology in this study, we developed a system to support reasonable appropriate diagnosis and evaluation for adaptability about various seismic performance methods.

This system has the following two functions, a) and b).

a) Benchmark support system

- The control models of this system are utilized as the benchmark tests of a variety of the technologies for the seismic capacity evaluation.

b) Applicability assessment and analysis support system

- The effect (sensitivity) of changing the parameters specific to each analysis program is obtained by this system to facilitate the applicability of the program and improvement of the accuracy about each analysis.

5. CONCLUSION

There are over 100 thousand small-scale earthfill dams constructed before the modern era in Japan. About 2,000 of them are classified at high risk dams requiring improvement measures.

However, it is difficult to evaluate detailed seismic performance against the large-scale ground motion of all the dams in Japan. Therefore, the development of a simpler method to reproduce the behavior of the embankments quite similar to reality is required.

The approach we have taken in this study requires accumulation of result data from a large number of analysis cases and acquisition of soil test data (results of cyclic triaxial test). Development of measures to improve the accuracy of the analyses with these data is a major issue in further development of this approach.

The accuracy improvement of the benchmark test in the shaking table test is considered to have high academic value because it could become one of various seismic evaluation technologies to reproduce behavior of dams at the time of earthquake.

We intend to continue the development of the simple approach mentioned above and improve method by implementing further study on model cases.

6. ACKNOULEGDEMENT

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