Fujinuma Dam Performance during 2011 Tohoku Earthquake, Japan and Failure Mechanism by FEM

Mahdavian Abbas
Powue and Water University of Technology, Tehran, Iran

Shiro Takada
Tehran University, Tehran, Iran

Shabdiz Sepand
Power and Water University of Technology, Tehran, Iran

SUMMARY:
Fujinuma Dam Failure and Human Casualty Analysis of failure mechanism and resident sedulity policy 86 Reservoir and agriculture dams were damage during the 3.11 East Japan earthquake. Among them, Fujinuma Dam located in Fukushima prefecture had severe damage of earth dam -embankment, causing 8 person casualties. The dam is an earth-dam constructed 62 years ago. The bank of 18 m height and 133m length failed just after earthquake occurrence. Human casualty by dam failure is the first event since 1930. Only 140,000,000 Yen will be supported by Central Government for this dam failure restoration no Tsunami occurred in this area and failure was considered to be caused by ground shaking.
Based on our field survey and hearing investigation to residents, at first, Black water flow in the river and many persons escaped from river side to mountain areas. A lot of water attacked residential area, especially at the curved corner of river route. The maximum acceleration at this area was about 403 gal by K-Net recording. The dam was not designed under consideration of seismic forces though the current design considered 700 gal acceleration spectra for earth-dam. To make clear the mechanism of dam failure, FEM analysis had been done and compared to the resisting capacity of the dam embankment. The results show that the dam failure is considered to occur just after the earthquake, not by the penetration of ground water long after the earthquake. The Liquefaction phenomena may be concerned to the failure mechanism. After that, resident security policy in that area has been investigated. Human casualty is the serious problem due to dam failure.

Keywords: Dam, Fujinuma, Failure, Earthquake

1. INTRODUCTION

In March of 2011, Strong earthquake with a magnitude 9 occurred in Japan and resulted in a big Tsunami. 86 Reservoir and agriculture dams were damage in 7 Prefectures of Aomori, Iwate, Miyagi, Fukushima, Ibaragi, Tochigi and Gunma during the earthquake of 3.11 East Japan.

Present paper treats the severe damage of Fujinuma dam in Sukagawa city and causing 8 person casualties. This dam is constructed 62years ago. The dam is located in the south of damaged Fukushima Nuclear Plant with distance of 240 km and the nearest fault exists in80 km from the dam. The dam had 18.5 meters height and 1.5 million cubic meters water reservoir that in used for irrigation purpose [JCOLD, 2011].

According to JCOLD this dam was constructed very well and has suitable maintenance after finishing construction in 1949. According to EERI, their Satellite image observation shows the embankment dam started to fail after the earthquake occurred and completely destroyed during 20 minutes. Before the earthquake occurrence, the dam reservoir was full.

EERI also noted that the only reason of the failure was uncontrolled behavior of reservoir water level when the dam had a good performance. The factors caused failure must be considered.

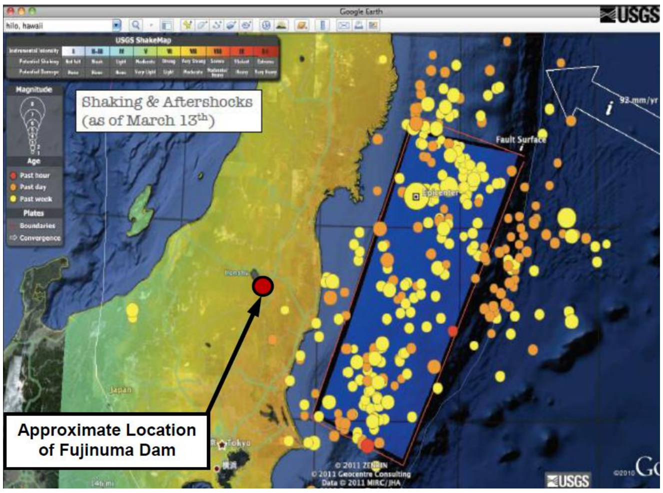

Figure 1. Fujinuma site location [Kayen et al., 2011]

Present paper tries to make accurate model of dam to understand failure mechanism of dam body. Analytical results improve recognition of dam behavior and failure mechanism. Dam studies and modeling is based on objective observations of authors and experimental data and reference books.

2. SITE OBSERVATION

Site observation is the most important resources that used for investigation and dam modelling. EERI Published some photographs of occurring earthquake on dam that shows discharging of reservoir water.

The photos 2, 3 and 4 shows that some reasons caused the storage water to flow over dam and to destroy it. This article try to become clear the main cause of event.

Figure 2. Dam during the earthquake

Figure 3. Dam failure after earthquake

Figure 4. Dam Section after earthquake

3. DAM ANALYSIS AND RESULTS

Modeling and Analysis of Fujinuma dam runs with ABAQUS finite element program and tries to define exact information with our engineering experiences.

3.1. Dam property

Fujinuma dam was Earth dam (Fig. 5) with 18.5 meters height and 133 meters crest length and reservoir volume equal to 1.5 million cubic meters. Width of dam crest was 6 meters. Upstream slope of dam was 2.5H: 1V and 2.8H: 1V and downstream slope was 2.5H: 1V. [JCOLD, 2011]

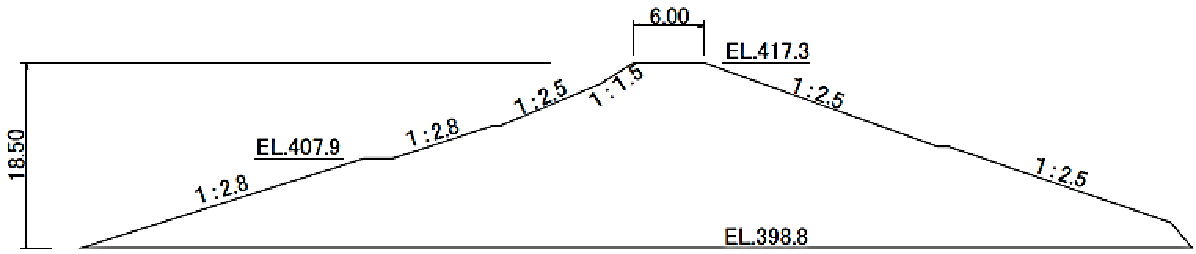

Figure 5. Cross Section of fujinuma dam

3.2. Materials

Materials used in this dam are homogenous. Given that experimental data on materials used in the dam is not available so this article attempt is to use reliable and optimistically data. Information obtained from the observation site and Data was extracted due to principals of geotechnical engineering [Braja, 2006].

It should be noted that according to Harder et al. (2011) Fujinuma dam has some problems on permeability that repaired with performing diaphragm wall in 1994. It goes without doing that, it reduces the seepage in some degree through the dam and this issue is incorporated in the model.

The following photo shows the details of dam material d. From the observation in dam site and reliable references, authors decided to use following parameters in model of dam materials. According to views, dam has 3 layers and above layer with fix depth has one material property that shows the cover of dam in upstream and downstream side has above materials of dam.

Table1. Material properties of dam

Profile Depth (m)	Density	Elastic		Permeability		Mohr Coulomb Plasticity	
		Young's Modulus(MPA)	Poisson's Ratio	K(m/s2)	Void Ratio	ϕ(degree)	c(kilo Pascal)
0-4	1900	50	0.3	1.00E-09	0.5	27	15
4-8	2000	60	0.35	1.00E-09	0.5	30	20
8-18.5	2200	70	0.4	1.00E-09	0.5	--	--

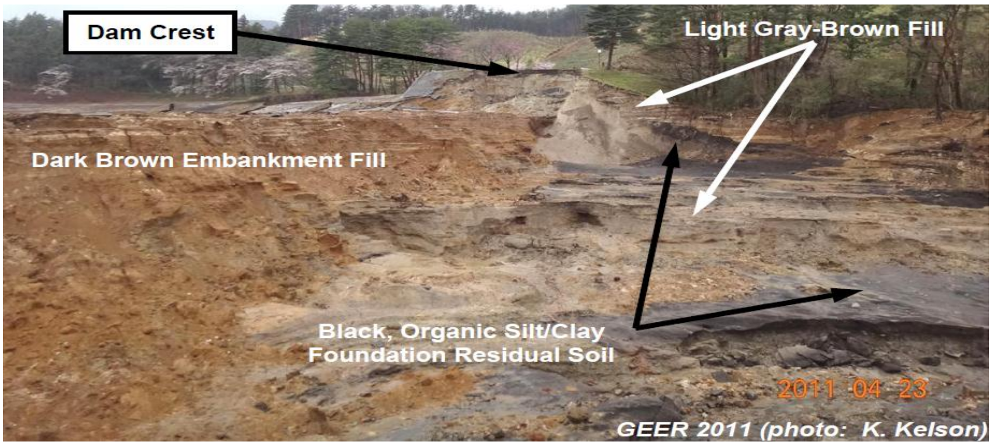

Figure 6. Cross section after earthquake [Harder et al., 2011]

3.3. Analysis Steps

The model steps assumes that first step is gravity of materials and then, in order to withstand the stress from upstream pressure and fixing stresses and the pore water pressure for 10 days under the effect of consolidating relations are analyzed. After this two-step static conditions imposed and then in 96 seconds step, effective duration of Tohoku earthquake time history is entered in model. Present analysis assumes that 95 percent of reservoir volume was full. This earthquake has been entered in both the horizontal and vertical and the dam model is well established.

3.4. Interactions

Connecting the dam body and foundation assumes node to node tie property. This condition shows the direct relationship between node stresses and pore pressure also full dynamic analysis of dam was performed with the assumption of Seed & Idriss attenuation relations for seismic boundary conditions. This boundaries cause to damp reflected waves [Seed and Idriss, 1970].

3.5. Loads and Boundary conditions

Loads on structure are weight of dam in all steps and upstream water head on upstream side. Head of water loads are pore water pressure and surface pressure on the dam. In contrast, downstream of the dam should be zero boundary conditions for the absence of water, to be entered. Earthquake loads entered as acceleration time history on bottom of dam foundation in two directions.

Time history of earthquake was taken from K-net Network. Naganuma station is the nearest location with 2.8 km distance to dam that records earthquake on 11 marches 2011. Maximum recorded acceleration equal to 0.315g and Earthquake has continued for 300 seconds that effective duration is equal to 96 seconds. Effective duration of earthquake is the time that has 95 percent of whole energy of earthquake (Fig.7, 8 and 9).

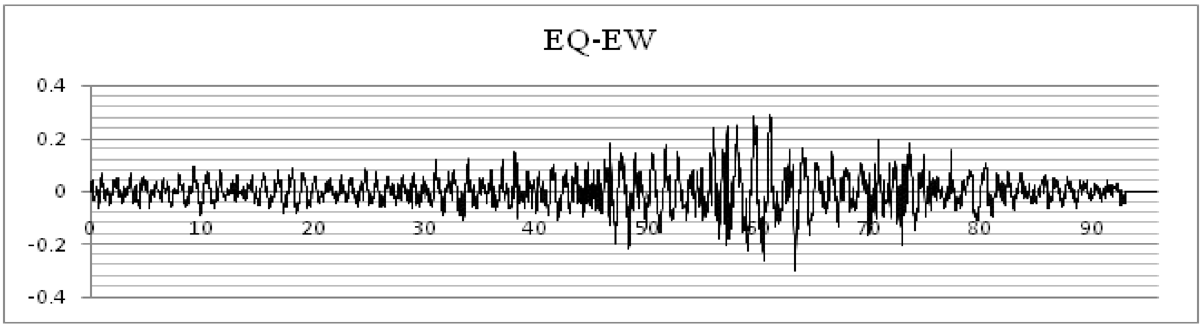

Figure 7. East-west japan time history diagram

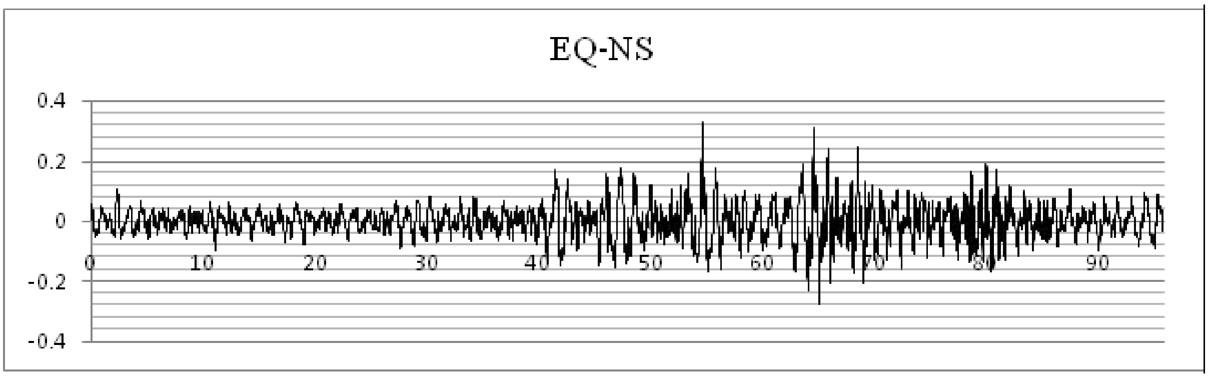

Figure 8. North-South japan time history diagram

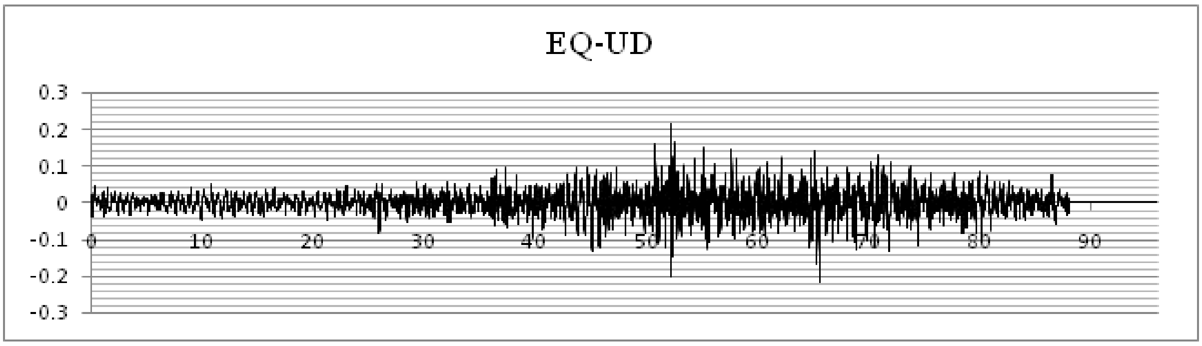

Figure 9. Up-Down japan time history diagram

3.6. Mesh

Element size depends on dam size and relationship of seepage (Fig.10). This value is equal to 2 m in the general case considered. The results of dam in this condition are suitable and analysis of dam complete very well.

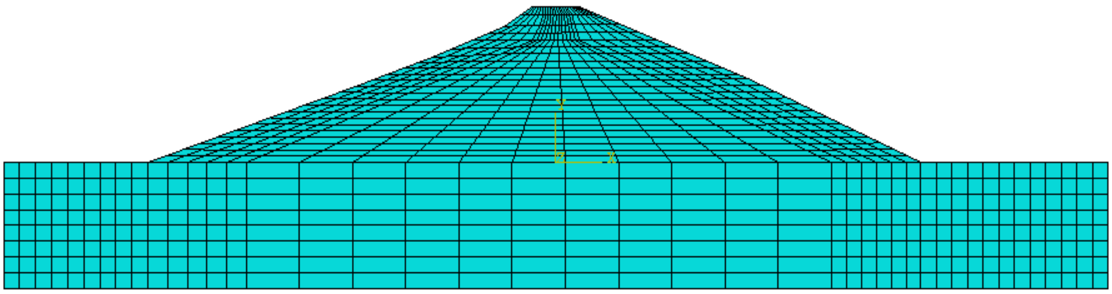

Figure 10. Dam mesh size and modelling.

Element type for analysis is pore pressure/stress and all of the elements are tetrahedral.

4. ANALYSIS RESULTS

Following Figures (11 to 15) show the analysis results of Fujinuma dam in Abaqus program. All of the units in SI system and length unit are in meters.

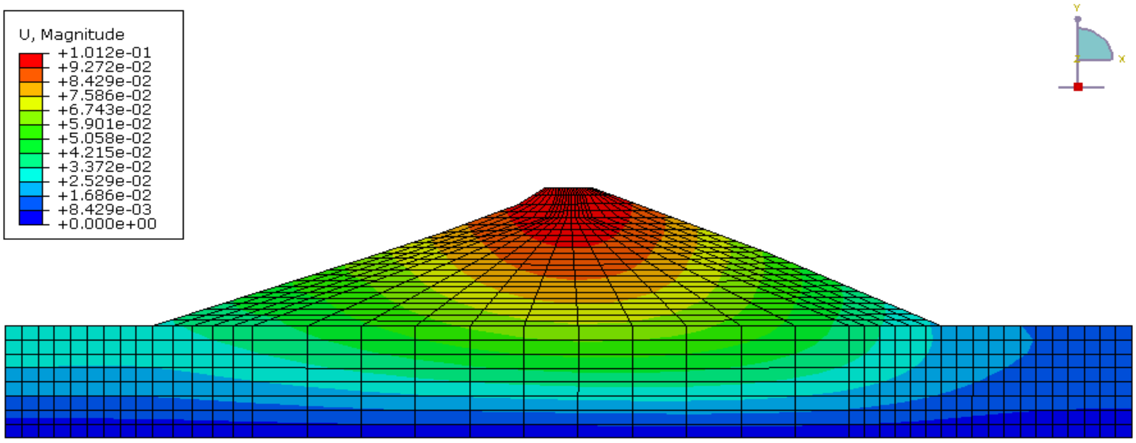

Figure 11. Displacements in t=0s of earthquake

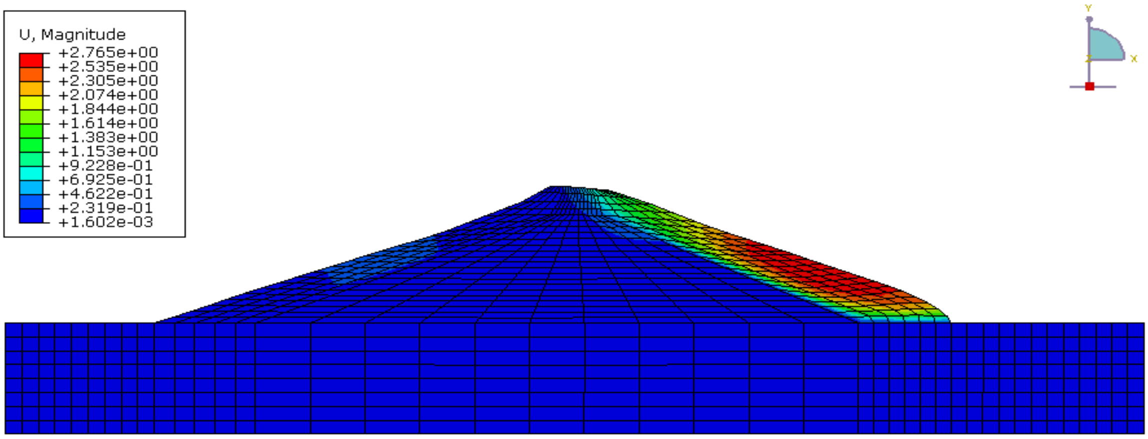

Figure 12. Displacements in t=30s of earthquake

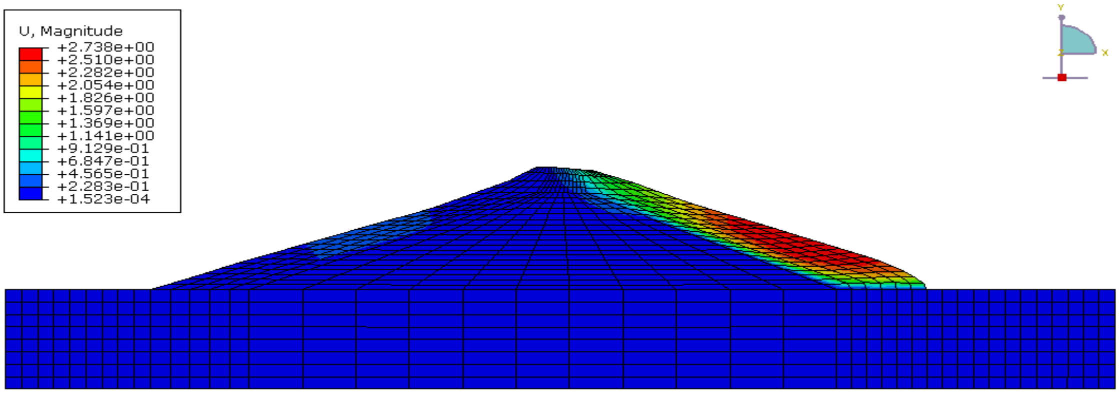

Figure 13. Displacements in t=60s of earthquake

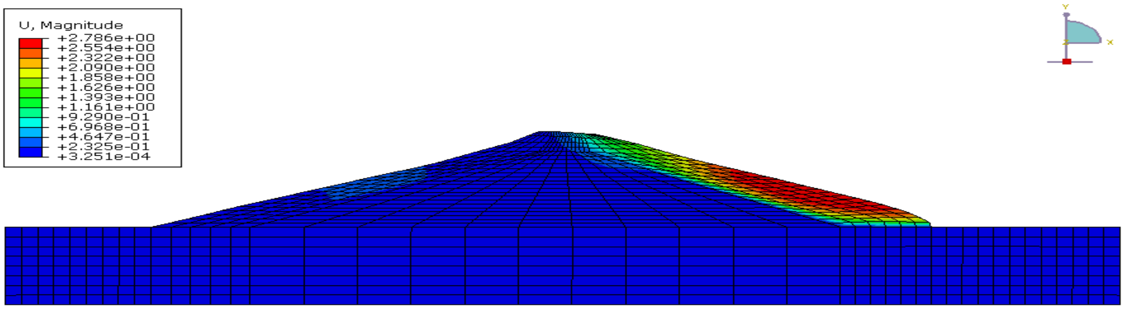

Figure 14. Displacements in t=96s of earthquake

Displacements results show that in downstream sides of dam the slip phenomenon occurred and maximum displacements of downstream sides is equal to 2.78 meters.

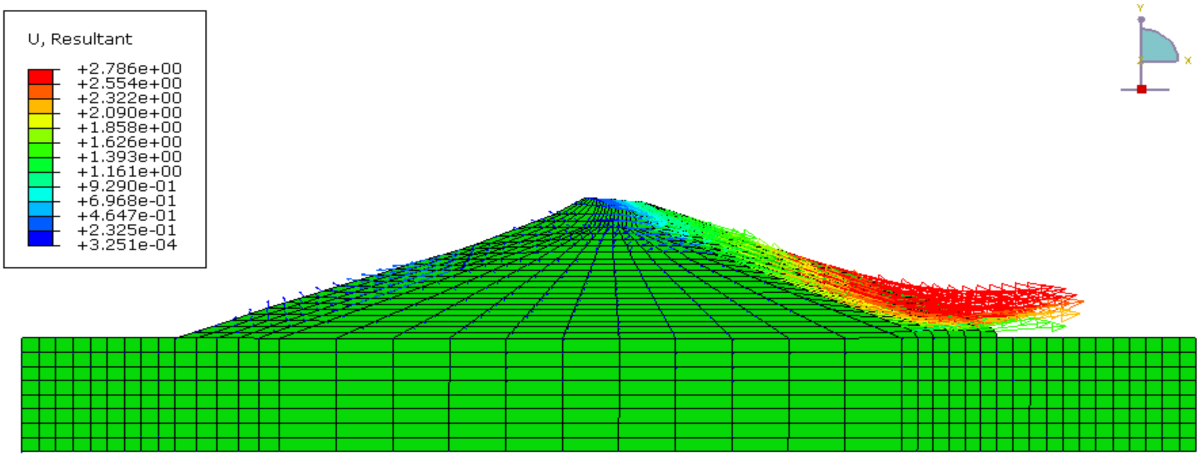

Figure 15. Displacements Vectors in t=96s of earthquake

Above photos relate to displacements vectors that show the maximum displacement of elements in base of downstream side. Also, the settlement of dam crest is very clear and equals to 1.1 meter therefor the reservoir water can easily flow above dam crest.

5. CONCLUSION

According to information presented in this paper, the general trend of the earthquake can be determined. A summary of the overall process has occurred, so, during the earthquake, dam is deformed and experienced some settlements. In downstream side, slip phenomenon occurred. This phenomenon is due to seepage of dam and relatively low resistance of downstream layer. Effect of earthquake escalated these conditions and cause to fail downstream during earthquake.

With overall settlements of dam, the wavy water of reservoir under the earthquake excitation flow over the dam crest and during the earthquake and after that in 20 minutes the whole dam gets washed.
The final evaluation results of fujinuma dam failure also tells that maximum acceleration on dam crest is equal to 0.45g and time of the effective duration that accelerations are over 5 gals was 100 seconds and dam had not experienced 0.45 g acceleration. Dam material consolidation of fujinuma dam compared to modern dams was low and soil strength was not enough. Especially in surface layers that have higher saturation and soil strength was very low. The results of the research team that worked on dam, confirm the results of model of this paper.

REFERENCES

Braja, M. Das (2006), "Principles of Geotechnical Engineering" Fifth Edition, California State University, Sacramento.

Harder, L. F. et al. (2011), "Preliminary Observations of the Fujinuma Dam Failure Following the March 11, 2011 Tohoku Offshore Earthquake, Japan", Geotechnical Extreme Events Reconnaissance Report No. GEER-25e, www.geerassociation.org

JCOLD (2011), "Quick Report on Dams", Japan Commission on Large Dams, 2011/04/14:http://www.jcold.or.jp/e/Pdf/Quick_report_of_the_Earthquake.pdf

Kayen, R. et al. (2011), "LiDAR and Field Investigation of the March 11, 2011 M9.0 Great Tohoku Offshore Earthquake, and April 7, 2011 M7.4 Aftershock", Geotechnical Extreme Events Reconnaissance Report No. GEER-25f, www.geerassociation.org

Matsumoto, N. & Sasaki T., (2011) "The 2011 Tohoku earthquake and dams" Japan Dam Engineering Center, Japan.

Sakamoto, Tadahiko, Chairman, (2012), "Review of the Cause of Fujinuma-ike Failure, Panel to evaluate the seismic stability of dams and small ponds for agricultural purpose of Fukushima Prefecture" Summary Report, January 25, 2012, JCOLD.

Seed, H.B. and Idriss, I. M. (1970), "Soil Moduli and Damping Factors for Dynamic Response Analyses," Report No. UCB/EERC 70/10, Earthquake Engineering Research Center, University of California, Berkeley.