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CENTRIFUGAL MODEL TEST FOR DESTRUCTION OF DAM BODY INDUCED BY THE LIQUEFACTION OF ITS FOUNDATION*

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SUMMARY

Huge earthquakes have been occurred frequently in Japan and there are about 1200 irrigation fill dams which have passed over 50 years after construction. Some of such irrigation fill dams (especially, earth dams) have the problem about leakage and loss of cross section by aging. In these dams, countermeasures to constructing impervious zone on the upper slope of dam body as countermeasure against leakage and reinforcement are adopted frequently.

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* *Test de modèle centrifuge pour la destruction d'un corps de barrage causée par la liquéfaction de sa fondation*

Purpose of this study is to acquire the fundamental scientific knowledge about deformation and destruction behaviors of dam body with inclined core zoning, especially, in sight of the liquefaction of its foundation which is one of principal factor to induce large deformation during earthquake. Destruction mechanism of dam body developed by interactions among liquefiable foundation, dam body and reserved water are verified by the centrifugal liquefaction experiment. From results, it is clarified that dam body effects to the behavior of pore water pressure in the liquefiable layer. Increased value of pore water pressure under shaking become several times when dam body exists. However, retrofitting at the toe of downstream slope of dam body can inhibit the typical increasing of pore water pressure. And it is supposed that behavior of pore water pressure in liquefiable layer closely related to the deformation behavior of dam body.

Fracture of dam body with inclined core develop progressively according to the interactions among liquefiable foundation and dam body. And it is supposed that deformation of upstream slope of dam body is dominant factor to induce catastrophic destruction of dam body. Retrofit at the toe of downstream can restrain such deformation and, even though dam body damage severally, catastrophic destruction inducing over topping is prevented.

Keywords: Eathfill Dam, Seismic Behavior, Liquefaction, Centrifugal Test.

RÉSUMÉ

De violents tremblements de terre ont fréquemment lieu au Japon, et il existe environ 1200 barrages d'irrigation datant de plus de 50 ans depuis leur construction. Certains de ces barrages d'irrigation (en particulier les barrages en terre) connaissent des problèmes de fuite et de perte de section transversale causés par le vieillissement. Dans ces barrages, des contre-mesures contre les fuites et un renforcement sont fréquemment adoptées afin de construire une zone imperméable sur la pente supérieure du corps de barrage.

Le but de cette étude est d'acquérir les connaissances scientifiques fondamentales sur les comportements de déformation et de destruction du corps de barrage avec zonage du noyau incliné, notamment en vue de la liquéfaction de sa fondation qui est l'un des principaux facteurs causant une grande déformation durant un séisme. Le mécanisme de destruction du corps de barrage développé par les interactions entre la fondation liquéfiable, le corps du barrage et l'eau réservée sont vérifiés par l'expérience de liquéfaction centrifuge. D'après les résultats, il est précisé que le corps de barrage a des effets sur le comportement de la pression interstitielle dans la couche liquéfiable. La valeur accrue de la pression interstitielle sous secousse augmente fortement lors de la

présence du corps de barrage. Cependant, la rénovation à l'extrémité de la pente en aval du corps de barrage peut empêcher une augmentation caractéristique de la pression interstitielle. Il est également supposé que le comportement de la pression interstitielle dans une couche liquéfiable est étroitement lié à celui de déformation du corps de barrage.

La fracture du corps du barrage avec noyau incliné se développe progressivement en fonction des interactions entre fondation liquéfiable et corps de barrage. Il est également supposé que la déformation de la pente en amont du corps de barrage est un facteur dominant provoquant une destruction catastrophique du corps de barrage. La rénovation à l'extrémité de l'aval peut restreindre cette déformation, et malgré les dommages causés sur le corps du barrage, une destruction catastrophique pouvant causer un déversement est empêchée.

1. INTRODUCTION

Huge earthquakes have been occurred frequently in Japan, for example the 2011 off the Pacific coast of Tohoku Earthquake, the 2016 Kumamoto Earthquake and so on. And there are about 1800 irrigation fill dams, containing earth dams constructed before 1960s, when modern design methods were established for the construction of such dams. Tani .et.al. [1] report that there are 1208 fill dams with above 15m height constructed before 1960s and they account for almost 70% of irrigation fill dams. These dams have stood for over 50 years since they were first operated. And it is supposed that these dams were constructed without modern design methods and scientific knowledge of liquefaction, then their reliability about the safety against earthquakes are lower than those constructed based on modern methods. From these facts, accumulation of fundamental scientific knowledge about seismic behavior is very important to check the seismic performance. And some of fill dams passing long time after construction need to be repaired. Especially, dams that are importance in terms of agricultural activity and prevention against secondary disaster induced by burst are necessary to be repaired and retrofitted to increase their seismic performance. Constructing impervious zone on the upper slope of dam body as countermeasure against leakage and reinforcement is frequently adopted in repair of irrigation fill dams (especially, earth dams) which have the problem about leakage and loss of cross section by aging. Purpose of this study is to acquire the fundamental scientific knowledge about deformation and destruction behaviors of dam body with inclined core zoning, especially, in sight of the liquefaction of its foundation which is one of principal factor to induce large deformation during earthquake. Then, deformation and destruction mechanism of dam body developed by interactions among liquefiable foundation, dam body and reserved water are verified by the centrifugal liquefaction experiment.

2. EXPERIMENTAL CONDITIONS

Three models are used in these experiments to compare their behaviors. One is the model imitating the only liquefiable foundation and called as Case 1. Another is the model imitating the liquefiable foundation and dam body with inclined core zoning, called as Case 2. The other is the model imitating the retrofitting condition in which the toe of the downstream slope in Case 2 is buried and refilled with non-liquefiable materials, called as Case 3. Schematics of these models are shown in Fig. 1.

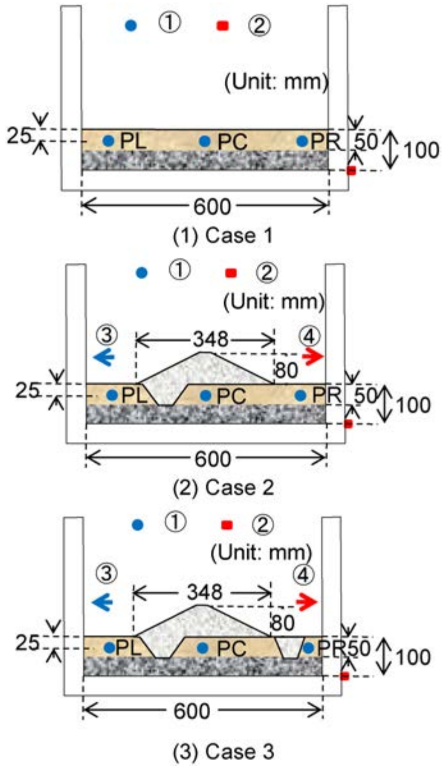


Fig. 1
Schematics of models
Schéma des modèles

1	Pore water pressure transducer	*1*	*Transducteur de pression intersitielle*
2	Accelerometer	*2*	*Accéléromètre*
3	Upstream	*3*	*En amont*
4	En aval	*4*	*En aval*

The depth of the liquefiable layer in each model is 50 mm. Basement layer is arranged below the liquefiable layer in order to moderate the influence of the bottom boundary of soil box. In Case 2 and Case 3, dam bodies, whose height is 80 mm, width of crest is 28 mm, and slope gradient is 1:2, and slope gradient of core trench is 1:1, are constructed on the liquefiable layer. In Case 3, slope gradient of improved zone at the toe of downstream slope is 1: 0.4. In each model, pore water pressure transducers are set at below 25 mm from the surface of liquefiable layer and an accelerometer is set at the bottom of soil box. In the centrifugal test, centrifugal acceleration is set as 200 m/s^2, then the height of estimated prototype of dam body is 1.6 m and the depth of estimated prototype of liquefiable layer is 1.0 m.

Procedures of making a model are shown in Fig. 2. Basement layer is made of coarse silica sand by tamping in dry condition. Liquefiable layer on the basement layer is made of fine silica sand with water content 5 % by tamping and its relative density (D_r) is 50 %. Density of liquefiable layer is controlled by checking the material weight dropped into soil box and the height of compacted soil layer. Fig. 2 (1) shows the situation of compacting material by hand and Fig. 2 (2) shows the overview of the compacted soil layers as liquefiable foundation. Before making dam body, prescribed area of liquefiable layer is dug and shaped into the core trench (Fig. 2 (3)). Dam body and core trench are made of mixture of fine sand and kaolin with mixing ratio 8:2 by tamping. Water content of mixture is 11 % and their degree of compaction (Dc) are 92 %. Degree of compaction of dam body

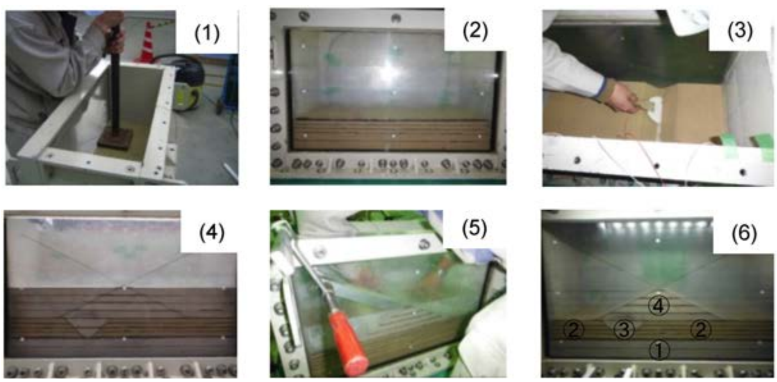
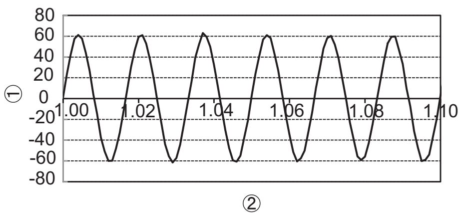


Fig. 2
Procedures of making model
Procédures de fabrication du modèle

1	Basement	*1*	*Sous-sol*
2	Liquefiable foundation	*2*	*Fondation liquéfiables*
3	Cut off	*3*	*Parafouille*
4	Dam body	*4*	*Corps du barrage*

and core trench is determined from the results of trial tests in which density of liquefiable layer does not change according to the compaction of dam body and core trench. Density control method of them is same as that of liquefiable layer. Fig. 2 (4) show the overview of compacted material of dam body. Here, black colored sand layers are arranged along the inner surface of acrylic board on liquefiable layer and dam body for easy observation of deformed model during the experiment. Dam body is shaped by cutting the compacted soil mixture layer as shown in Fig. 2 (5). Fig. 2 (6) shows the overview of completed model. Methods proposed by Okamura et.al. [2] are used as reference for saturating liquefiable layer. At first, CO_2 gas is fully flow into the liquefiable foundation from the bottom of soil box at vacuum state. Then soil box is kept at vacuum state and set on the centrifugal equipment. And the solution of cellulose ester (viscous fluid) is poured into the liquefiable foundation from the bottom of soil box by utilizing potential head between the tank setting on the soil box and bottom of soil box. Viscous fluid with viscosity *n* times of water is generally used in liquefaction experiment under centrifugal acceleration with *n* times of gravity acceleration. Centrifugal acceleration 200 m/s^2 is loaded in this experiment, then viscosity of cellulose ester solution is adjusted to 20 cSt. In test case with dam body, Case 2 and Case 3, solution of cellulose ester with higher viscosity 2000 cSt is poured as reserved water because effect of loads by reserved water is focused on and effect of seepage of reserved water into dam body and liquefiable foundation is inhibited.

Liquefaction experiment is performed under centrifugal acceleration 200 m/s^2. Amplitude of input wave is 3 m/s^2, frequency is 3 Hz and duration time is 400 s in prototype scale. Hereafter time converted into prototype scale is called as “converted time” to distinguish from real time scale. Pore water pressure is measured at each point shown in Fig. 1 and the movies of experiment are recorded by cameras set at front and top of the soil box during experiments. Acceleration at the bottom of soil box is recorded by accelerometers shown in Fig. 1 to confirm that shaking device can reproduce the prescribed wave properly. Accelerations measured at the bottom of soil box from 1.0 sec (converted time: 20 sec) to 1.1 sec (converted time: 22 sec) are shown in Fig. 3. Acceleration values are



1 Acceleration (m/s^2) — *1 Acceleration (m/s^2)*
2 Elapsed time (s) — *2 Temps écoulé (s)*

Fig. 3
Acceleration at the bottom of soil box
Accélération au fond de la boîte au sol

shown as real scale in Fig. 3. Then converted amplitude as prototype is almost 3 m/s^2 and frequency is 3 Hz, same as prescribed input wave.

3. RESULTS AND CONSIDERATION

3.1. BEHAVIOR OF PORE WATER PRESSURE

Time history of increase of pore water pressure are shown in Fig. 4. Here, elapsed time is expressed as real time and duration period of shaking is from 0 to 20 sec. Legend of each data in this figure is coincide with the accelerometer shown in Fig. 1.

From Fig. 4 (1), in Case 1 which imitate only liquefiable foundation, pore water pressures at all points increase immediately after start of shaking and decrease after reaching the peak even during shaking. Behaviors of increase of water pressure at PC and PR show almost same and maximum values of increase of water pressure reach to 4 kPa each other. However, times to reach the peak are different. It takes 2.5 sec (converted time: 50 sec) at PR and 4 sec (converted time: 80 sec) at PC after start of shaking. Behavior of increase of water pressure at PL show the same tendency as PR and PC. But maximum value of increase of water pressure at PL reaches to 7 kPa larger than the other points. Time to reach the peak at PL is 4 sec (converted time: 80 sec) same as PC. Hence these results have variations quantitatively but they show qualitatively the similar tendency such that pore water pressure values increase. From this results, it is supposed that liquefaction phenomena can be reproduced in this experiment.

In Case 2, as shown in Fig. 4 (2), maximum values of increase of water pressure reach to 15 kPa at PL, 16 kPa at PC and 17 kPa at PR respectively. These values show several times compared with those in Case 1. Behavior of increase of pore water pressure at PC and PR show the similar tendency at first. They increase immediately after start of shaking such as all points in Case 1, but behaviors after 3 sec (converted time: 60 sec) from start of shaking show different tendency. Pore water pressure at PC decreases after 3 sec (converted time: 60 sec) from start of shaking and then increases again after 6 sec (converted time: 120 sec) from start of shaking. It reaches at the peak after 11 sec (converted time: 220 sec) from start of shaking and then decreases. While pore water pressure at PR does not decrease but increase ratio of it decreases after 3 sec (converted time: 60 sec) from start of shaking. Pore water pressure at PR reaches at the peak after 13 sec (converted time: 260 sec) from start of shaking and then decreases. Pore water pressure at PL continues to increase during shaking and reaches at the peak after 20 sec (converted time: 400 sec) from start of shaking. Thus pore water pressure at PL increase gradually until end of shaking and its tendency is quite different from the other points.

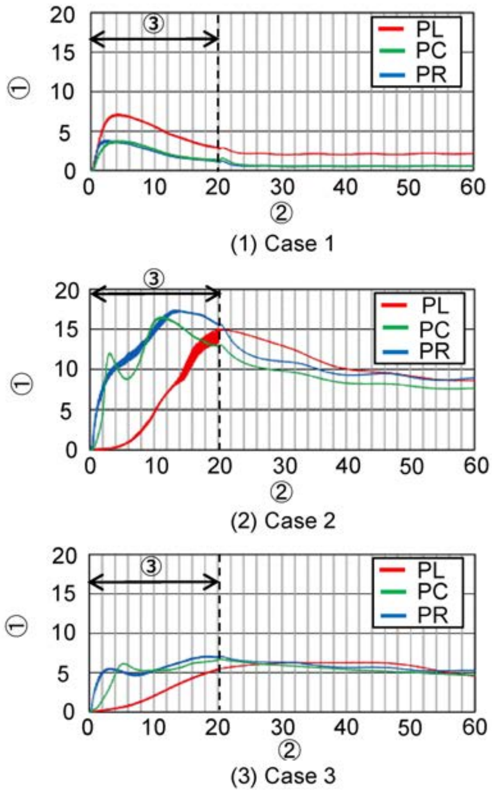


Fig. 4
Time histories of increase of pore water pressure in each case
Historique de l'augmentation de la pression interstitielle pour chaque cas

1	Increase of pore water pressure (kPa)	*1*	*l'augmentation de la pression interstitielle (kPa)*
2	Elapsed time (s)	*2*	*Temps écoulé (s)*
3	Shaking	*3*	*Secouant*

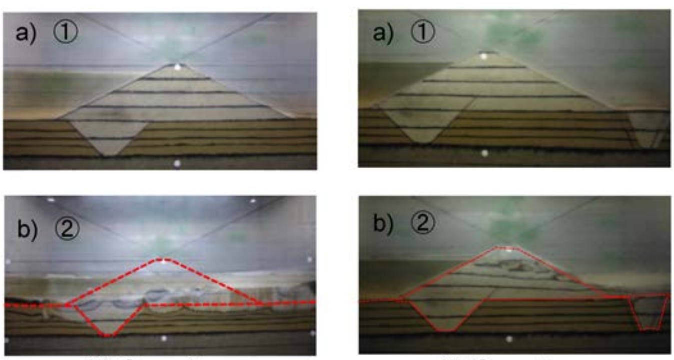
In Case 3, as shown in Fig. 4 (3), maximum values of increase of water pressure reach to 6 kPa at PL and 7 kPa at PC and PR. These values are almost same as Case 1. Pore water pressure at PR increases immediately after start of shaking and then decreases after 3 sec (converted time: 60 sec) from start of shaking. It increases again after 7 sec (converted time: 140 sec) from start of shaking and reaches at the peak after 20 sec (converted time: 400 sec) from start of shaking. While pore water pressure at PC does not show the rapid increase at the beginning of shake but continues to increase until 5 sec (converted time:

100 sec) and then decreases. It increases again after 12 sec (converted time: 240 sec) from start of shaking and reaches at the peak after 20 sec (converted time: 400 sec) from start of shaking. Pore water pressure at PL continues to increase during shaking and reaches at the peak after 20 sec (converted time: 400 sec) from start of shaking. Its behavior is same as PL in Case 2.

From these results, it is clarified that dam body effects to the behavior of pore water pressure in the liquefiable layer. Increased value of pore water pressure under shaking become several times when dam body exists. However, retrofitting at the toe of downstream slope of dam body can inhibit the typical increasing of pore water pressure and increased value of pore water pressure become almost same as the case of liquefiable foundation only without dam body.

3.2. DEFORMED SHAPES OF DAM BODY

Fig. 5 show the shapes of dam models before and after shaking in Case 2 and Case 3 respectively. In these figures, a) show the shapes of dam model before shaking and b) show the shapes of dam model after shaking. Dotted lines shown in b) express the original shapes of dam body. From figures shown in a), models don't deform under centrifugal acceleration 200 m/s^2 and reserve the water properly. It takes several hours after poring the reserved water but change of reserved water level is negligible. From this fact, it is confirmed that seepage of reserved water into dam body and liquefiable foundation is inhibited.



(1) Case 2 (2) Case 3

1 Before — *1 Avant*
2 After — *2 Après*

Fig. 5
Defromed shapes of dam body in Case 2 and Case 3
Formes crénelées du corps du barrage dans les cas 2 et 3

In Case 2, shown in Fig. 5 (1) b), dam body deform catastrophically and dam body and foundation become as one. Dam body settles into liquefiable layer and deforms toward downstream with large lateral flow. Core trench and upstream part of dam body deform toward upstream with lateral flow, but magnitude of the deformation is smaller than downstream part of dam body. From the situation of colored sand layer, it is recognized that center of core trench at the level of dam base rises but lower part of core trench does not deform remarkably. Similarly, from the situation of colored sand layer in liquefiable layer, it is found that upper half of liquefiable layer deforms predominantly. From these fact, it is supposed that remarkable flow of liquefiable layer arises in its upper part in Case 2.

While, from Fig. 5 (2) b), it is recognized that upper part of dam body deform severely but dam body can reserve water until end of the experiment in Case 3 retrofitted at the toe of downstream slope. It is found that crest and downstream portion of dam body deforms severely but large flow toward downstream such as Case 2 is inhibited, and flow in the core trench and upstream portion of dam body is negligible. Thus it is concluded that deformation of dam body and liquefiable layer, especially remarkable flow towards upstream and downstream, is prevented by retrofit at the toe of downstream slope.

3.3. Destruction mechanism of dam body

Destruction mechanism of dam body induced by liquefaction of its foundation is examined from the behaviors of pore water pressure in liquefiable layer and deformation of dam body. Tendencies of increase of pore water pressure in Case 2 and Case 3 are more complicated than those in Case 1 during shaking. It is supposed that the difference of increase of pore water pressure in liquefiable layer at the beginning of shake between in liquefiable foundation only model (Case 1) and model with dam (Case 2 and Case 3) is caused by difference of initial stress conditions. From the recorded movie, it is clarified that the times, at which tendencies of deformed behavior of dam body change, is correspond to time, at which tendencies of pore water pressures in liquefiable layer (shown in Fig. 6.4) change. From this fact, it is supposed that behavior of pore water pressure in liquefiable layer closely related to not only initial stress condition but also the deformation behavior of dam body. Remarkable difference of increase of pore water pressure between Case 2, in which dam body deforms catastrophically because of lateral flow of liquefiable layer and dam body, and Case 3, in which deformation of dam body is restricted by the retrofit at the toe of downstream slope, may cause this relationship.

From the movie of Case 2, it is recognized that downstream portion of dam body remarkably deform toward downstream at first and then crest and upper part of upstream slope deform toward downstream like falling down. And then cracks on the upstream slope of dam body arise and dam body begins to flow toward not only downstream but also upstream. Thus deformation behavior of dam body changes progressively on the way of shaking, and dam body reaches to catastrophic destruction finally. While arise of cracks on the upstream slope is restricted in Case 3. From this results, it is considered that progress of deformation at crest and upper part of upstream slope is moderated by the retrofit at the toe of downstream slope in Case 3, and then dam body is damaged severely but catastrophic destruction inducing over topping is prevented.

Thus destruction of dam body induced by liquefaction of its foundation develops progressively by interaction between increase of pore water pressure in liquefiable foundations and deformation of dam body.

4. CONCLUSION

Destruction mechanism of dam body developed by interactions among liquefiable foundation, dam body and reserved water are verified by the centrifugal liquefaction experiment in sight of the liquefaction of foundation which is one of principal factor to induce large deformation of dam body during earthquake.

From results of experiment, it is clarified that fracture of dam body with inclined core develop progressively according to the interactions among liquefiable foundation and dam body. And it is supposed that deformation of upstream slope of dam body is dominant factor to induce catastrophic destruction of dam body. It is clarified that retrofit at the toe of downstream can restrain such deformation and, even though dam body damage severally, catastrophic destruction inducing over topping is prevented.

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