INTERNATIONAL SYMPOSIUM ON
DAMS FOR A CHANGING WORLD
-Need for Knowledge Transfer across the Generations & the World
Kyoto, Japan June 5, 2012

Effects of the 2011 Tohoku Earthquake on Dams

N. Matsumoto & T. Sasaki
Japan Dam Engineering Center, Japan
matsumoto@jdec.or.jp

N. Sato
Technical Center, Japan Water Agency, Japan

ABSTRACT:
The Tohoku earthquake on March 11, 2011 caused catastrophic effects to East Japan including heavy loss of life, serious damage, tsunamis and nuclear accidents at Fukushima No.1 Nuclear Power Plant. About 400 dams were inspected immediately after the event. While most dams sustained no damage, there were some dams which suffered damage. Japan Society of Dam Engineers (JSDE) dispatched the investigation teams twice and site-surveys were conducted for total 14 facilities. This report describes the findings of the field survey on dams along with the analytical results of seismic ground motions at dams. The frequency characteristics of acceleration record at dam foundations show that the component of long period is not large for huge scale inter-plate earthquake and the duration of the motion is ever so long. Those of significant effects of the earthquake on dams are cracking, settlements, and slope failure of the embankment dams, cracking of asphaltic concrete face of the rockfill dams and cracking of appurtenant RC structure of the concrete gravity dam. All of those except one did not threat the overall safety of dams. One homogeneous earthfill dam for irrigation, however, failed completely with the loss of eight lives downstream.

Keywords: Tohoku Earthquake, Field Investigation, Earthquake record, Damage, Ground motion

1. EARTHQUAKE

The 2011 Tohoku earthquake resulted from thrust faulting which plane is on or near the subduction zone plate boundary between the Pacific and North America plates. According to National Institute of Earth Science and Disaster Prevention (NIED 2011), the size of the main fault was 500km in length and 200km in width (see fig.1). After the main shock, numerous after shocks including several events of the magnitude greater than 7 have been following.

Since 1793, six earthquakes with the magnitude greater than 7.3 had occurred near the coast of Miyagi Prefecture before the 2011 Tohoku earthquake. The occurrence probability of magnitude around 7.5 event (the magnitude is 8.0, in case the southern plate is associated) had been estimated to be 99 % in coming 30 years by the Headquarters for Earthquake Research Promotion (HERP 2010). The magnitude 9.0 was beyond its prediction. The Jogan earthquake of magnitude 8.4 which is now considered to be the predecessor of the 2011 Tohoku earthquake occurred on July 13, 869 in this region, when Sendai area was swept by a big tsunami.

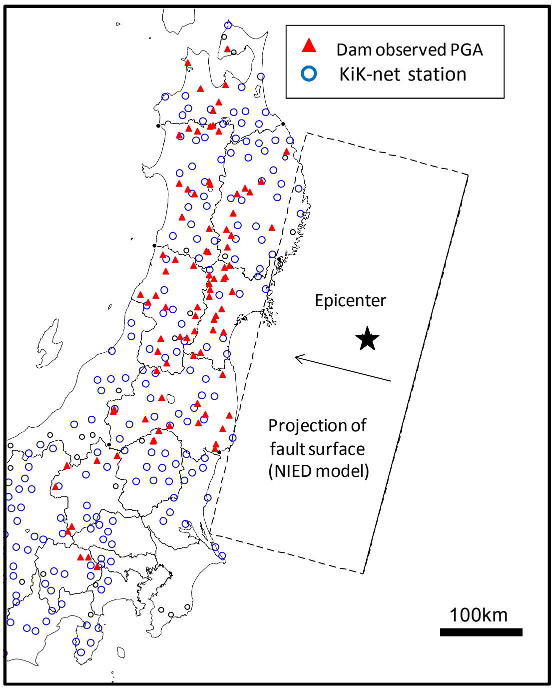

Figure 1. Location of fault area, KiK-net stations and dams

2. EARTHQUAKE MOTIONS AT DAMS

2.1. Earthquake Motions Recorded at KiK-net

The digital strong-motion seismograph network, KiK-net, by NIED recorded a lot of strong motion data of main shock and after shocks. Fig. 1 shows the location of instrumentations of KiK-net of NIED. Fig. 2 shows the attenuation of horizontal PGA observed by KiK-net and the shortest distance to the fault. In this figure, Peak Ground Accelerations (PGA) observed at ground surface and at underground are shown together and PGAs at ground surface are classified by the shear wave velocity of ground surface. Vs1 stands for the shear velocity of uppermost velocity layer and the Vs1 of 300m/sec is selected the threshold for the boundary of hard and soft ground. Most of seismographs at underground are installed in the rock foundations.

Fig. 2 indicates that PGA at underground is smallest, PGA at ground surface of Vs1<300m/sec is largest.
Fig. 3 shows the attenuation of vertical PGA by KiK-net and the magnitude relation of PGA is the same as the horizontal PGAs. The PGA at the ground surface depends on the response of the ground surface.

For the investigation of the frequency characteristics of the Acceleration Response Spectrum (ARS) observation stations with the shortest distance to the fault less than 70km and the PGA larger than 100 gal were selected. Fig.4 shows the ARS of horizontal accelerations at underground of selected stations. The variation of ARS is not large and ARS shows almost the same value in the range of 0.07 sec to 0.8 sec of period and does not contain much long period component for large magnitude of the main shock, M=9.0.

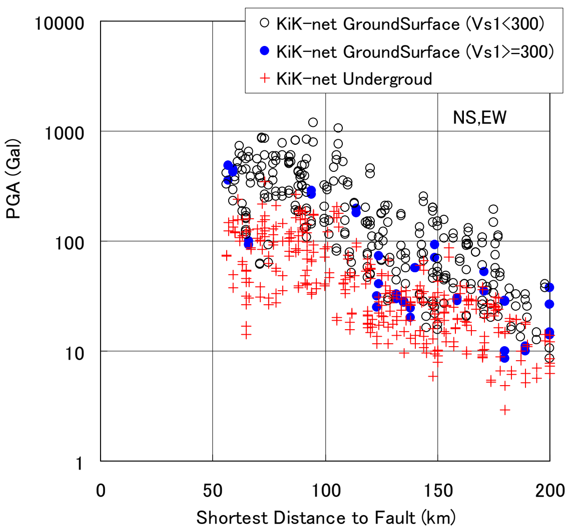

Figure 2. Attenuation of horizontal PGA by KiK-net

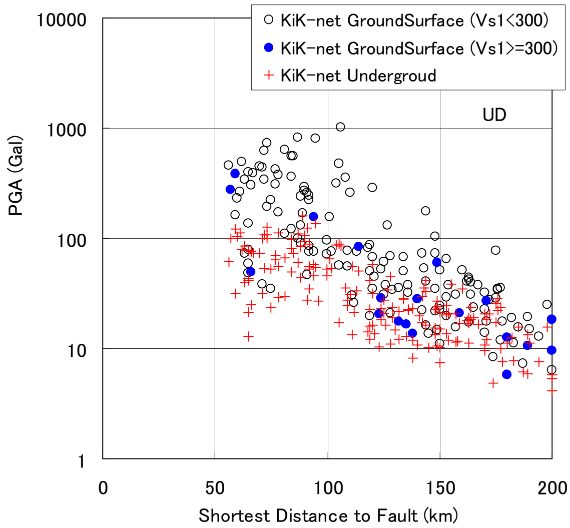

Figure 3. Attenuation of vertical PGA by KiK-net

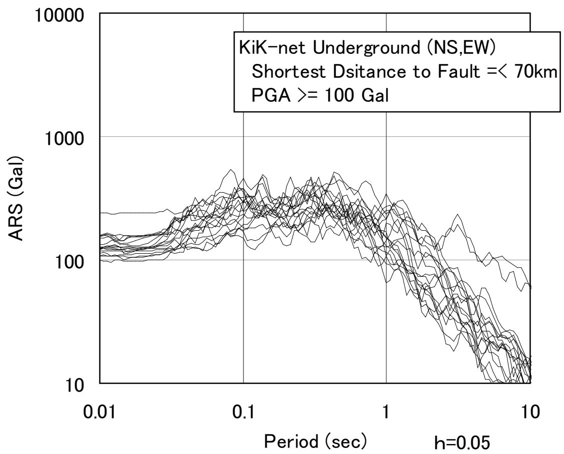

Figure 4. Horizontal ARS at KiK-net (in the ground, distance to the fault less than 70km)

2.2. Earthquake Motions Recorded at Dam Foundations

Strong motions were also recorded at more than 70 dams. PGA at dam foundations ranges mostly 0.1 to 0.5g in three prefectures of Iwate, Miyagi and Fukushima. Fig. 5 shows the comparison of horizontal PGA at dam foundations and KiK-net stations and Fig.6 shows PGA in the vertical direction. The solid line is for PGA at hard ground surface (Vs1>300 km/sec) and broken line for the underground, both being obtained from least square method. PGAs at dam foundation show some scattering, but, similar to PGAs at underground and lower than PGAs at ground surface. The ground surface motions by KiK-net contain the amplification due to soft surface layers depending upon the nature of its ground, while the underground motions by KiK-net do not contain such amplification. On the other hand, the foundations of dams mainly consist of hard rock and do not contain much effects of amplification. Accordingly, both are free from amplification effects of surface layers and comparable to each other.

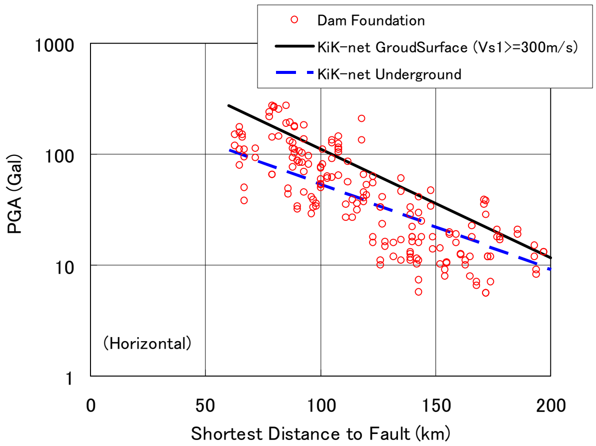

Figure 5. Attenuation of horizontal PGA at dam foundation

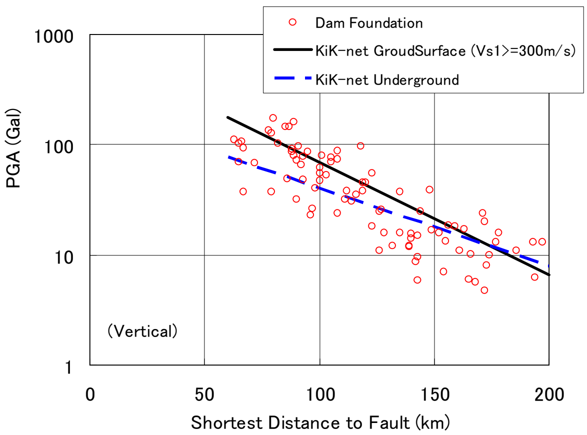

Figure 6. Attenuation of vertical PGA at dam foundation

Fig. 7 shows the time histories of acceleration recorded at the foundation (bottom inspection gallery) of the Isawa Dam (ER, 130m in height), the Minamikawa Dam (PG, 46m in height) and Takashiba Dam (PG, 59.5m in height). Fig. 8 shows ARS of those acceleration records. The locations of those dams are shown in Fig.9.
The duration of motion exceeds 200 seconds for most records which are extraordinary long. This was caused due to the consecutive rupture of faulting spreading from north to south.

The accelerations of the Isawa dam and the Minamikawa dam show two range of large vibration which affected the early first and second fault movement. On the other hand, the acceleration of the Takashiba Dam has only one range because it was probably cased mainly by the third fault movement.

The period characteristics of ARS at dam foundations which contain much component between 0.1 and 0.5 sec are similar to those of the ARS at underground of KiK-net stations.

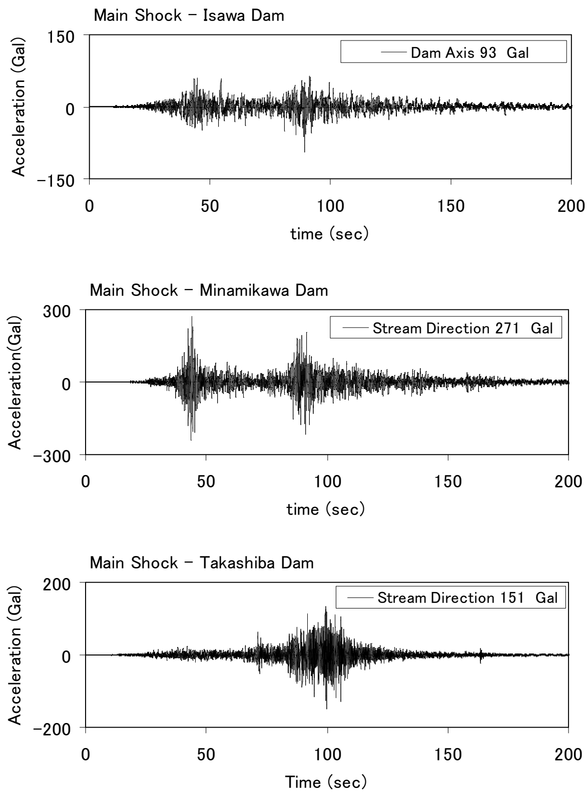

Figure 7. Time history of acceleration at dam foundation

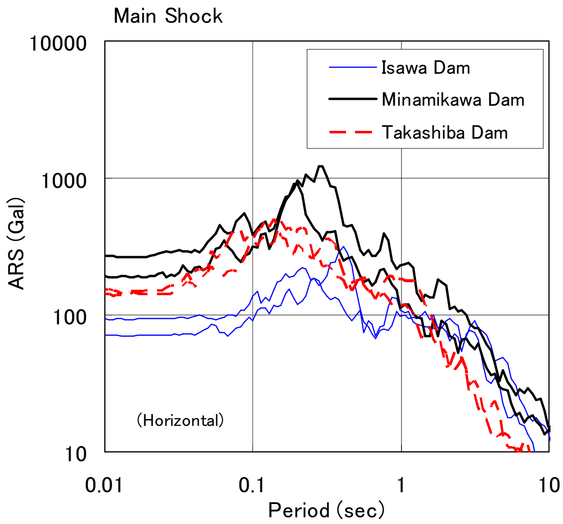

Figure 8. Horizontal ARS of dam foundations

3. EFFECTS ON DAMS

3.1. Inspection of Dams

Immediately after the earthquake, inspection of dams was started. As of March 31, about 400 dams were inspected. Table 1 is the summary of inspection results after the quake by dam owners. Generally dams performed well with minor or moderate cracking occurring at embankment dams. However, one earthfill dam for irrigation failed. Fujinuma-ike ("ike" means pond, it was not called as "dam") was an 18.5 meter high earthfill structure. Fujinuma-ike was on a non regulated river and hence Fujinuma-ike does not fall under the regulation of River Act.

Table 1. Inspection of dams after the main shock

Jurisdiction	Owner	Number of dams	
		inspected	unusual behavior or damage (failure)
MLIT*	Central Gov.	46	11
	Local Gov.	104	8
MAFF**	Central Gov.	51	4
	Local Gov.	121	23(1***)
Power Companies		69	2
Total		391	48(1)

* Ministry of Land, Infrastructure, Transportation & Tourism
** Ministry of Agriculture, Forestry & Fishery
*** The failed one was on a non regulated river.

3.1. Effects on Dams

Japan Society of Dam Engineers (JSDE) sent field investigation teams twice to several dams in Fukushima Prefecture on March 29 to 30 in Miyagi and Iwate Prefecture on April 25 to 27, 2011. The teams met local officials of several local government and dam owners. Fig. 9 shows the locations of dams which were visited by teams of JSDE. Table 2 is summary of JSDE's investigation result.

The preliminary investigation about ground motions suggests that a very long duration of ground motion and a number of subsequent strong aftershocks rendered more effects on embankment dams than on concrete dams.

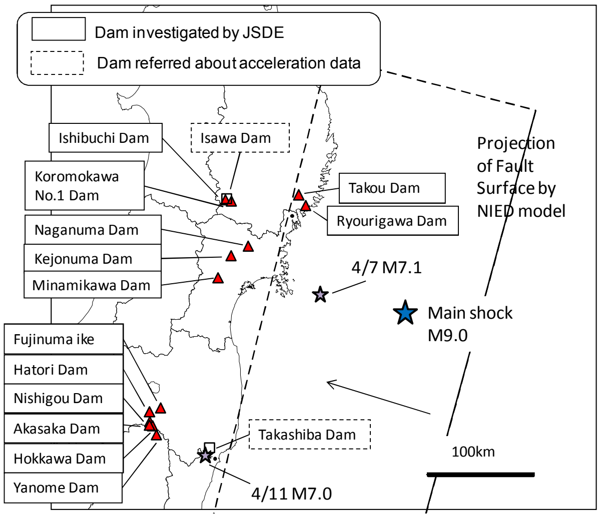

Figure 9. Location of Dams investigated by JSDE

Table 2. Outline of JSDE's investigation result

Name of Dam	Year of Complition	Type	Height(m)	Purposes*	Main Effects
Takou	2006	PG	77.0	CSX	Cracking in concrete structure on crest
Ryourigawa	2000	PG	43.0	CSX	None
Ishibuchi	1953	CFRD	53.0	CIH	Small cracking in base concrete of balustrade on crest
Koromokawa No.1	1963	TE	35.5	CI	Cracking on surfaces and crest of dam
Naganuma	(2012)	TE	15.3	CRX	Longitudinal cracking on surfaces of Sub-embankment
Kejonuma	1995	ER	24.0	CX	Small transversal cracking in pavement on crest
Fujinuma-ike	1949	TE	18.5	I	Breach of main dam, sliding of sub-dam
Hatori	1956	TE	37.1	I	Longitudinal cracking in pavement on crest
Nishigou	1955	TE	32.5	I	Londitudinal cracking on crest, cracking and tumoring on upstream surface
Akasaka	1965	TE	18.3	I	Longitudinal cracking on crest
Hokkawa	2000	ER	57.0	CSX	Transversal cracking in pavement on crest
Yanome	1990	TE	29.0	I	Longitudinal and transversal cracking in pavement on crest

* C : flood control, F : fish breeding, H : hydropower, I : irrigation, N : navigation, R : recreation, S : water supply, X : others

The relative large effects on dams by the quake are outlined below

Fig. 10 is Takou Dam (PG, 77 m in height) in Iwate Prefecture. The distance to the epicentre is 155 km, and the shortest distance to the fault is 59 km. Due to blackout, the earthquake records of this dam were not obtained. On April 7, the after-shock of M7.1 was occurred and horizontal PGA of 372 gal at foundation was observed. The duration was about 100 sec. Main damage of the quake in Takou Dam was cracking of the wall of intake tower and elevator tower on the crest (see Fig. 11). The dam body suffered no damage.

In the intake tower, the hoist equipment was displaced due to breakage of anchored bolts (see Fig. 12).

Figure 10. Takou Dam after the earthquake

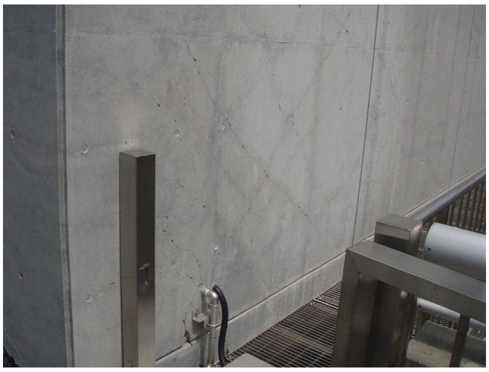

Figure 11. Cracking at gate house of Takou Dam

Figure 12. Shifting of hoist equipment and breaking of anchored bolts

Fig. 13 is Koromokawa No.1 Dam (TE, 35.5 m in height) in Iwate Prefecture. The distance to the epicentre is 200 km, and the shortest distance to the fault is 89 km. The maximum acceleration of 106 gal at foundation of the Koromokawa No.4 Dam located 5 km from No.1 Dam. This Koromokawa No.1 Dam was suffered from cracking damage by the former earthquake, 2008 Iwate Miyagi Inland Earthquake and the restoration countermeasure by re-embankment had been conducted.

The main effects by the Tohoku quake were cracking on the crest (see Fig. 14) and longitudinal cracking of at least tens of centimetres on upstream surface and downstream surface. By the trench excavation, the crack on the crest was found to be shallow and not to reach at the top of impervious zone of the dam.

Minamikawa Dam is located in Miyagi Prefecture. The distance to the epicentre is 183 km and the shortest distance to the fault is 85 km. The maximum acceleration recorded at the bottom inspection gallery of Minamikawa Dam was 271 gal. The saddle dam (AFRD, 19.6 m in height, see Fig. 15) of Minamikawa Dam was suffered two rows of cracking on the asphalt facing, one at center and another near right abutment by the quake. The leakage through dam increased from 2 liter/min to 70 liter/min temporarily after the quake, but decreased to 4 liter/min no within one month after the event.

The horizontal displacement is 50 mm, and settlement is 90 mm by the main shock and after shocks, cracks were revealed to penetrate through asphalt face by the coring.

Figure 13. Downstream View of Koromokawa No.1 Dam

Figure 14. Cracking at crest at Koromokawa No.1 Dam (after removal of asphalt pavement)

Figure 15. Upstream side of saddle dam of Minamikawa Dam

Figure 16. Cracking of asphalt facing at saddle dam of Minamikawa Dam

Fujinuma-ike was breached shortly after the earthquake with the loss of eight lives. It is located in the southern Fukushima Prefecture. The epicentral distance is about 240km and the shortest distance to the fault is about 80km. The accelerometer was not installed at the site. The attenuation relationship obtained from KiK-net indicates that PGA at ground surface of the same fault distance is around 0.2 to 0.7g. Fujinuma-ike is an earthfill structure with the height of 18.5 m. The crest length is 133m, crest width is 6m and reservoir capacity is 1.5Mm^3. Spillway is ungated.

Construction began in 1937 for irrigation and was suspended during World War II. It was competed in 1949. When the earthquake occurred, the reservoir level was almost full. According to witness, 20 to 25 minutes after the earthquake, the water was overflowing on the crest. Later big discharge occurred and it was breached completely as shown in Fig. 17. The embankment had lost the height to retain water. The review team to find the cause of the failure was set up by the Fukushima Prefecture and the investigation is going on as of November, 2011.

Figure 17. View of breached Fujinuma-ike from right bank

4. CONCLUSIONS

Investigation of seismic motion was conducted using data observed at KiK-net observing stations and at dam sites. The ground motion at dam foundation was revealed to be similar to the ground motion at underground of KiK-net and smaller than that at ground surface.

Immediately after the earthquake, inspection of dams was started. As of March 31, about 400 dams were inspected. Generally dams performed well with minor or moderate cracking occurring at embankment dams. They withstood severe ground motion. However, one earthfill dam for irrigation failed. Fujinuma-ike ("ike" means pond, it was not called as "dam") was an 18.5 meter high earthfill structure which was completed in 1949. Fujinuma-ike was on a non regulated river.

ACKNOWLEDGEMENT

The authors thank NIED. They are grateful to the personnel of Fukushima, Iwate and Miyagi Prefecture for their help.

REFERENCES

KiK-net by NIED
http://www.kik.bosai.go.jp/kik/index_en.shtml

NIED(2011):
http://www.bosai.go.jp/news/oshirase/20110315_01.pdf
http://www.bosai.go.jp/e/international/Preliminary_report110328.pdf

HERP(2010):
http://www.jishin.go.jp/main/nihonjishin/2010/tohoku.pdf,
http://www.jishin.go.jp/main/index-e.html

Matsumoto. N (2011) : Perspective of the 2011 Tohoku Earthquake and Tsunami, ANCOLD, 2011