Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-1897

Seismic stability evaluation and criteria of rockfill dam basing on residual deformation

Evaluation de la stabilité sismique et critères des barrages en enrochement basés sur la déformation résiduelle

T.Okamoto
Civil Engineering Laboratory, Central Research Institute of Electric Power Industry, Abiko, Japan

ABSTRACT

In this study, some measurement results of acceleration response and residual deformation of actual dams under strong earthquakes have been analized to clarify the effect of rockfill density and embnkment method, and residual deformation of rockfill dam by centrifuge test under strong earthquake is verified, and then stability criteria based on residual deformation are discussed taking account of dam performance. It found that density of embankment affects residual deformation and big displacement of the embankment is restricted near the surface and the crest without slip circle. Relationship between crest settlement and maximum base acceleration in this test almost agrees with that of in-situ observation for existing dams. Beside allowable and critical settlement ratio is discussed for soil core and facing type RD.

RÉSUMÉ

Texte du résumé Dans cette étude, nous analysons des mesures de réaction d'accélération et de déformation résiduelle de barrages existants suite à des tremblements de terre de forte intensité, ceci dans le but de mieux comprendre l'effet de la densité d'enrochement et de la méthode du remblai. La déformation résiduelle d'un barrage en enrochement a été vérifiée par un test centrifuge dans des conditions de fortes secousses sismiques. Puis, on discutera des critères de stabilité basés sur la déformation résiduelle en tenant compte du rôle du barrage. Nous avons trouvé que la densité du remblai a un effet sur la déformation résiduelle et, que les déplacements importants du remblai sont limités à la proximité de la surface et la crête sans cercle de glissement. Le test confirme à peu près la relation entre le tassement en crête et l'accélération maximale à la base qui a été dégagée d'observations in-situ de barrages existants. De plus, nous traiterons des ratios de tassement tolérable et critique pour la R&D du sol et du type de revêtement.

1 INTRODUCTION

The response under strong earthquake and residual deformation of rockfill dam are not clarified, because it is difficult to evaluate dynamic characteristics of large size particle rock and to evaluate response of actual big size dam. On the other hand, some measurement results of acceleration response and residual deformation of actual dams under strong earthquakes have been reported (Bureau G. et al., 1985, Okamoto T., 1999) and these data have been clarifying the actual behavior. And then centrifuge test is able to simulate actual size model and the test equipment has been modified and scaled up. In this study, residual deformation of rockfill dam by centrifuge test under strong earthquake is verified, and some comparison with in-situ observation and then stability criteria based on residual deformation are discussed taking account of dam performance.

2 IN-SITU OBSERVATION OF EXISTING DAMS

2.1 *Residual deformation*

Actual crest settlements have been reported by in-situ observation (Bureau G. et al., 1985, Okamoto T., 1999). For Matahina dam 80 cm settlement was observed at the toe of the upstream side slope, but the settlement at the toe of the downstream side slope was 10.2 cm. The larger settlement were 60 cm for Cogoti, 50 cm for Makio and 32 cm for LaVillita, and many of observed settlement are less than 10 cm for 50～130m of dam height. If settlement ratio is defined to crest settlement / dam height, the relationship between settlement ratio and maximum base acceleration is shown in Fig.1 (Okamoto T., 1999). The estimated maximum acceleration value of Cogoti dam is reviewed recently (Noguera G. L. et al., 1998). According to Fig.1, it found that LaVillita and Infernillo dam showed large settlement for even comparatively smaller base acceleration, and that settlement ratio is 0.008 in maximum and is less than 0.005 in many cases. However damaged earthfill dams showed 1.0 m and more of crest settlement even for 10 m height, so the settlement ratio exceeded 0.1 in many cases (Tani S., 1992). Because many earthquakes often caused liquefaction failures both in the embankment and the foundation of earthfill dam.

The relationship between settlement ratio and maximum base acceleration of existing dams has wide distribution and the maximum base acceleration is 50～400 gal for the settlement ratio as described above. Beside all center soil core type RDs have adequate poundage performance without leakage increment after earthquake, so the settlement ratios as described

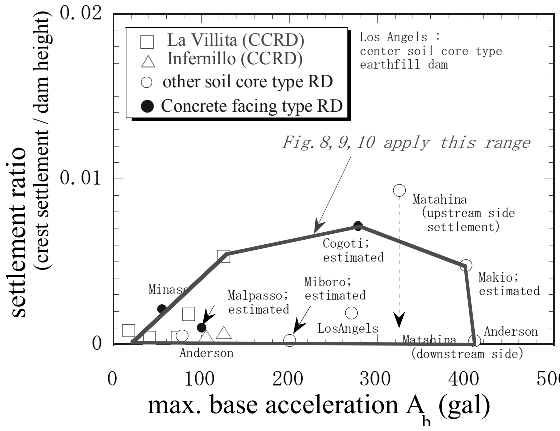

Figure.1 Residual Crest Settlement and Max. Base Acceleration of In-situ Observation (Okamoto T., 1999)

above reveals to be adequately small. On the other hand for concrete facing type RD Cogoti and Minase dam caused leakage increment even though settlement ratio was less than 0.005. So detailed consideration on dam performance is needed.

2.2 *Effect of embankment method on seismic damage*

Many factors influence on residual deformation, and Bureau G. et al. (1985) and Okamoto T. (1999) analyzed taking account of earthquake property such as Fig.1. However the effect of geo technical property have been not clarified. Especially because the density of embanked material generally affects on strength and deformation, embankment method should be clarified.

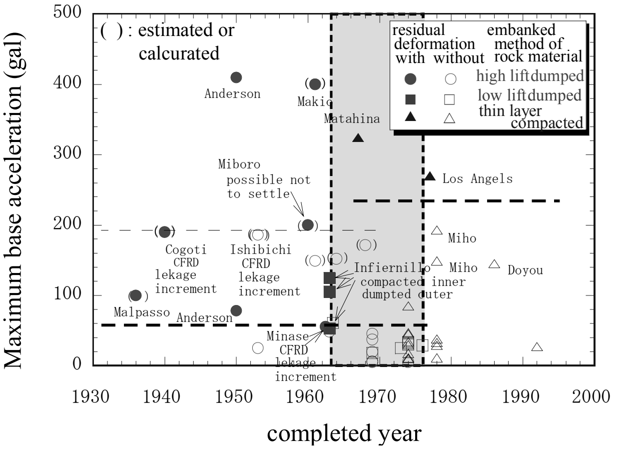

Figure.2 Relation between Maximum Base Acceleration and Completed Year with and without Seismic Damage (Okamoto T., 2004)

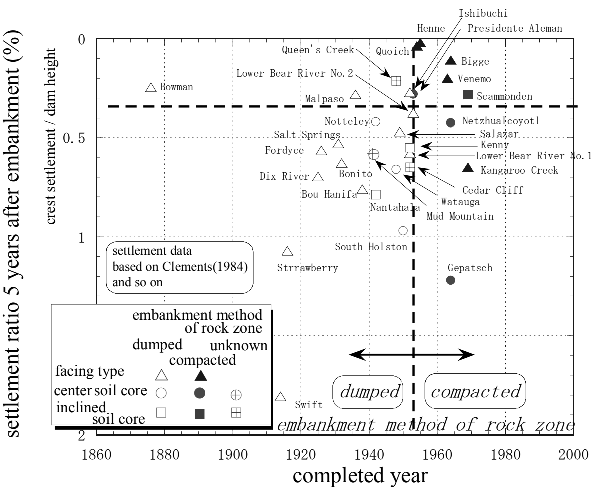

Figure.3 Dependency of Embankment Method on Settlement Ratio after Completed Embankment for Japanese Dams (Okamoto T., 2004)

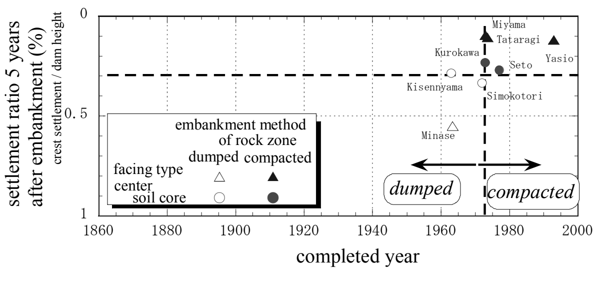

Figure.4 Dependency of Embankment Method on Settlement Ratio after Completed Embankment except Japanese Dams (Okamoto T., 200)

Fig.2 (Okamoto T., 2004) concludes that embankment method of rock zone changed to thin layer compaction from high and low lift dumping among 1965 and 1975, and that even medium strong earthquake caused residual settlement especially before 1970. Fig.3 and 4 presented the change of embankment method of rock zone and static long-term settlement after embankment (5 year after completed embankment). It is recognized that the year changed embankment method of rock zone in Japan is different from other countries, and static long-term settlement after embankment heavily depends on embankment method of rock zone. Fig.5 shows the examples of the density of rock zone by in-situ compaction test (Okamoto T., 2004). Actual embanked material has almost 40-90%of relative density assuming most dense and loose density to maximum (21.6-22.5kN/m^3) and minimum (16.7-17.6 kN/m^3) density by in-situ compaction test such as Fig.5.

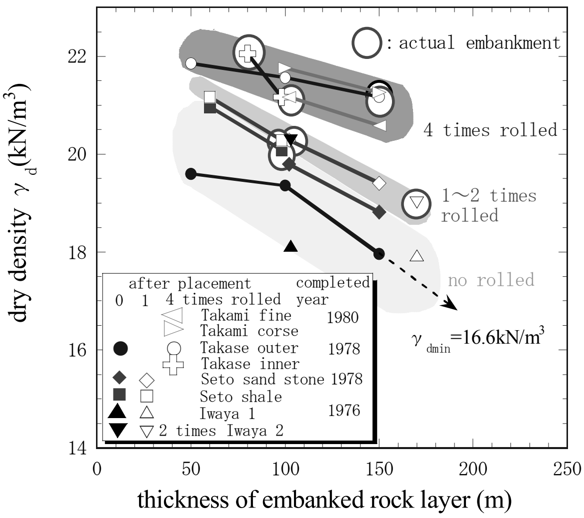

Figure.5 Density of Rock Zone by In-situ Compaction Test (Okamoto T., 2004)

3 CENTRIFUGE TEST RESULT

3.1 *Deformation mode and strain*

Okamoto T. et al. (2004) presents centrifuge test result of rockfill dam with 55cm height and 1:1.4 of both slopes under 50G. Fig.6 shows shear strain distribution for D2 (loose 10 cycles Sin wave) and D3 (dense Minowo wave recorded in Hy ougo-Ken

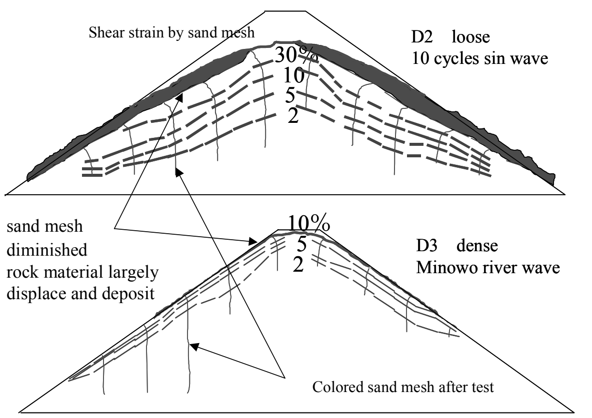

Figure.6 Final Residual Deformation and Shear Strain by centrifuge shaking table test (Okamoto et al. : 2004)

Nanbu E.), which provided of biggest and least residual deformation of 4 test cases shown by Okamoto et al. (2004). Generally shear strain is expressed as $\gamma = (\partial v/\partial x) + (\partial u/\partial y)$ here x, y : horizontal and vertical axis, in this test it can be assumed as $\gamma \cong \partial u/\partial y$ because the vertical displacement u is adequately less than the horizontal displacement v . So shear strain are calculated by the displacement of colored vertical sand mesh that is placed at the sidewall of test box. Fig.6 reveals that sand mesh diminished and rock material displace and deposit when shear strain is beyond 10% or several ten %, and that big displacement of the embankment is restricted near the surface and the crest without slip circle.

Fig.7 shows the vertical strain along the centerline and it depends on the density and loading wave as same as shear strain (Okamoto et al., 2004). The vertical displacement transducer LV installed 5m deep from the crest hardly moves except in D2 case. Therefore vertical displacement at the crest depends on the strain of the layer upper than 5m from the crest. Also horizontal displacement near the crest happens in the layer upper than 5m from the crest, so vertical displacement at the crest highly depends on the horizontal shear comparing with vertical compressive strain.

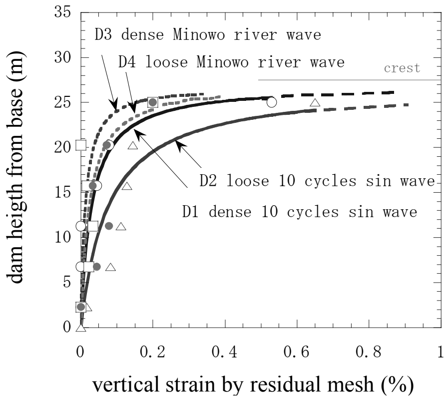

Figure.7 Vertical Strain along Center Axis after Shaking by Okamoto et al. (2004)

3.2 *Relationship between acceleration and settlement*

Several items should be discussed before comparison with in-situ observation results. Firstly the relationship between crest settlement and maximum base acceleration is valid and typical for residual deformation under strong earthquake, so crest settlement ratio is useful for this comparison as a non-dimensional parameter. Fig.8 shows the relation settlement ratio and maximum base acceleration by centrifuge test. And 1:1.4 of slope gradient is applied in this test, therefore the effect of slope gradient on the relationship shall be taken into account and this is evaluated later. Also sin and Minowo river waves are applied in this test, so the effect of input motion shall be taken into account, this is evaluated here. After Minowo river wave with 591 gal of maximum base acceleration is loaded in dense condition, additional same loading is applied. The incremental crest settlement by 2nd loading almost agrees with that by 1st loading and the residual deformation mode does not change. Therefore it is recognized that incremental settlement is valid for the relationship settlement is valid for the relationship as shown in Fig.8 (Okamoto et al., 2004, Okamoto T., 2004).

Calculating energy of loading waves, 1.8 Hz 10 cycles sin wave applied in this test has biggest energy of strong earthquake with almost magnitude 8.0, and Minowo rivser wave has smaller energy comparing with magnitude. Therefore it can be recognized that 1.8Hz sin wave loading shows almost upper biggest residual deformation and Minowo wave loading shows almost lower smallest residual deformation in all of cases with same maximum acceleration.

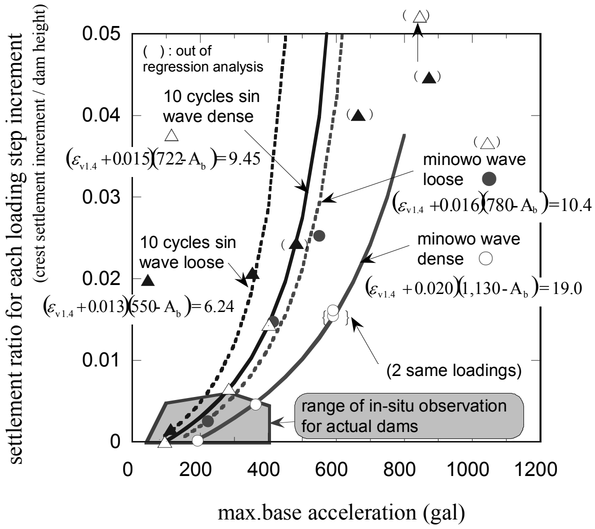

Figure.8 Incremental Crest Settlement and Max. Base Acceleration by Centrifuge Test (Okamoto et al. :2004)

4 CONSIDERATION AND CRITERIA ON RESIDUAL SETTLEMENT

4.1 *Effect of slope gradient on settlement*

Fig.9 and 10 indicate the effect of slope gradient on crest settlement using Fig.1 and 8 (Okamoto et al., 2004, Okamoto T., 2004). If 1.8Hz sin wave-loading shows almost biggest residual deformation and Minowo wave loading shows almost lower smallest residual deformation, the relationship between crest settlement ratio and maximum base acceleration by this centrifuge test with 1.4 of slope gradient is in good harmony with that by in-situ observation. However the result for center soil core type RD by Iwashita (2002) indicates smaller settlement ratio than the facing type RD, so detailed study is needed.

As above mentioned, 0.1-0.8% is critical crest settlement ratio in which impervious zone had some damage but not large enough not to be not able to repair the dam. Due to Fig.9 and 10, it found that crest settlement of dense dam is adequately small even if slope gradient is 1:1.4 in case of 200 gal of maximum base acceleration, and crest settlement ratio sometimes exceeds0.1-0.8% even with adequate compaction in case of 400 gal of maximum base acceleration.

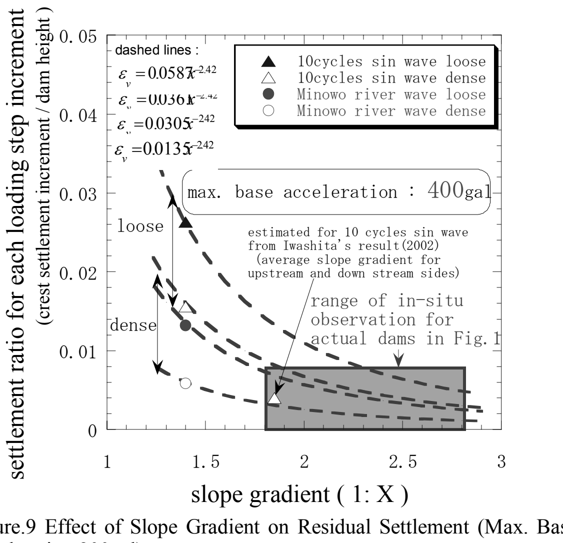

Figure.9 Effect of Slope Gradient on Residual Settlement (Max. Base Acceleration 200gal)

According to the results in Fig.8 and 9, some equations are derived and settlement ratio is estimated by following relation. For large magnitude ($M \cong 8-9$) (Okamoto et al., 2004) and for loose and dense dam each other,

$$\varepsilon_v = \{6.24/(550 - A_b) - 0.013\} \cdot (1.4/x)^{2.42}$$

$$\varepsilon_v = \{9.45/(720 - A_b) - 0.015\} \cdot (1.4/x)^{2.42} \quad (1)$$

For small magnitude ($M \cong 6.5-7$)(Okamoto et al., 2004) and for loose and dense dam each other,

$$\varepsilon_v = \{10.4/(780 - A_b) - 0.016\} \cdot (1.4/x)^{2.42}$$

$$\varepsilon_v = \{19.0/(1{,}130 - A_b) - 0.020\} \cdot (1.4/x)^{2.42} \quad (2)$$

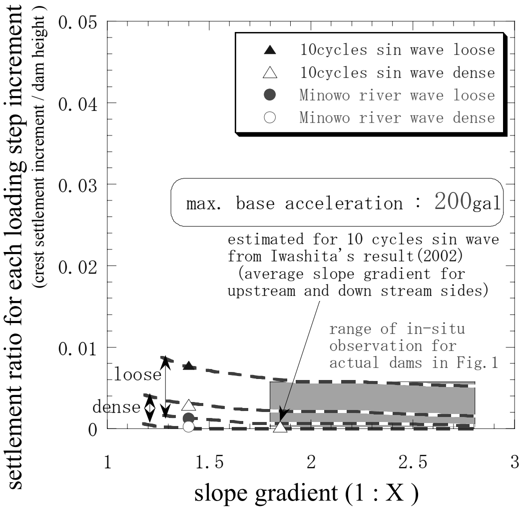

Figure.10 Effect of slope gradient on residual settlement (max. base acceleration 400gal)

4.2 *Criteria on residual settlement*

Freeboard has been often applied for recent evaluation of impounding performance by seismic analysis of fill dam in USA (Beikae et al., 1996). It means that if calculated crest settlement does not exceed freeboard i.e. embankment height upper than H.W.L., overflow will not cause and the dam will keep impounding performance. Freeboard of Japanese already constructed dams is shown in Fig.11 and the minimum freeboard is considered to be 3m. Leakage increment after earthquake has not been reported for all of soil core type rockfill dams as

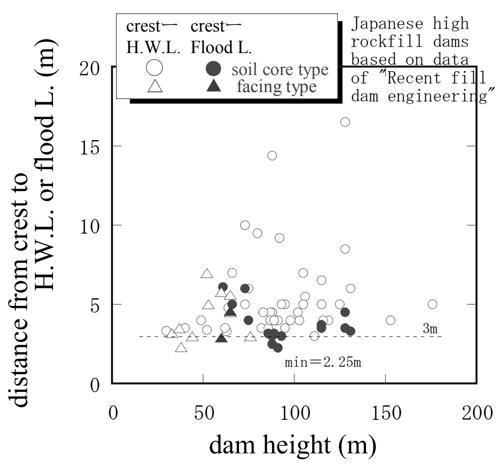

Figure.11 Freeboard of Japanese rockfill dams

shown in Fig.1. If allowable settlement assumes to be 50 cm which is close to maximum crest settlement for already constructed dams as shown in Table 1, it means that impounding performance is kept and severe damage is not caused for even 50 cm settlement. Only examples of Malpasso, Cogoti and Minase are reported for Concrete Facing RD and Cogoti and Minase were repaired for some leakage increment after earthquake. Crest settlement ratios are 0.00097, 0.0072 and 0.0021 for Malpasso, Cogoti and Minase. If critical crest settlement ratio is 0.001-0.008, it leads that it would cause leakage increment and damage of facing but it is not severe damage and it would be able to be repaired.

Table 1 Criteria of Residual Settlement

Damage or stable condition	Allowable level	Allowable quantity	Allowable Settlement or ratio for 50～200m of dam height
Overflow	Freeboard	＞Almost minimum is 3m due to each dam	＞Almost 6～1.5%
Stable for facing type RD But small leakage increment	Max. observed settlement or settlement ratio	Almost 0.5m	1.0%～0.25%
		Almost 0.8%	0.4～1.6m
Stable for center soil core RD And no leakage increment	Max. observed settlement or settlement ratio	Almost 0.5m	1.0%～0.25%
		Almost 0.8%	0.4～1.6m

5 CONCLUSIONS

Centrifuge test result of rockfill dam is compared with in-situ observation of existing dam. It is concluded as follows. Density of embankment affects residual deformation and big displacement of the embankment is restricted near the surface and the crest without slip circle. Relationship between crest settlement and maximum base acceleration in this test almost agrees with that of in-situ observation for existing dams, and it is affected by slope gradient and density of embankment. Beside allowable and critical settlement ratio is discussed for soil core and facing type RD.

REFERENCES

Beikae, M. M., Barneich, Luebbers J. and Osmun, D. 1996. Seismic deformation analysis of eastside reservoir dams, *Seismic design and performance of dams*, USCOLD, pp.315-331

Bureau, G., Volpe, R. L, Roth, W. H. and Udaka, T. 1985. Seismic analysis of concrete face rockfill dams, *proc. of the symposium on concrete face rockfill dams*, annual convention ASCE, pp.479-50

Noguera G. L. and Espinoza B. O. 1998. Seismic history of Cogoti dam, *Symp. of Rehabilitation of dams*, pp.213-220

Iwashita, T. 2002. Centrifuge test of rockfill dam and analysis by dynamic elasto-plastic effective stress program, *J. of dam engineering*, No.184, pp.32-42

Okamoto, T. 1999. Evaluation of measured vertical and horizontal residual deformation at crest of rockfill dam under earthquake, *IS-Shikoku 99, International Symp. on Slope Stability Engineering : Geotechnical and Geoenvironmental Aspects*, Nov. 8-11, pp.631-630

Okamoto, T., Uchita, Y., Tsuruta, S., Hoshino, Y. and Matsuda, T. 2004. Centrifuge test of rockfill dam and seismic stability evaluation basing on seismic response and residual deformation, *13th World Conference on Earthquake Engineering*

Okamoto, T. 2004. Recent trend for earthquake induced residual settlement of rockfill dam and some consideration of affecting factors, 4th International Conference on Dam Engineering, *New Developments in Dam Engineering*, pp.705-716

Tani, S. 1992. Earthquake damages of existing earth fill dam and evaluation of safety, *.J. of large dam*, Japanese society of large dam, No.140, pp.32-50