A Practical Consideration on the Damage to Old and Small Irrigation Dams by the 2011 Tohoku Earthquake

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ABSTRACT:

In Japan, numerous small dams have been constructed and operated for the irrigation of paddy since ancient times. Taking into consideration of the increase of the numbers of aging dams in the world, the practical engineering learnt from the experience through the ages in Japan should be placed additional emphasis. Under these circumstances, the catastrophe that is "The 2011 Tohoku Earthquake" occurred. The agricultural facilities including small and old dams were severely damaged although large dams adhering to the sophisticated design standard were not suffered from severe damage. In three main disaster prefectures located in North-East of the Main Island of Japan, about 12,521 small dams are still in use for irrigation. It is reported that approximately 1,800 dams, about 14% out of total, were damaged and about 500 dams within the 1,800 were damaged so seriously as to need immediate care. Approximately 890 items of defects were identified on 500 dams. Most of them are slides, cracks, openings, displacement, depressions and settlement of embankments and failures of appurtenances. The on-site conditions and assumed causes of these defects stated above should be practically examined and evaluated in this paper, referring to several case studies.

The practical knowledge obtained may contribute to proper remedial designs and provide important clue to the appropriate revision of standards or criteria of not only small old dams but also large dams in some cases. This knowledge is also considered to be very useful for the appropriate operation and maintenance of aging dams around the world.

Keywords: The 2011 Tohoku Earthquake, Aging dam, Seismic damage, Seismic safety examination

1. INTRODUCTION

In Japan, the small and old irrigation dams are called "TAMEIKE" that literally mean "reserve water tank". Whenever earthquakes occur, special attention is paid to TAMEIKE because they are so numerous and so old that their structural and hydraulic integrity is cause for concern. Most of TAMEIKE are constructed, at least 100 years ago or more, for the cultivation of paddy. The embankments and appurtenances of TAMEIKE have been damaged and collapsed several times. The remedial repairs, modifications and alternations have been carried out repeatedly by farmer's organizations through the ages. The 2011 Tohoku Earthquake occurred on March 11, 2011 and ensuing destructive Tsunami ,the strongest to ever hit Japan, caused catastrophic damage mainly in three prefectures, Fukushima, Miyagi and Iwate. The incredible and incomprehensible temblor and waves destroyed entire towns, communities, public facilities and left death and destruction in its wake. The horrific scenes will remain in our collective consciousness forever. TAMEIKE were also severely damaged although large irrigation dams which were constructed adhering to the design standards directed by the Ministry of Agriculture, Fisheries and Forestry (MAFF) fortunately saved many from disastrous damages and failures. It is reported by MAFF that about 1,784 TAMEIKE, 14% out of a total of about 12,520 in the main disaster prefectures, were damaged and four TAMEIKE collapsed. It is considered to be the important issues to grasp the total outline of the characteristic of the damages such as the main defects and the locations of the defects caused by the earthquake for the appropriate seismic safety examination of TAMEIKE. The authors have tentatively tried to figure out numerically these issues depending on the general miscellaneous data publicized so far by the Tohoku Regional Office (TRO) of MAFF. Therefore, the numerical values identified in this paper are not accurate at all. In due time, it is expected that the accurate data shall be publicized by TOR of MAFF. The damage to about 500 TAMEIKE is considered so serious as to need urgent engineering and financial assistance from local or central governments. This paper focuses on the damages and failures of about 500 TAMEIKE on which about 890 defects are identified. The data shows that the main defects are slides, cracks, openings, displacement, depressions and settlements in the top one-half and on the upstream face of the embankments and failures of the appurtenances. Many defects are interrelated mutually and plural defects are identified on one dam. The practical engineering knowledge obtained from the on-site investigation introduced in this paper may provide important clue to the appropriate criteria or guidelines and will help with the seismic safety examination of about 210,000 TAMEIKE in this quake prone archipelago, Japan.

2. BACKGROUND OF TAMEIKE

There is no clear definition of TAMEIKE. For the convenience of technical classification, the small irrigation dams which were constructed before 1957 when the design standard of fill-type reservoir for agriculture was directed by MAFF, are defined as TAMEIKE. Most TAMEIKE were constructed about 100 years ago or more, for the cultivation of paddy. Frequently, they are called superannuated dams. The construction have been encouraged in proportion to the expansion of the paddy field since the age of around 700A.D. and TAMEIKE have been extended all over Japan. The construction works such as remedial repair, modification and alternation of embankments and appurtenances have repeatedly carried out through the ages. However, very little data on the construction and materials of TAMEIKE remain even in local archives. The types of embankments are homogeneous earth-fill. However, strictly speaking, they are not homogeneous. Even in one embankment, several kinds of soils from different borrow-pits were used. Several important characteristics of the soil used, such as density, permeability, particle size, and strength (cohesion and angle of internal friction) are different even in one homogeneous embankment from a section to another section. The conditions of foundations are not recorded at all. Most dimensions of embankments were decided depending on the rule of thumb. These facts make seismic safety examination of existing TAMEIKE so difficult.

The main purpose of TAMEIKE is to supplement water for paddy field. The capacity of TAMEIKE is usually 1,000-10,000m^3. It is not enough to supplement total water requirement of paddy field. TAMEIKE serve to supplement water only during critical period or at the early stage of paddy cultivation. This function is similar to Waduk-Lapangan in Indonesia and Water Tank in India and Sri Lanka. In 1995, MAFF established a data-base of all the TAMEIKE in order to maintain TAMEIKE systematically and to prevent or alleviate the disaster caused by TAMEIKE. About 300,000 TAMEIKE were registered in the data-base. Most of them are located in west Japan where paddy cultivation is dominant. In proportion to the decrease of paddy field areas due to urbanization in recent years, the numbers of TAMEIKE presently used for paddy fields have decreased to about 210,000. Most of them changed the main purposes and are used for water-friendly parks or similar purposes.

The heights of embankments are almost within 10 meters with some exceptions due to engineering and financial restrictions. Although normally they are not high enough to cause hydraulic problems, most TAMEIKE have suffered from large amounts of leakage or seepage of pond water through embankments, foundations or abutments because of the lack of proper engineering. On many embankments, cement milk has been grouted at the center of the cross-section in order to install more impervious membranes. The capacities of appurtenances such as spillway and inlet-facilities are not sufficient for maintaining structural and hydraulic integrity.

At present, most TAMEIKE are owned, managed and operated by farmers' water use organizations or land improvement districts. The appropriate engineering and financial assistance must be required by local or central governments.

3. THE 2011 TOHOKU EARTHQUAKE AND TSUNAMI ON MARCH 11, 2011. AT14:46

It is easy to access to the detailed and accurate data on this catastrophe by visiting the website of the following organizations, Japan Meteorological Agency (JMA), National Research Institute for Earth Science and Disaster Prevention. (NIED, K-net, KIK-net and HIR-net); http://www.hir-net.com/link/quake/observe.html and Japan Science and Technology Agency; http://www.jst.go.jp/pr/pdf/great_east_japan_earthquake/

In order to avoid duplication, these data related are not included in this paper.

It is noted that the incredible acceleration of 2,529gal was observed at Tsukidate, Miyagi Prefecture.

It is also drawn attention that the explanation of Prof. Kojiro IRIKURA et al. in the proceedings of international symposium, 2012 that is "Very little damage during this earthquake is explained by spectral characteristics of ground motions with predominant periods shorter than 0.5sec, although accelerations were so high". This is applied for large dams and buildings but not for such low dams as TAMEIKE.

4. DAMAGES TO TAMEIKE

As stated in the Introduction, the numerical values in the tables below are tentatively estimated by the authors depending on the general miscellaneous data publicized by the TRO of MAFF. The tables below are considered to be the clear compendia or delineations about the damages to TAMEIKE caused by the giant earthquake.

The approximate numbers of damaged TAMEIKE in main disaster Prefectures are shown in the Table 1.

Table 1. Approximate Numbers of Damaged TAMEIKE in Main Disaster Prefectures

	Prefecture			Total	Remarks
	Iwate	Miyagi	Fukushima		
TAMEIKE in Total	3,160	6,074	3,287	12,521	
Damaged TAMEIKE	395	589	800	1,784	14.2%
(Collapsed TAMEIKE) *		(1)	(3)	(4)	
(Severely Damaged TAMEIKE) *	(121)	(128)	(256)	(505)	(4.0%)

* included in Damaged TAMEIKE

The approximate numbers of the defects identified on 500 severely damaged TAMEIKE are shown in Table 2.
The latent defects and the pollution of the reserved water by radioactive sedimentations are not included in this Table.

Table 2. Approximate Numbers of Defects found on 500 Severely Damaged TAMEIKE

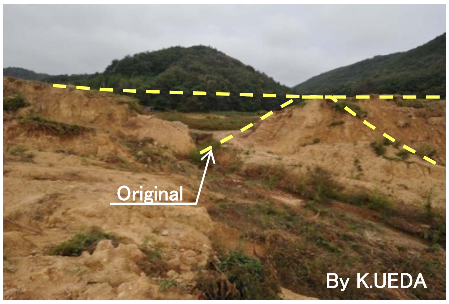
	Prefecture			Total	Remarks
	Iwate	Miyagi	Fukushima		
Collapse		1	3	4	
Cracks, Slides, Displacements	117	111	223	451	51%
Damages of Parapets, Walls & Erosion Protections, Fall of Trees	4	6	140	150	17%
Settlements	20	16	138	174	20%
Piping			2	2	
Tsunami	7	1		8	
Damages of Spillway & Inlet Facilities	3	24	74	101	11%
Total	157	159	580	890	

(Plural defects were identified and counted on one TAMEIKE and they are interrelated mutually.)
The approximate numbers of defects identified in respective partitions of the embankments are tentatively shown in Table 3. The numbers are limited only the defects identified on the surface of embankments. Therefore the latent defects such as settlements and failures of related structures such as parapets and erosion protections etc. are excluded.

Table 3. Approximate Numbers of Defects identified in respective partitions of the Embankments (Tentative)

	Upstream Face	Downstream Face	Total
Top One-half	371 (58%)	110 (18%)	481 (76%)
Lower One-half	137 (22%)	16 (2%)	153 (24%)
Total	508 (80%)	126 (20%)	634 (100%)

The main defects identified by on-site examination shall be illustrated with photographs for the sake of clarify. The examination and evaluation shall be referred to in the chapter below.



a) Fujinuma-ko **b)** Aotashinn-ike

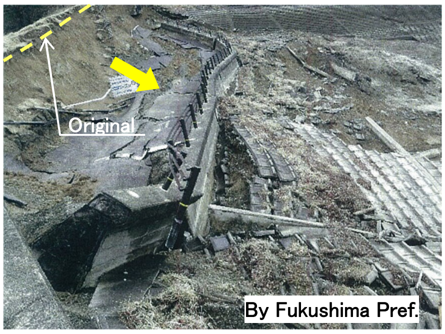
Figure 1. Collapses

a) Jyanohananaka-ike **b)** Iwaneoo-ike

Figure 2. Slides

a) Sasahira-ike **b)** Mitsugamori-dam

Figure 3. Cracks and displacements

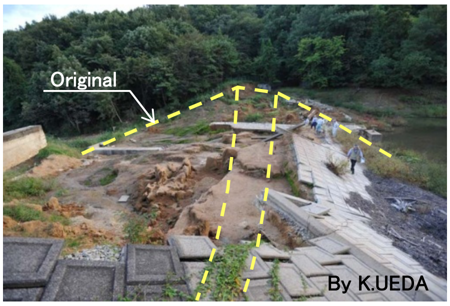


a) Fujinuma Auxiliary dam **B)** Oya-ike (Gunma Pref.)

Figure 4. Failures of parapets and retaining walls

a) Kozuka-dam **b)** Jyanohanakami-ike

Figure 5. Failures of erosion protections and Fall of trees



a) Naka-ike **b)** Mega-ike

Figure 6. Piping

a) Aotashinn-ike **b)** Ozakishita-tameike

Figure 7. Settlements and Erosion by Tsunami

5. CONSIDERATIONS AND RECOMMENDATIONS

The locations of the local governments in which 500 severely damaged TAMEIKE are concentrated, the seismic intensities(JMA) and the Max. accelerations observed are shown in Fig.8

The seismic ground motion can be considered to be amplified in the embankments.

The observed accelerations at the crest and the foundation of a certain large irrigation dam is shown in Fig.9.(T.Miyamori and et al.,2013) The some acceleration which were recorded in large dams, (Surikamigawa, Miharu, Yamanoiri and Gozennyama-Dams) also indicate amplitude motion in the embankment. The ratio of amplifications at the crest to the foundation varies from about 2.3 to 4.8. (JSDE, 2011) Although, these data should be used for dynamic analyses, it is important to keep in mind this characteristic for the safety examination of TAMEIKE.

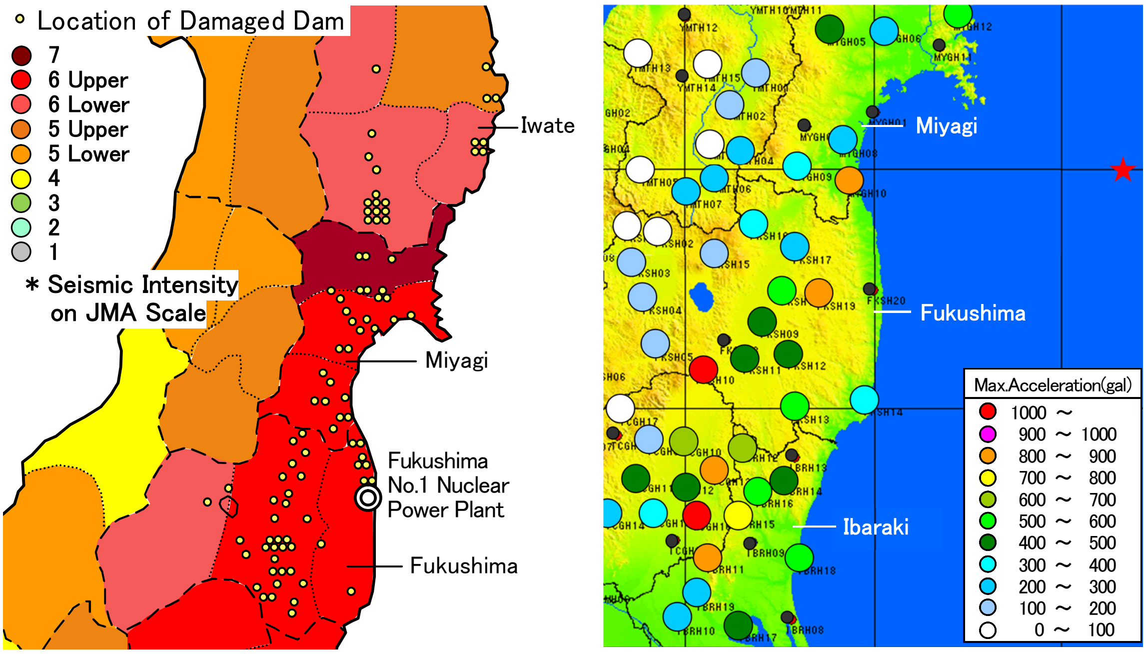


Figure 8. Locations of damaged dams, Seismic Intensity and Max. Acceleration

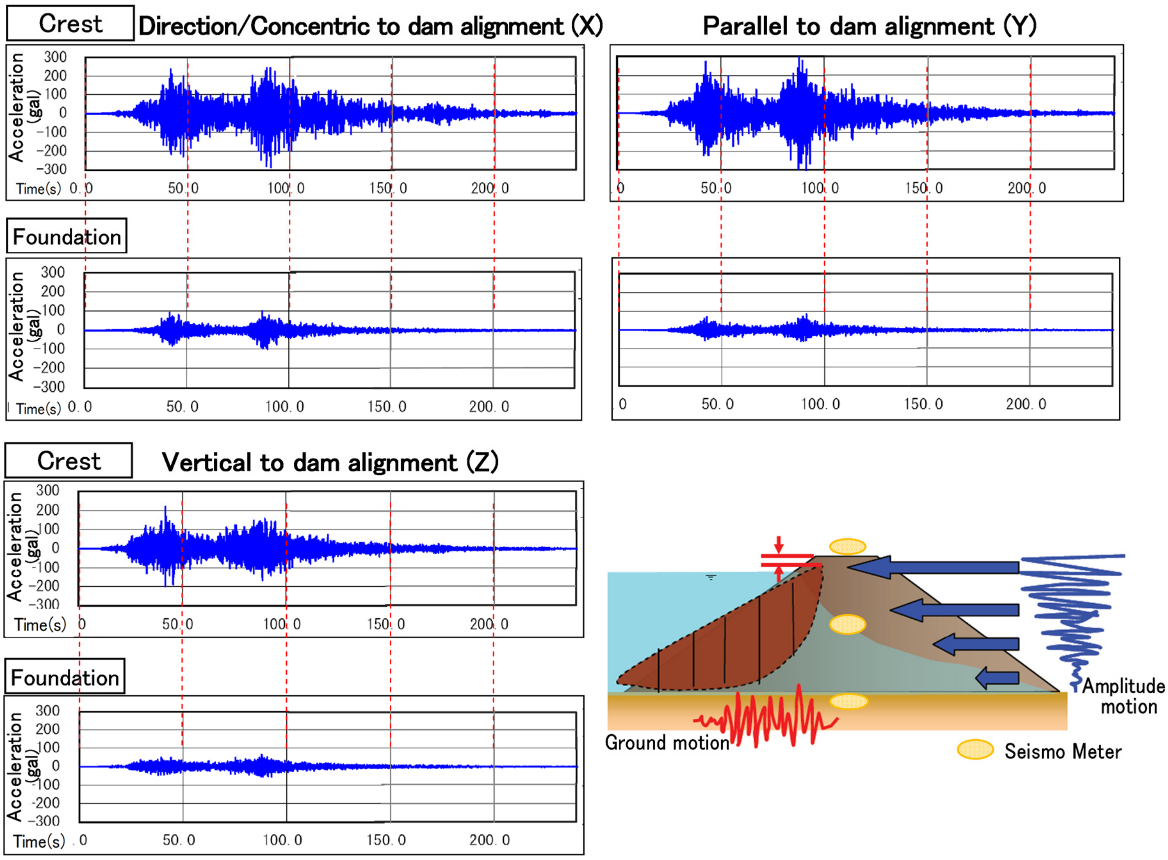


Figure 9. Accelerations observed at the crest and foundation of the embankment

This amplitude motion and the saturated condition in the upstream face may be the main reason that the defects are concentrated on the crest or on the top one half and the upstream face of embankments. Even small the cracks, slides and displacements which usually

would not be taken into consideration, may trigger next massive slides and displacements and finally may cause overtopping as seen in Fujinuma-ko. The soil strength (sheer strength) which are directly related to the compaction of soils on top one half and the upstream face of the embankments may be considered to be most essential issues for seismic safety examination. The high frequency up to 80% on the upstream face may be caused by the settlements of the foundations, the failures of the top one half of the embankments and the appurtenances structures. The reduction of soil strength may also be considered under the saturated condition.
However, the authors have not yet reached definite conclusion on this subject. The further studies and researches are keenly expected.
When this part of embankments is deteriorated, the soils should be removed and properly compacted newly. The application of geosynthetic engineering will also be reasonable. (F.Tatsuoka,JSDE,2013)
Prof. Dr. T.Tanaka and et al. examined the mode of failure of Fujinuma-ko in detail, stating that "Because the shear force which acts during an earthquake is short term response and the embankment is in undrained condition, in order to evaluate the state of damage, it is important to perform analysis by the Modified Newmark method considering the condition that cyclic shear loading is received in saturated undrained condition." (T.Tanaka,ICOLD,2012) The consideration stated may be reasonable option which should be adopted. Various kinds of methods for safety examination should be applied for the appropriate evaluations case by case. The correlation between the acceleration and the pore pressure in the properly compacted clay was recorded when the earthquake occurred in Gozenyama-dam which have recently completed in Ibaraki-Pref. The significant change of pore pressure which could reduce the bearing capacity of the soil was not found. (M.Iseki,JSIDRE,2012)

The design standard of fill-type dam for agriculture directed by MAFF stipulate that sophisticated state-of-the-art dynamic analyses have to be applied for the safety examination of embankments. However, in case of TAMEIKE, the numbers of the examinations concerned would be too numerous and staff resources and budget for analyses are generally very limited. Only when TAMEIKE could pose a potential hazard to life and important public facilities located downstream, the sophisticated dynamic analyses for LEVEL 2 (Anticipated Maximum Probabilistic Earthquake) should be adopted. In other case, it is adequate to examine the safety of the embankment by applying such simplified method as the Slip Circle Method adding the regional seismic coefficient, following the criteria and standards. (MAFF, 1943, 1957), although the defects which have taken place in embankments by the earthquake might be apparently different from the assumed such slip circle as the surface of rapture to be a cylindrical surface. Needless to say, when serious defects and deterioration are identified on the dams and appurtenances, several sophisticated methods to examine dam safety should be applied case by case .The slide which have occurred in Fujinuma-ko Auxiliary dam was caused by rapid water drawdown.
The accurate investigation of soils by boring many test pits may not be justified in case of TAMEIKE. The conventional low-cost methods such as Corn Penetration Test or New Swedish Sounding Test would be adequate.

Many cracks and deteriorations of soil layers by the settlements embankments and foundations can be found in many dams. The settlements and subsidence are latent defects. It is assumed that liquefaction and so-called mudding might have occurred in embankments and foundations. These defects cannot be overlooked because they sometimes trigger the fatal consequences. When new construction may not be financially viable or technically feasible, the modification of slope to gentle one or placing random materials on the both toes must be effective.(USBR,2011) The correlation between the slopes and the damages of existing TAMEIKE when the earthquake occurred, was not clear, because the most existing slopes are between 3:1 and 2:1.

The parapets, retaining walls, trees and appurtenances of which eigenfrequency are different from that of the massive soils are considered to behave separately and easily to be damaged. The inlet-conduits in the embankment cause serious piping alongside the structures. These structures should be removed.
When it cannot be justified, some counter measures should be adopted.
The erosion protections must be the flexible structure. The protective works for TSUNAMI overflow will not be justified because the occurrence period may be once in thousand years or more.
The cement milk injected in embankments in order to install impervious membranes, cause seem and openings and finally piping after earthquake. Other methods to control the seepage should be considered.

In March, TAMEIKE are not usually being used for irrigation. This may alleviate the damages such as piping and slides. However, it is noted that some TAMEIKE store water fully for the aquaculture of carps.
The landslide along lakeside is reported on large irrigation dam named Aratozawa dam, in Miyagi prefecture.

6. CONCLUSIONS

All TAMEIKE are prioritized with respect to the potential hazard and to the level of seriousness.(USBR,1995) Considering the numerous numbers of the safety examinations and limitations of the budget and staffs, the simplified methods such as Slip Circle Method are recommended unless TAMEIKE could pose a potential hazard to life and important public facilities located downstream.
When TAMEIKE could pose a potential hazard, the sophisticate state-of-the-art dynamic analyses should be applied.
Needless to say, when the serious deterioration and unreasonable defects were identified, the various kinds of sophisticated methods should be applied for the safety examination case by case.

The damages by the earthquake to the embankments and appurtenances have concentrated into the top one half and the upstream face of the embankments. This subject should be carefully studied and researched in detail. The results also should be systematically included in the related standards and criteria.
The deteriorated soils in these zone should be removed and newly compacted well.
The parapets and retaining walls on the crests are easily failed due to the difference of seismic behavior. These structures are recommended to be removed.
The erosion protections should be flexible structure.

The conduits and cement grout in the embankments have provided water passes by creating seem and opening alongside the structures. The alternation of structures to prevent the pipings should be considered.

When the remedial repair, modification and alternation stated above may not justified, financially and technically, several effective countermeasures should be examined and evaluated.

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