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DISCUSSION ON THE MECHANISM OF THE DESTRUCTION OF A SMALL-SCALE DAM BY THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE AND RECONSTRUCTION AND REINFORCEMENT*

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SUMMARY

In Japan, where rice farming is the main agricultural activity, the advancement of civil engineering technology has facilitated the development of new paddy fields and new agricultural facilities and there are approximately 210,000 small-scale

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* *Discussions sur le mécanisme de destruction d'un petit barrage par le séisme de 2011 de la côte pacifique du Tôhoku et sa reconstruction/renforcement*

dams that irrigate farmland in areas where there are no large rivers. Many of these small-scale dams are earthfill dams. Because of the shortage of suitable embankment materials, the embankments of many of these small-scale dams have an insufficient degree of compaction. The reconstruction of the Fujinuma Dam, a small-scale dam in Fukushima Prefecture, which was destroyed by the Great East Japan Earthquake, incurring loss of human lives, is described in this paper.

The safety standard for the reconstruction of the Fujinuma Dam was defined as “constructing a safe and reliable dam that is overwhelmingly more seismic resistant than the failed old dam,” based on the results of analysis of the causes of the failure of the old dam. The technical goal for the reconstruction was defined as “ensuring the safety of the dam against the largest possible ground motion expected in future.” As the new dam had to be constructed as a high-quality dam with a larger degree of compaction than the old one to satisfy the standard and achieve the goal, a standard for the degree of saturation, which had not been used in the conventional dam construction, was defined for the reconstruction of the Fujinuma Dam. The design and the results of the execution control tests are discussed in this paper.

Keywords: Body of Dam, Dam, Damage, Design, Fill Dam, *Quality Control*, Reinforcement, Repair, Risk Analysis, Safety of Dams, *Strengthening*, Zoned Dam, Fujinuma Dam.

RÉSUMÉ

Au Japon, où la riziculture est l’activité agricole principale, les progrès des technologies de génie civil ont facilité le développement de nouvelles rizières et de nouveaux ouvrages agricoles; ainsi, quelque 210.000 petits barrages irriguent des terres agricoles dans des régions dépourvues de grandes rivières. Beaucoup de ces petits barrages sont des barrages en terre. À cause du manque de matériaux d’endiguement adaptés, les digues de beaucoup de ces petits barrages ont un degré de compactage insuffisant. La reconstruction du Barrage de Fujinuma, un petit barrage dans la Préfecture de Fukushima détruit par le Séisme de 2011 de la côte Pacifique du Tôhoku, qui a entraîné la perte de vies humaines, est décrite dans cet article.

La norme de sécurité adoptée pour la reconstruction du Barrage de Fujinuma a été : « construction d’un barrage sûr et fiable largement plus antisismique que l’ancien barrage défaillant », sur la base des résultats d’analyse des causes de la défaillance de l’ancien barrage. Et « assurer la sécurité du barrage contre le plus important mouvement du sol prévu dans l’avenir » a été défini comme objectif technique de la reconstruction. Le nouveau barrage devant être construit en tant que barrage de haute qualité à degré de compactage plus élevé que l’ancien pour satisfaire cette norme et réaliser cet objectif, une norme de saturation, qui n’était pas encore appliquée pour la construction d’un barrage, a été définie comme la norme spécifique pour la reconstruction du Barrage de Fujinuma. La conception et les résultats des tests de contrôle de l’exécution sont présentés dans cet article.

1. INTRODUCTION

In Japan, where rice farming is the main agricultural activity, the advancement of civil engineering technology has facilitated the development of new paddy fields and new agricultural facilities. In Japan, there are approximately 210,000 small-scale damsthat irrigate farmland in areas where there are no large rivers. Many of these dams were constructed many years ago. Approximately 70% of the reservoirs irrigating an area larger than 2ha were constructed before the year 1600. They were constructed using technology developed locally based on experience through repeated trial and error. Most of these small-scale dams are earthfill dams constructed with multiple earth materials. Like river levees, their embankments have been raised, damaged and reconstructed repeatedly. Heterogeneous materials such as volcanic sandy soil and cohesive soil with high water content found near dam sites have been widely used as the embankment materials of these dams in Japan where layers of volcanic ash are widely distributed. Because of the use of heterogeneous materials, as well as the shortage of suitable embankment materials, the embankments of many of these small-scale dams have an insufficient degree of compaction.

In view of this situation, we analyzed the mechanism of the failure of the Fujinuma Dam in Fukushima Prefecture caused by the 2011 off the Pacific coast of Tohoku Earthquake and took measures focused on the design and construction control for reconstruction of the dam, which is describedin this paper.

2. CONDITION OF THE SOIL MATERIALS IN THE FAILED OLD DAM AND ANALYSIS OF THE PROGRESS OF THE DESTRUCTION BY GROUND MOTION

2.1. DAMAGE CAUSED BY THE GREAT EAST JAPAN EARTHQUAKE

The record of damage to small-scale dams caused by natural disasters in recent years shows that approximately 70% of the damage was caused by heavy rain and approximately 30%was caused by earthquakes. One of these earthquakes, the Great East Japan Earthquake that occurred on 11th March 2011, caused damage to numerous small-scale dams, including cracks and breakages of dam crests and subsidence, deformation and slope failure of dams. (Table 1)

Table 1
Estimated number of damaged reservoirs and the damage

DESCRIPTION OF DAMAGE	NUMBER OF DAMAGED RESERVOIRS (IN IWATE, MIYAGI AND FUKUSHIMA PREFECTURES)
Dam failure	4
Cracks, slip failure and displacement	451
Damage to parapets and protective walls, fallen trees	150
Subsidence	174
Piping	2
Tsunami	8
Damage to ancillary facilities	101
Total	890

The earthquake caused the failure of the Fujinuma Dam and the failure caused serious damage including the loss of human lives in the area downstream of the dam. The Fujinuma Dam is an irrigation dam in Sukagawa City, Fukushima Prefecture. Its reservoir had a water storage capacity of 1.5 million m3. At the time of the earthquake, a large quantity of water was stored in the reservoir for the coming farming season and the water level was close to the high water level. The earthquake caused the failure of the 18.5m-high 133.2m-long embankment of the dam. A large quantity of water stored in the reservoir flooded the area downstream of the dam and the flood water caused the loss of eight precious human lives. The failure of a small-scale dam or an irrigation dam caused by an earthquake has very rarely incurred casualties in Japan. Fig 1 shows the failing embankment of the Fujinuma Dam.

Fig. 1
Failing main embankment of the Fujinuma Dam
(ataround 15:11, 11th March 2011)
Digue principale défaillante du Barrage de Fujinuma
(vers 15 h 11, le 11 mars 2011)

2.2. CAUSES OF THE FAILURE OF THE FUJINUMA DAM

After the failure of the Fujinuma Dam, Fukushima Prefecture established the “Committee for the Verification of Seismic Resistance of Irrigation Dam/Reservoirs in Fukushima Prefecture,” whichconsists of three experts. The committee investigated the causes of the failure and conducted a risk analysis. In the conclusion to their investigation, the committee assumed that the poor quality and loose compaction of the soil embankment materialsused in the damhad been the direct cause of the failure and that the characteristics of the ground motion and the specific form of the development of slip failure triggered the failure [1], [2] (Fig. 2).

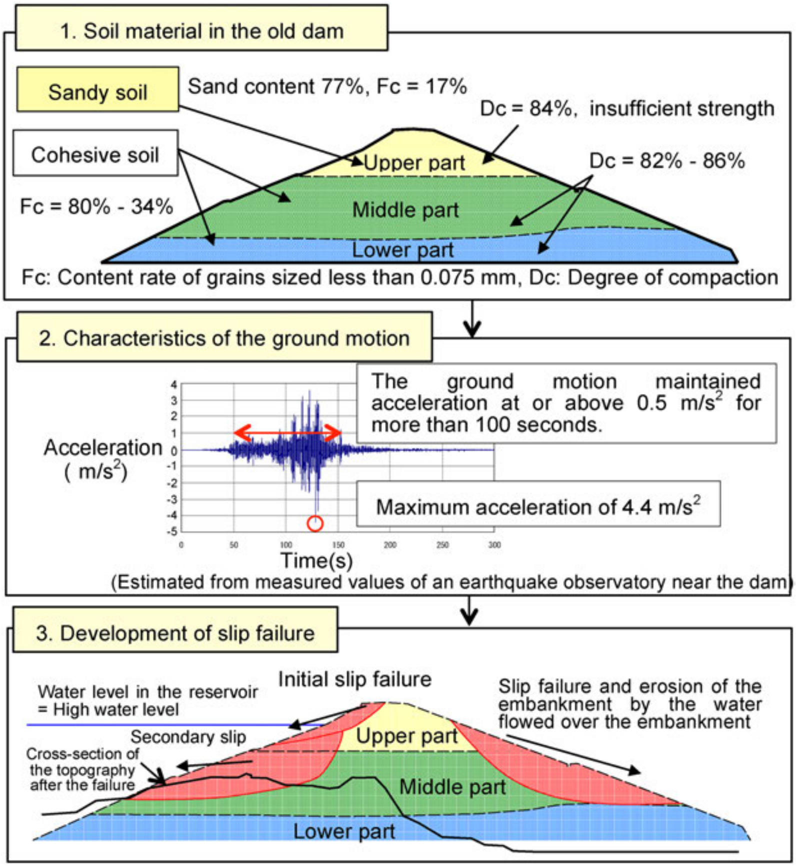

Fig. 2
Causes of the failure
Causes de la défaillance

Fig. 3
Scene of the main embankment failure 60 minutes after the earthquake
Scène de défaillance de la digue principale 60 minutes après le séisme

3. LESSONS LEARNED FROM THE RISK ANALYSIS OF THE FAILED DAM AND SAFETY STANDARDS FOR DAM RECONSTRUCTION ACCEPTABLE TO THE BENEFICIARIES AND VICTIMS

3.1. Reconstruction Plan

Fukushima Prefecture established the "Fukushima Prefecture Fujinuma Dam Reconstruction Committee," a committee of experts. The committee was expected to conduct technical studies on the design and construction methods to reconstruct safe and reliable dams that would prevent the occurrence ofsimilar incidentsat the Fujinuma Dam site.

The committee developed a safety standard and basic policies for the reconstruction of the Fujinuma dam. The safety standard was defined as "constructing a safe and reliable dam that is overwhelmingly more seismic resistant than the failed old dam" and the basic policies were defined as 1) "constructing a dam 'markedly' more stable than the failed old one," 2) "constructing a dam that is stable underthe influence of ground motionat the level equivalent to that caused by the 2011 Tohoku Earthquake," and 3) "conducting a detailed study of the design and its seismic performance and using the results of the study to construct a dam that satisfies the above-mentioned conditions." The design described in Tables 2, 3 and 4 and Fig. 4 was prepared forthe new Fujinuma Dam based on the results of the risk analysis of the damaged dam (Table 2).

Table 2

Results of the risk analysis of the damaged dam and reconstruction plan

ANALYSIS POINT	**RISK FACTOR OF THE DAMAGED DAM**	**RECONSTRUCTION PLAN**
Characteristics of material	The strength of the dam whensaturated with seepage water was compromised by the ground motion.	Materials that can be compacted tightly shall be used for construction. Construction control standards shall be established.
Dam structure	The homogenous structure made it difficult to drain seepage water out of it.	The new dam should have a cross-section structure that allowsquick drainage of seepage water (*i.e.* a dam with a central core with a wastewater drain).
Quality Control	Different materials compacted to different degrees were used in the upper, middle and lower parts of thedam.	Quality control standards shall be established to use homogenous materials and a homogenous degree of compaction in the construction of each zone in the embankments.
Ground motion	The strongest-ever ground motion hit the dam.	A seismic performance analysis should be conducted to verify that it would be stable under the influence of a ground motion equivalent to that caused by the 2011 Great East Japan Earthquake.

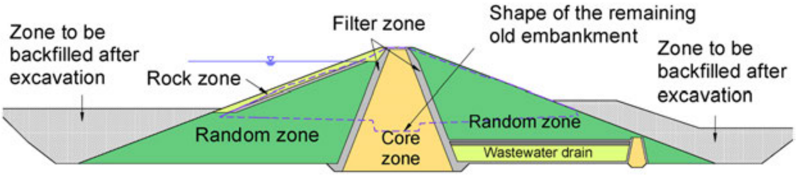

Fig. 4

Standard cross-section of the new dam

Coupe transversale standard du nouveau barrage

The new damwas designed as a dam with a center core, the width of which was greater at the bottom than the depth of the water to be stored in the reservoir. This core width is required to ensure water-shielding of the core zone. A filter zone was to be installed in the downstream side of the core zone. The water seeped into the embankment was to be drained out and the drain was to be connected to the filter zoneto prevent the formation of a phreatic surface in the downstream side of the embankment. The proposed foundation ground of the new dam should have an N value of 30 or more. Therefore, the foundation of the new dam was to be excavated deeper in the ground than the level of the foundation of the old one. The excavated portions were to be backfilled to the original ground level after the construction of the new dam (Fig.4).

Table 3
Materials of the major zones

ZONE	MATERIAL
Core zone	Mixture of clayey soil and gravelly soil ((clayey soil): (gravelly soil) =1:3 (dry weight ratio))
Random zone	Mixture of materials excavated in the foundation work (tuff) and crashed stone ((tuff): (crashed stone) =1:3 (dry weight ratio))

Table 4
Dimensions of the dams

DIMENSION	RECONSTRUCTION PLAN	OLD EMBANKMENT
Height	31.4m	18.5m
Length	149.2m	133.2m
Volume	230,000m^3	99,000m^3

3.2. Verification of the Seismic Performance of the New Dam

We conducted a detailed study of the seismic performance of the design cross-section of the planned new dam against the ground motion presumably caused by the 2011 Tohoku Earthquake. We used the Modified Newmark D Method in this study. The purpose of the study was to verify that the new dam “is ‘markedly’ more stable than the failed old dam” and “is stable under the influence of ground motion at the level equivalent to that caused by the 2011 Tohoku Earthquake.” The study revealed that, while the old dam would suffer large slip failure and large subsidence from a Level 2 ground motion, the slippage and subsidence of the new dam caused by the same motion would be close to 0. The results of this study confirmed that a safe dam would be reconstructed with this design in the design stage.

Table 5
Results of the study to verify the seismicperformance of the new dam

TYPE OF DAM	LEVEL 2 DESIGN GROUND MOTION (VERIFICATION USING THE NEWMARK D METHOD)	
	EQUIVALENT TO THE 2011 TOHOKU EARTHQUAKE (MEGATHRUST EARTHQUAKE)	INLAND EARTHQUAKE
Old dam	Slippage: 2.6 m Maximum vertical subsidence: 1.97 m	
New Dam	Both slippage and subsidence: 0.0 m	Slippage: 0 - 3.3 mm

Level 2 design ground motion: The largest possible earthquake within the assumed range

4. CONSTRUCTION CONTROL STANDARDS AND QUALITY CONTROL METHODS FOR DAM RECONSTRUCTION

Actual construction work must reflect the results of the detailed study of the design and seismic performance, and the reconstruction of a safe and reliable dam must realize the level of safety verified in the design stage. Therefore, in order to ensure the safety of the dam to be constructed, prior to the commencement of construction work, we developed construction control standards including those for embankment materials, the field water content working range, a compacted density and degree of saturation Sr (a new standard on the optimum degree of saturation not included in the conventional standards) of the embankments and the subjects and frequency of the investigation of roller compactors and embankment management.

Before commencement, we conducted an embankment test using different numbers of compaction with roller compactors and different field water content working ranges and identified the most cost-efficient combination of the specifications of these two factors on the condition that the embankment to be constructed would satisfy the required conditions by comparing a characteristic of the roller compaction (the density of embankment materials measured on-site) and the permeability characteristics of the test embankments. As it was known that the core materials and random materials had to be dried before use in construction due to their large water content, we determined the condition for a field water content working range that gave greater compacted density and water-shielding performance with an amount of drying that would not affect the work schedule.

When we established the standards for the density and field water content working range of embankments, we used not only the control of the compaction degree, a conventional control method, but also the control focused on the degree of saturation of the embankment. This control of the saturation degree is a method to control soil compaction proposed by Professor Fumio Tatsuoka, professor emeritus of the University of Tokyo/part-time professor of Tokyo University of Science. It sets a control range of the degree of saturation for a required quality usingthe ‘optimum degree of saturation’ as the standard [3] (Fig. 5). It isthe degree of saturation when soil has the maximum dry density, which is characteristically within a limited range if the changes in the energy of compaction and soil characteristics are within certain ranges. This control of the degree of saturation has enabled better management of the execution of the embankment work as such control can prevent soil strength reduction due to over-compaction and strength reduction and collapse subsidence due to the seepage of water into relatively dried soil, which have been difficult to prevent with conventional methods.

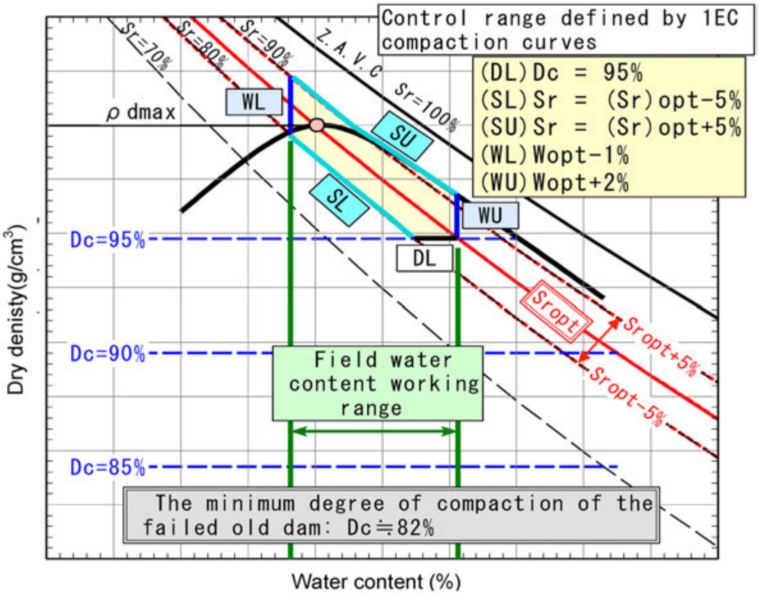

Fig. 5

Control conditions of the core zone

Conditions de contrôle de la zone centrale

Table 6

Concept of embankment saturation regulation

LIMIT OF CONTROL RANGE	**REQUIRED PERFORMANCE**			
	LARGE STRENGTH AND RIGIDITY	**SUPPRESSION OF STRENGTH REDUCTION AND SUBSIDENCE WITH WATER SEEPAGE**	**WATER-SHIELDING PERFORMANCE**	**PREVENTION OF OVER -COMPACTION**
Water content lower limit: WL	º	•	º	
Water content upper limit: WU	•			•
Degree of compaction lower limit: DL	•		º	º
Degree of saturation lower limit: SL		•	•	
Degree of saturation upper limit: SU*	º			•

•: Performance highly required

º: Performance required

* The upper limit of the degree of saturation, SU, is used when the embankment work commences because Sr after compaction is not known at that point. This limit will no longer be used after the embankment work has commenced.

We established the specifications for the embankment work in dam reconstruction that ensured that the reconstructed dam had the required degree of compaction, permeability and shear strength based on the results of the embankment test (Table 7). We also set the subjects and frequency of the control tests during the construction period so that the embankment work could be implemented while the quality of finished work being evaluated regularly (Table 8).

Table 7

Specifications for the embankment work in dam reconstruction

ZONE	**SPREADING PROCESS**		**COMPACTION PROCESS**	
	FINISHED THICKNESS	**MAXIMUM GRAIN SIZE DMAX**	**TYPE OF ROLLER COMPACTOR**	**NUMBER OF COMPACTION**
Core zone (water-shielding materials)	20 cm	$\leq$ 150 mm	19 ton-class vibratory/ tamping roller	$\geq$ 8
Filter zone (permeable material)	20 cm	$\leq$ 40 mm	11 ton-class vibratory roller	$\geq$ 4
Random zone (Semi-permeable material)	20 cm	$\leq$ 150 mm	19 ton-class vibratory/ tamping roller	$\geq$ 8
Rock Zone (permeable material)	80 cm	$\leq$ 600 mm	11 ton-class vibratory roller	$\geq$ 8

Table 8

Quality control standards and frequency of quality control (core zone)

CONTROL ITEM			**CORE ZONE (WATER-SHIELDING MATERIAL)** **STANDARD CORE** **[MIXED MATERIAL]** **(FINE GRAINED MATERIAL) : (GRAVELLY MATERIAL) = 1: 3 (DRY WEIGHT RATION)**	
			CONTROL VALUE	**CONTROL FREQUENCY**
Field density control	Degree of compaction	Dc (%)	$\geq$ 95%	Once/day (Three samples/round)
	Degree of saturation	Sr (%)	Sropt-5% - Sropt+5% (Target value: Sropt)	
Field coefficient of permeability	Coefficient of permeability	k (cm/sec)	$\leq 1 \times 10^{-5}$ cm/sec	Once/day (Three samples/round)

*The values of Wopt, Sropt and Dc in the table above are water content, degree of saturation and degree of compaction, respectively, when the energy of compaction, Ec, = 100%, is applied to the embankment material.

5. METHOD OF EVALUATING THE SAFETY OF THE RECONSTRUCTED DAM

The technical goal of the safety evaluation of the new damwas selected as “ensuring the safety of the dam against the largest possible ground motion expected in future.” Therefore, we confirmed the results of the control test of embankment materials and embankment work and installed measuring equipment in the dam foundation and embankment to monitor the behavior of the dam during the construction period from the start. We commenced reconstruction in October 2013 after conducting studies on these plans based on the discussion in the Reconstruction Committee and completed the embankment work in November 2016 [4].

Fig. 6
Embankment work
Travauxd’endiguement

6. RESULTS OF EXECUTION CONTROL AND TEST IMPOUNDING OF THE RESERVOIR AFTER THE COMPLETION OF RECONSTRUCTION

We conducted the execution control tests and confirmed that all the zones in the dam, i.e. the core, random, filter and rock zones, satisfied all the control standards. The core and random zones of the reconstructed dam have a particularly large degree of compaction compared with the failed old dam. Tables 9 and 10 shows the results of the density control test of the core and random zones, respectively. The test showed that both the core and random zones have a large degree of compaction close to the degree of compaction of Dc = 100% (Dc ≈ 97% and Dc ≈ 98.1% for the core and random zones, respectively).

Table 9
Results of the core-zone density control test

	RESULTS OF THE CORE-ZONE DENSITY CONTROL TEST				
	DRY DENSITY	**WATER CONTENT (%)**	**DEGREE OF SATURATION**		**DC**
	$\rho\mathbf{d}_{-19.0mm}$	$W_{-19.0mm}$	**Sr**	**Sropt-Sr**	
	(t/m^3)	**(%)**	**(%)**	**(%)**	**(%)**
Number of data	507	507	507	507	507
Mean	1.708	19.0	87.3	-0.6	97.0

Table 10
Results of the random-zone density control test

	RESULTS OF THE RANDOM-ZONE DENSITY CONTROL TEST				
	DRY DENSITY	**WATER CONTENT (%)**	**DEGREE OF SATURATION**		**DC**
	$\rho\mathbf{d}_{-19.0mm}$	$W_{-19.0mm}$	**Sr**	**Sropt-Sr**	
	(t/m^3)	**(%)**	**(%)**	**(%)**	**(%)**
Number of data	108	108	108	108	108
Mean	2.051	9.6	82.9	-2.2	98.1

Fig. 7 shows the results of the field density test of the core zone. In this figure, the field density test values measured at each point of measurement in the core zone are plotted with the average compaction curve derived from multiple compaction curves obtained in the control test of the core zone.

Fig. 7 shows that Point A, which represents the mean degrees of compaction and saturation of the core zone (Dc = 97.0% and Sr = 87.3%, respectively), is near the center of the control zoneand that a dam that has a degree of compaction much larger than that of the failed old dam (Dc = 84% in the upper part of the embankment shown as Point C) has been constructed. Although we observed oversaturation at some measuring points in the test, we concluded that this oversaturation will not cause any problems because the embankment was designed on the condition at Point B to be on the safe side, the number of points with oversaturation was not large andthe minimum control standard of the degree of compaction, Dc = 95%, was achieved in all the observation points.

We have also confirmed that all the measuring equipment installed in the embankment and foundation worked normally in the test. We have managed to

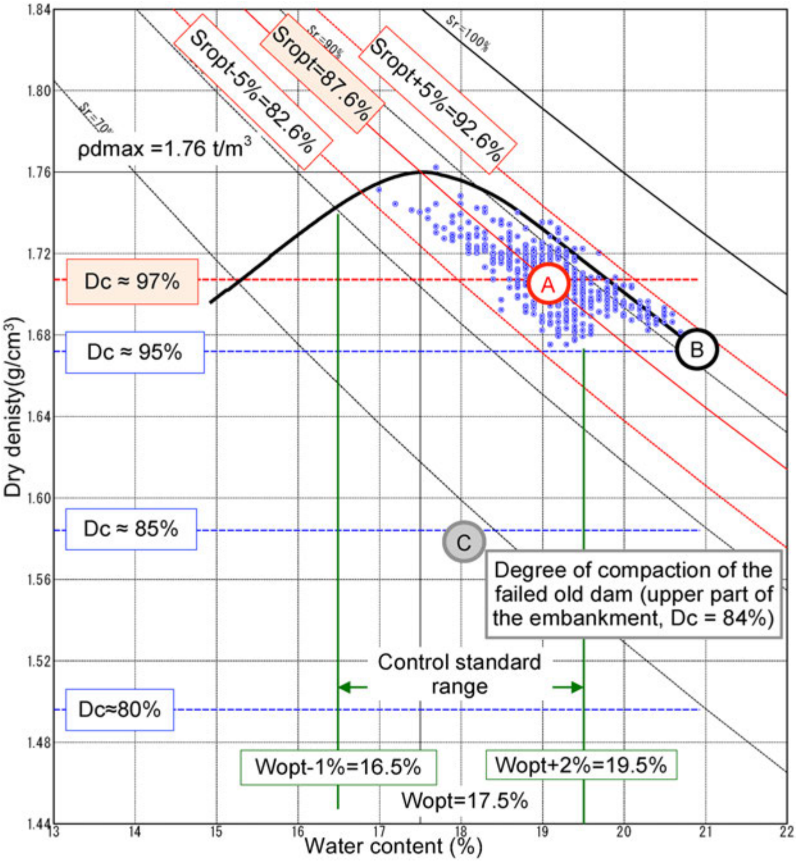

Fig. 7

Results of the field density test of the core zone (presented against the mean compaction curve)

Résultats du test de terrain pour mesurer la densité de la zone centrale (par rapport à la courbe de compactage moyenne)

achieve the basic policy of "conducting a detailed study of the design and its seismic performance and using the results of the study to construct a dam that satisfies the two above-mentioned conditions."

As we had confirmed that the new dam was much stronger than the failed old one and satisfied the required quality, as mentioned above, we began test impounding of the reservoir on 18th January 2017.

Fig. 8
Embankment at the commencement oftest impounding
Digue principale au commencement de la mise en eau d'essai

The water level in the reservoir reached EL 412.75 (1.05 m below the full water level of F.W.L. 412.75) on 18th April 2017. As the local residents were waiting fora supply of irrigation water from the reservoir, the discharge of water from the reservoir commenced on 20th April 2017 while test impounding of the reservoir continued. We observed no deformation of the dam or abnormal behavior of seepage water during the impounding period. We planto begin test impounding in mid-October 2017 to reconfirm the behavior of the dam up to the point where the water level in the reservoir reaches the full water level.

7. CONCLUSION

The ground motion caused by the 2011 Tohoku Earthquake triggered the failure of the Fujinuma Dam. A plan for reconstruction of the dam was prepared using lessons learned from the analysis of the factors of the failure. A dam that fully satisfied the performance requirements of the plan was reconstructed based on concerted effort in design and construction work. The construction of an embankment with a large degree of compaction was achieved due to the use of control standards that focused on the degree of saturation of the embankment, which had not been used in the management of dam construction work before. As the dam has also shown sufficient water-shielding performance and stability in test impounding, we consider that the Fujinuma Dam has been reconstructed as a dam that is safe and stable against large-scale ground motions.

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