On Damage of Oil Storage Tanks due to the 2011 off the Pacific Coast of Tohoku Earthquake (Mw9.0), Japan

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SUMMARY:
The 2011 off the Pacific coast of Tohoku Earthquake (Mw9.0) caused damage to oil storage tanks and other hazardous materials facilities in wide area. Damage of oil storage tanks is classified into three types on the basis of external forces, that is, tsunami, long-period ground motions, and short-period strong ground motions. Oil storage tanks and pipelines on the pacific coast of northeast Japan were drifted and collapsed by the tsunami. At the Japan Sea coast of northwest Japan and Tokyo Bay area, long-period strong ground motions excited large liquid sloshing of oil storage tanks and brought sinking of floating roofs and other damage such as failure of pontoons of floating roof. Although PGA more than 500 gals was observed near tank sites along the coast of northeast Japan, oil storage tanks were not damaged directly but indirectly by liquefaction of soil.

Keywords: the 2011 off the Pacific coast of Tohoku Earthquake, Oil Storage Tank, Damage, Tsunami, Sloshing

1. INTRODUCTION

The 2011 off the Pacific coast of Tohoku Earthquake (Mw9.0) occurred on March 11, in the northeast Japan accompanying great tsunami which caused severe damage to the pacific coast of Tohoku area. Damage of oil storage tanks and other hazardous materials facilities in petrochemical industrial complex was also caused by the tsunami and ground motions, such as fires and oil leakage from oil storage tanks and pipelines. According to the questionnaire survey by the Fire and Disaster Management Agency (FDMA, 2011a), facilities damaged by the earthquake amount to 3,324, this is 1.6% of the total surveyed hazardous materials facilities (211,877) in the east Japan area. 1,404 hazmat facilities were damaged by the strong ground motion. On the other hand, 1,807 hazmat facilities were damaged by the tsunami and the rest 113 remain unknown. Among the damage, fires occurred in 42 facilities, oil leakage occurred in 122 facilities.

Since hazardous materials facilities were damaged over the wide area in eastern Japan, we have investigated damage including the fires and failures of the oil storage tanks and other hazmat facilities in the 10 areas to be considered as severely damaged, such as Kesen'numa city, Sendai area (Sendai city, Tagajo city, Shichigahama town), Iwaki city, Kashima area (Kashima city, Kamisu city), Sakata city, Shibata city, Niigata city, Ichihara city, Kawasaki city and Kuji city as shown in Fig.1. The investigations were carried out from the following viewpoints.

1) Extent of damage of the oil storage tanks (e.g. failure in shell plates, bottom plates and floating roofs) for verification of the technical standard of the Fire Service Law,
2) Cause of the fires in the Sendai area and in the Ichihara area,
3) Situation of damage of the hazmat facilities suffered by the tsunami.

2. CHARCTERISTICS OF DAMAGE BY AREA

The damage of the oil storage tanks and hazmat facilities has a different aspect by area. The area for

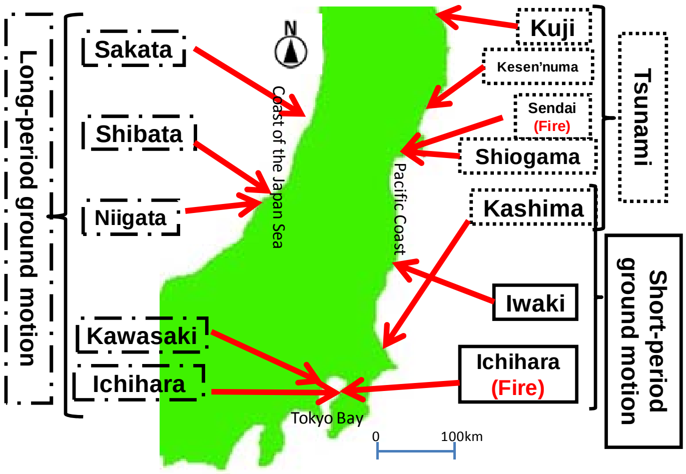

Figure 1. Type of damage observed mainly in Petrochemical Complex

on-site survey is separated into three areas as 'the Pacific coast', 'the coast of the Japan Sea' and 'the Tokyo Bay'. Typical damage of the hazmat facilities in each area is described below.
Along the Pacific Coast,
(a) Many tanks and pipelines floated and displaced by the buoyancy and the force of the tsunami,
(b) Foundations of the tanks were swept away by the tsunami,
(c) No severe damage of the floating roofs by the liquid sloshing,
(d) Few damage on storage tanks by the strong ground motions,
(e) Liquefaction by the strong ground motions.
Along the coast of the Japan Sea,
Sinking of the inner floating roof, fractures of the pontoons and oil spill onto the deck of the floating roofs due to the liquid sloshing and so on.
Along the coast of the Tokyo Bay,
Sinking of the floating roof and other damage by the liquid sloshing

3. DAMAGE BY TSUNAMI

Fig.2 shows the heavy oil spill in the dike. The tank indicated as #1 in Fig.2 is empty when the tsunami attacked, and submerged into the sea water up to 3.5m high from the bottom plate. The tank did not uplift nor displace even though it was empty. Many pipelines have been bent at the #2 in Fig.2 and the large amount of oil leaked from the pipelines spilled all over the dike and the road beside. These pipelines presumably washed away by the tsunami. The largest fracture was found at an elbow in one of the heavy oil pipelines. Its length is approximately 10cm and its width is approximately 3cm.

In Kesen'numa city, 22 out of 23 above ground oil storage tanks were washed away by the tsunami. The local fire authority announced that the total amount of oil flowed out of the oil storage tanks were assumed to be 11,721 kL and oil types are heavy oil, kerosene, diesel fuel and gasoline. Fig.3 shows an oil storage tank which was drifted and collapsed by the tsunami. It is reported that the large fires occurred in Kesen'numa city. It is not clear whether oil spill from destroyed tanks related to these fires or not.

In Kuji city, there are underground rock cavern oil tanks. The tanks suffered no damage by the tsunami, because the door of the tunnel was properly closed by the employee. However, the aboveground facilities were completely destroyed by the tsunami.

In Kashima area, a sea bank and berths were damaged by the tsunami of more than 6m high. The berth shown in Fig.4 was struck and collapsed by a drifted ship.

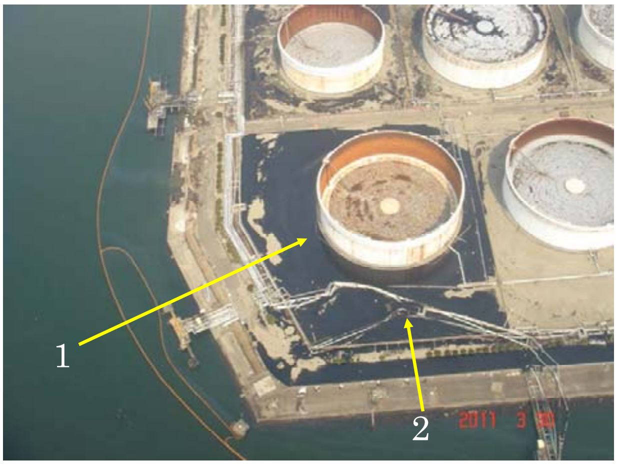

Figure 2. Heavy oil spilled in the dike

Figure 3. Oil storage tank drifted and collapsed by the tsunami

Figure 4. Berth collapsed by a ship strike

Fires occurred at a refinery in a petrochemical complex in Sendai area. Fig.5 shows a section of the refinery that was burnt out completely by the fires. There were a gasoline tank, asphalt tanks, molten sulfur tanks and oil handling facilities in the burned-out section. Fig.6 shows a burned-out gasoline tank. It seems that the tank inclined to the Pacific Ocean after the tsunami strike and it collapsed due to the fire. The soil of the dike and the foundation were washed away by the tsunami. The welded part of the gasoline tank between the shell plate and the bottom plate fractured along approximately 2.4m.

Although the precise cause of fires is as yet not well known, we now infer from both the on-site investigation and the interview to working staffs that the floating oil spill ignited due to the spark at the collision between tank lorries and oil handling facilities by the tsunami.

Figure 5. Burned-out section in a refinery

Figure 6. Burned-out gasoline tank

4. DAMAGE BY LONG-PERIOD GROUND MOTION

Typical damage of oil storage tank caused by liquid sloshing was found in Niigata and Sakata districts, such as sinking of inner roof, leakage of oil onto deck, deformation of gauge pole, and fracture of pontoon. We measured the sloshing wave height based on oil marks on the surface of the shell plates found in oil storage tanks in the Niigata district. Fig.7 shows the relation between sloshing wave height and natural period of liquid sloshing. Maximum sloshing is about 2m at a period of about 10.7 sec, where red and white circles correspond to the data at east- and west-side tanks at the Niigata-Higashi Port for petroleum reserve, respectively.

Fig.8 shows the pseudo-velocity response spectra (Sv) of 0.5% damping at the east site where we have installed velocity-type strong motion seismograph. Dashed gray lines show the regulation spectrum for Niigata district in the Japan Fire Service Law. Using the 2-D sloshing response analytical method

(Zama, 1985) based on the velocity potential theory for liquid sloshing, we calculated the sloshing wave heights and compared with the observed ones as shown in Fig. 9. Although the calculated heights agree well with the observed ones at the east site of the port, the calculated ones for the west site was underestimated as about 60cm. This means that about 50% of Sv at a period of 10.7sec varies from east to west site, despite of the short distance of 2.5km between east and west sites.

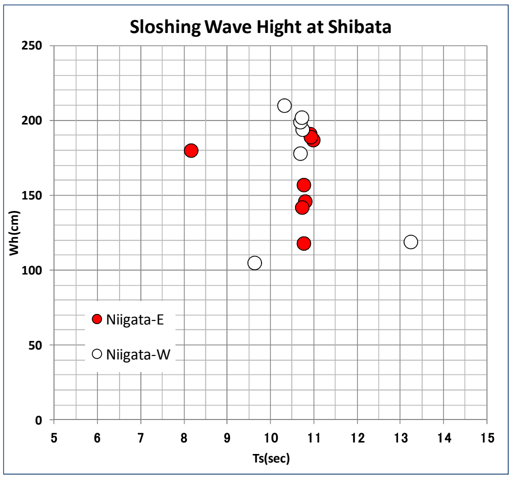

Figure 7. Relation between sloshing wave height and natural period of liquid sloshing

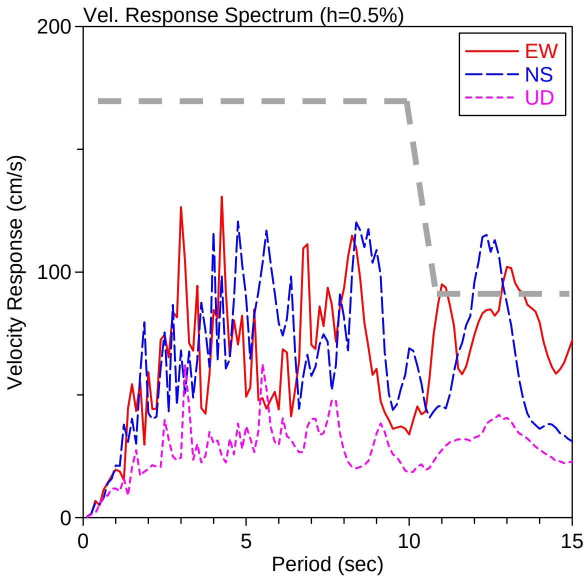

Figure 8. Pseudo-velocity response spectra (Sv) of 0.5% damping at the east site and the regulation spectrum (gray dashed line)

In Sakata city which locates on the thick sediment layers more than several km, the aluminum inner floating roof of gasoline tank was broken completely as shown in Fig.10. The length of broken float tube is about 6.7m and its diameter is 25.4cm. The velocity response at the site is about 200cm/s at the natural sloshing period of 4.19sec for the tank. The maximum sloshing height is calculated as 202cm by the 2-D response analysis. In addition, the frequency of more than 50% of maximum response, that is, sloshing height of 1m, is 73 from the sloshing response analysis using the one hour ground motion record. The cause of failure of the roof is considered as the large and frequent liquid sloshing, and also the situation of the inner floating roof fulfills the unsafe conditions proposed by FDMA (2011b), that is, (a) Sv is more than 100cm/s, (b) diameter is less than 30m, and (c) length of float tube is more than 6m.

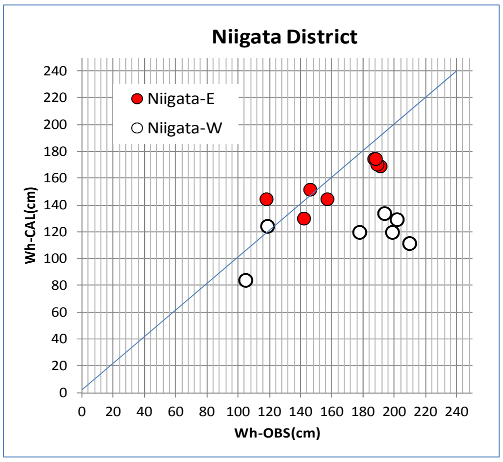

Figure 9. Comparison between observed (Wh-OBS) and calculated (Wh-CAL) sloshing height

In Kawasaki city, floating roof of heavy oil tank completely sank three days after the earthquake as shown in Fig.11. According to the regulation, this tank's roof should be reinforced by 2029, but not conducted yet. The cause of sinking is considered as the inadequate buoyancy by failure of the pontoons due to the liquid sloshing. According to our observation near the tank, Sv is, however, 75cm/s at the natural sloshing period of 7.8s of the tank as shown in Fig.12, and the estimated sloshing wave height is no more than 1.0m. As the liquid sloshing of the tank is seemed to be too small to explain the failure of the pontoons based on the technical standard of the Fire Service Law, a rational explanation is required.

Figure 10. Aluminum inner floating roof of gasoline tank completely broken in Sakata area

Figure 11. Sinking of floating roof

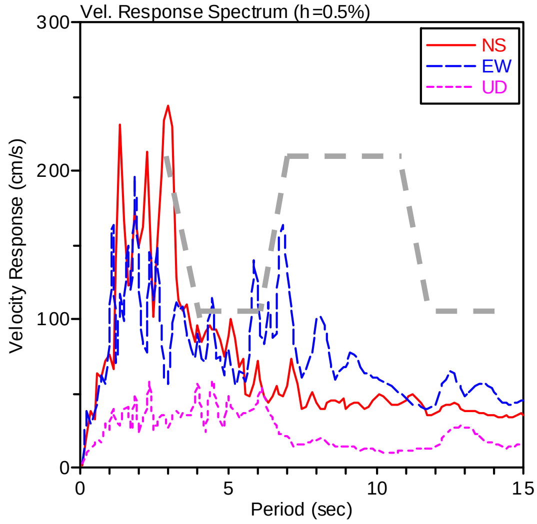

Figure 12. Pseudo-velocity response spectra (Sv) of 0.5% damping at the Kawasaki and the regulation spectrum (gray dashed line)

5. DAMAGE BY STRONG GROUND MOTIONS

Fig.13 shows the acceleration response spectra Sa of 10% damping near the tank sites, from the records at Fukushima (FKS010) and Kashima(IBR018) presented by National Research Institute for Earth Science and Disaster Prevention and at Sendai(Sendai-G) and Iwaki(Onahama-Ji-G) presented by Port and Airport Research Institute, compared to the spectra in the technical standard of the Fire Service Law, where Kh1 and Kh1×ν_p are corresponding to the level 1 and 2 earthquake ground motions, respectively. Although Sa exceeds the level 1 at the frequencies more than about 2Hz, and exceeds the level 2 more than about 3Hz, within our investigations, damage to cylindrical tanks due to strong ground motions was only found as the elephant foot bulge of a water tank at Sendai and the extraction of anchor bolts of an oil storage tank at Kashima.

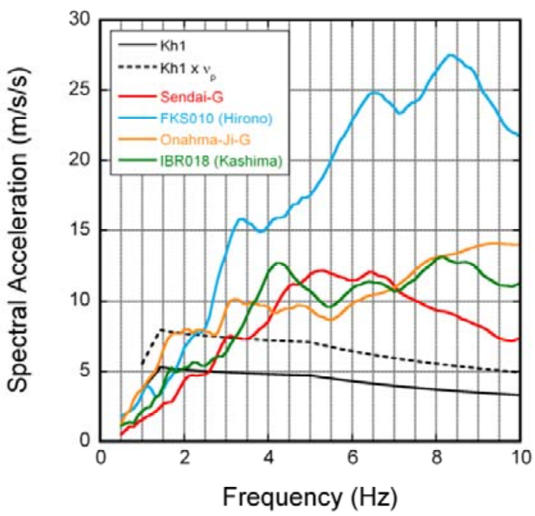

Figure 13. Acceleration response spectra Sa of 10% damping near the tank sites in Sendai (Sendai-G), Fukushima (FKS010), Iwaki (Onahama-Ji-G), and Kashima (IBR018) compared to the spectra in the Fire Service Law of Japan

On the other hand, an LPG spherical tank collapsed due to the strong ground motions and fires and explosions with fire balls occurred at the LPG tank site as shown in Fig.14 in Ichihara city which locates on the eastern shore along the Tokyo bay. It took ten days to extinguish fires. The diameter of the largest fire ball in the explosions is about 600m judging from the height of the plant extractor stack pipe. Many fragments of the LPG tanks scattered in the explosions, therefore the fire spread to the asphalt tanks, the control room and the neighboring factory. Furthermore, sheet metals flew several km to the adjacent inhabited areas, and the evacuation order to inhabitants near the tank site was issued by the mayor of Ichihara city.

According to the accident analysis report (Cosmo Oil Group, 2011), the processes to the outbreak of the fires and explosions in LPG tanks are considered that (1) braces of the tank filled with water for the inspection were cut off by the main shock, (2) the tank fell down onto and destroyed the gas pipes by the largest aftershock (M7.7), (3) the leaked LPG diffused and ignited for any reasons, and (4) BLEVE (Boiling Liquid Expanding Vapor Explosion) broke out finally.

Figure 14. Burned and exploded LPG tanks at Ichihara

In Iwaki city along the Pacific coast, there was damage due to liquefaction caused by strong ground motions as shown in Fig.15, which was recorded at the Onahama Port observatory near the tank site operated by Port and Airport Research Institute. PGA is 1533.8cm/s^2 and the cyclic mobility can be seen as phenomenon of strong non-linearity. Fig.16 indicates the situation of settlement of oil storage tank. The valve of the tank slightly contact to the ground, therefore the asphalt of the scarcement was removed in order to avoid the failure of the neck of the nozzle in the further settlement due to the future earthquakes. Furthermore, the center part of bottom plate was relatively uplifted about 50cm high owing to the lateral flow of neighboring soil of the tank, and the welding area of the bottom plate cracked and oil leaked.

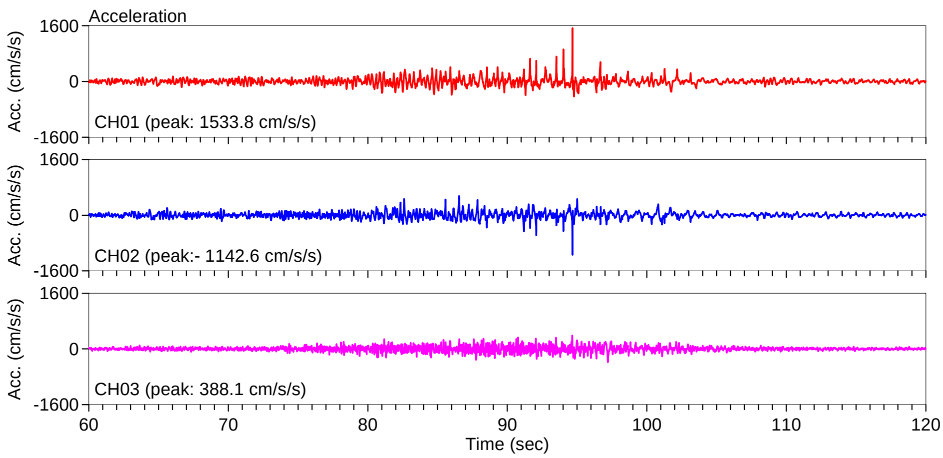

Figure 15. Acceleration waveforms indicating cyclic mobility at the at the Onahama Port observatory near the tank site operated by Port and Airport Research Institute

Figure 16. Tank settlement due to the liquefaction around the foundation

In Kashima area, the wall of the dike settled and inclined because of liquefaction. As shown in Fig.17, fractures of joints of the dikes were found in some walls. Some of them have rubber sheets protection in order to maintain its function in case of joint fracture. Some rubber sheets were torn and lost its function of retaining oil inside the dike.

Figure 17. Fracture of wall joint of the dike with rubber sheet protection

6. CONCLUSIONS

The 2011 off the Pacific coast of Tohoku Earthquake (Mw9.0), Japan occurred on 11 March 2011 caused various damage to oil storage tanks in wide area. Then, we have conducted field surveys to know what and why happened in hazmat facilities, such as oil storage tanks, pipes and so on. Damage of oil storage tanks is classified into three types on the basis of external forces, that is, tsunami, long-period ground motions, and short-period strong ground motions.

Damage by tsunami was found along the coast of northeastern Japan. Tsunami height is about 5 to 15 meters at the tank sites. Tsunami moved and collapsed tanks with the capacity of less than 500kl at Kuji and Kesen'numa Cities in the northern districts, washed away a part of foundation of a tank and footing of embankment of oil and moved small and empty tanks and collapsed pipes at Sendai District in the central part, and collapsed berths at Kashima District in the southern part of the northeastern Japan. Since the emergency shutdown valves of pipelines did not work because of the blackout after the earthquake, large amount of oil spilled out to the dike.

At Sakata, Niigata and Shibata cities in the northwestern Japan, we found damage due to the liquid sloshing excited by the long-period ground motions such as failure of pontoons, deformation of gauge poles, and leakage of oil onto the floating decks. We can roughly explain such damage of tanks in the areas based on the velocity potential theory using the seismograms, whose velocity response spectra Sv are about 100 to 200 cm/s at periods from 5 to 10 seconds at the tank sites. The floating roofs reinforced in compliance with the technical standard of the Fire Service Law revised in consideration of the damage in the 2003 Tokachi-oki earthquake did not suffer damage in the earthquake. On the other hand, it remains difficult to explain that a floating roof of a tank located in the Tokyo Bay area sank after 3 days of the event because of the failure of pontoons by the liquid sloshing, although Sv at the tank site is not more than 100 cm/s.

Strong ground motions corresponding to the level 2 earthquake ground motion in the technical standard of the Fire Service Law were observed near the tank sites along the coast of the northeastern Japan. No oil storage tank body was damaged directly by the strong ground motions, but damage such a crack in a bottom plate and oil leakage was indirectly caused by the liquefaction and the lateral flow of neighboring soil of the tank at Onahama, Fukushima Prefecture.

In addition, two big fires occurred at oil refineries. One is gas tank fires at Chiba in the Tokyo Bay area. A tank filled with water for the purpose of inspections, fell down onto gas pipes by strong ground motions at the largest after shock and fire broke out and induced the BLEVE and explosions. The other is fires of a gasoline tank, pipes, an asphalt tank, and oil shipping facilities at Sendai District. The cause of fires and damage of the hazmat facilities is still unclear in some parts. Therefore, further investigations and detailed analysis is needed in order to elucidate the mechanism of the damage.

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