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Earthquake Damages and Disaster Prevention of Aboveground Storage Tanks

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Abstract

Severe damages in aboveground storage tanks (AST) have been often experienced due to earthquakes in Japan. In this paper, earthquake damages of ASTs which occurred for the last several decades are reviewed. These are damages in the 1964 Niigata Earthquake, the 1978 Miyagi Earthquake, the 1983 Sea of Japan Earthquake, the 1995 Kobe Earthquake, the 2003 Hokkaido Earthquake and the 2011 Great East Japan Earthquake. The damages of ASTs can be classified into 3 types in accordance with the characteristics of earthquake. These are the impulsive motion due to a high frequency earthquake, the sloshing motion due to a low frequency earthquake and the tsunami attack. In the impulsive motion, buckling of sidewall plates and uplift of sidewall-to-bottom joints occurred. In the sloshing motion, sinking of floating roofs into liquid and buckling of sidewall-to-roof joints occurred. In the tsunami attack, ASTs moved and overturned to leak oil.

Keywords: Aboveground storage tank; disaster prevention; earthquake damage; impulsive motion; sloshing

1. Introduction

Aboveground storage tanks (hereafter, it is abbreviated as AST) are cylindrical and a welded steel structure. They are used to store crude oil, petroleum products, chemical products, etc. in oil refineries, chemical plants, thermal power plants, stockpiling bases and tank terminals. Severe damages in ASTs have been often experienced due to earthquakes in Japan. In this paper, earthquake damages of ASTs which occurred for the last several decades are reviewed. These are damages in the 1964 Niigata Earthquake, the 1978 Miyagi Earthquake, the 1983 Sea of Japan Earthquake, the 1995 Kobe Earthquake, the 2003 Hokkaido Earthquake and the 2011 Great East Japan Earthquake in Japan. Finally, the disaster prevention of ASTs is considered based on these damages.

2. AST and Earthquake

ASTs are a welded structure and they are made of carbon steel plates. A typical AST is shown in Fig. 1. An AST is classified into three types as illustrated in Fig. 2, a fixed roof tank, an external floating roof tank and an internal floating roof tank. The external floating roof tank is used in large diameter tanks to store crude oil, naphtha, etc. The fixed roof tank and the internal floating roof tank are used in small diameter tanks to store petroleum and petrochemical products.

Figure 1. Aboveground storage tank (AST)

Table 1 presents the number of ASTs in Japan as of March 2017. This table includes ASTs for oil storage only, and excludes water storage tanks which are used in nuclear power plants, food plants, agricultural facilities, etc. ASTs in table 1 are used in oil refineries, chemical plants, thermal power plants, stockpiling bases and tank terminals.

ASTs in Japan is not damaged by all the earthquakes. They have suffered damages in massive earthquakes which occurred at approximately 10 years interval. The epicenters of the massive earthquakes in which ASTs were damaged are shown in Fig. 3. Damages and failures of ASTs in these earthquakes are described in this paper.

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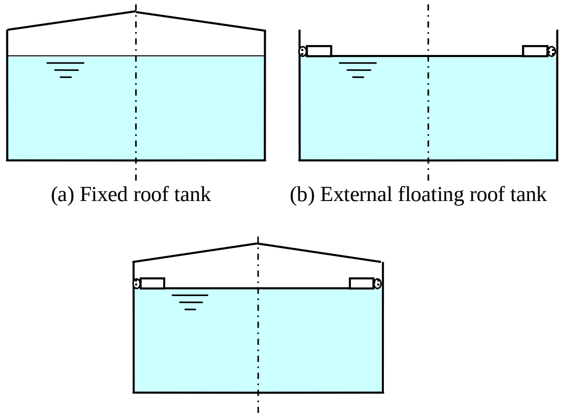


(a) Fixed roof tank (b) External floating roof tank

(c) Internal floating roof tank

Figure 2. AST types

Table 1. The number of ASTs for oil storage in Japan

Capacity range	AST quantity
1,000 m^3 or less	53,464
1,000 m^3 to 5,000 m^3	3,585
5,000 m^3 to 10,000 m^3	1,520
10,000 m^3 to 50,000 m^3	1,353
50,000 m^3 to 100,000 m^3	430
100,000 m^3 or more	448
Total	60,800

As of March 31, 2017

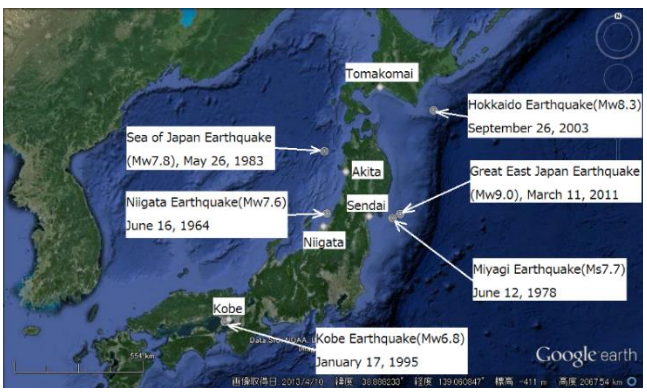


Figure 3. Epicenters of massive earthquakes in Japan

3. Failure Patterns of AST in Earthquake

3.1. High frequency earthquake and low frequency earthquake

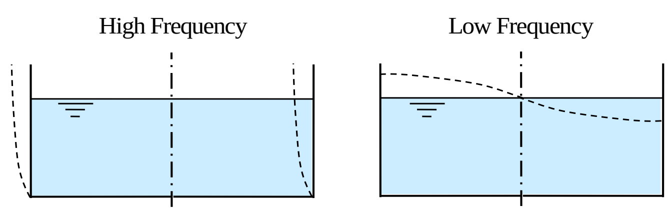
Damages of ASTs in earthquakes can be classified into 3 types in accordance with the the characteristics of earthquake. These are the impulsive motion due to a high frequency earthquake, the sloshing motion due to a low frequency earthquake and the tsunami attack. In the high frequency earthquake, a vibration occurs in sidewall plates as shown in Fig. 4(a), and it is referred to as an "impulsive motion". The natural period of the impulsive motion in an AST is between 0.1 s and 0.5 s. If a tank is large, the natural period becomes long. It is about 0.1 s in a 1,000 m^3 tank and about 0.5 s in a 100,000 m^3 tank. In the low frequency earthquake, a vibration occurs in the liquid surface as shown in Fig. 4(b), and it is referred to as a "sloshing motion". The natural period of the sloshing motion in an AST is between 3 s and 15 s. It is 10 s or more in a 100,000 m^3 tank.

If the predominant period of the earthquake wave is between 0.1 s and 0.5 s which is the high frequency earthquake, the impulsive motion occurs in ASTs. If the predominant period of the earthquake wave is between 3 s and 15 s which is the low frequency earthquake, the sloshing motion occurs. The earthquake waves may contain both the high frequency and the low frequency component. In some cases, the impulsive motion and the sloshing motion occurred simultaneously.

In the high frequency earthquake, an amplitude of the earthquake motion rapidly decreases with increasing a distance from an epicenter. On the other hand, it slowly decreases in the low frequency earthquake. The low frequency earthquake mainly consists of surface waves which are the Rayleigh wave and the Love wave. It can occur at a location where is far from an epicenter. Although there were no damages in buildings, civil engineering structures and industrial facilities at that location, ASTs had been only damaged by the sloshing.

3.2. Failures of ASTs due to high frequency earthquake

Most of the ASTs are unanchored and rest freely on flexible foundations. When an unanchored tank is subjected to lateral load induced by the high frequency earthquake, an overturning moment is developed at a base of the tank sidewall. The tank will rock in response to this overturning moment. As a result, a sidewall-to-bottom joint of the tank contacts and compresses the foundation strongly on one side, and lifts off from the foundation on the other side, as shown in Fig. 5.



(a) Impulsive motion (b) Sloshing motion

Figure 4. Vibration modes of AST in an earthquake

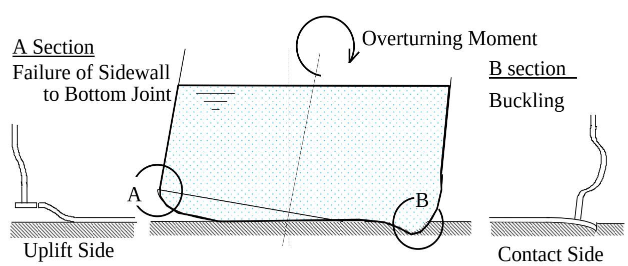


Figure 5. Rocking motion due to high frequency earthquake

On the contact side, buckling of the sidewalls may occur due to excessive vertical compressive force. This buckling is characterized by a "diamond-shape buckle" or an "elephant foot bulge". On the other hand, the uplifting causes large plastic strain at a toe of the sidewall-to-bottom fillet weld, and this leads to a catastrophic failure of ASTs.

3.3. Failures of ASTs due to low frequency earthquake

The sloshing in an AST may occurs due to the low frequency earthquake. When the sloshing wave reaches to roof plates in the fixed roof tank, the sidewall-to-roof joint is subjected to internal pressure as shown in Fig. 6. This pressure causes circumferential compression force in this joint, and the bifurcation buckling with a high circumferential wave number may occur. The sidewall-to-roof joint is usually designed to be weak from the viewpoint of the frangible roof joint. When an overpressurization occurs due to an ignition of flammable vapors existing inside tank, the sidewall-to-roof joint is expected to fail before failure occurs in the sidewall-to-bottom joint. This is a design concept of the frangible roof joint.

The floating roofs are used in many large ASTs to reduce evaporation. It may deform during the sloshing due to the low frequency earthquake (Fig. 7), and it may cause rupture. When the floating roof loses its buoyancy, it will sink into oil. The floating roof tank was considered to be safer than the fixed roof tank, because only a seal fire might occur and a full surface fire as shown in Fig. 8 could not occur. However, when the floating roof sinks, the full surface fire possibly occurs. The full surface fire will be extinguished when oil burns out in a large AST. It will take several days.

3.4. Failures of ASTs due to tsunami

When a small AST is empty or low oil level, it moves by tsunami. In the moving process, AST may float on tsunami and may overturn to cause rupture and leakage of oil. If it does not move, the sidewall may buckle due to external tsunami pressure. In a large AST, it is hard to move by tsunami.

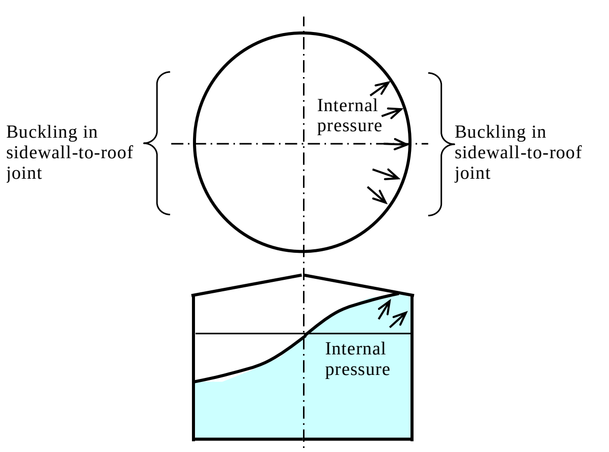


Figure 6. Buckling mechanism of a sidewall-to-roof joint in a fixed roof tank due to low frequency earthquake

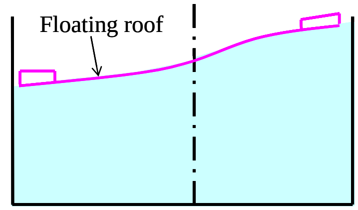


Figure 7. Sloshing of floating roof tanks due to low frequency earthquake

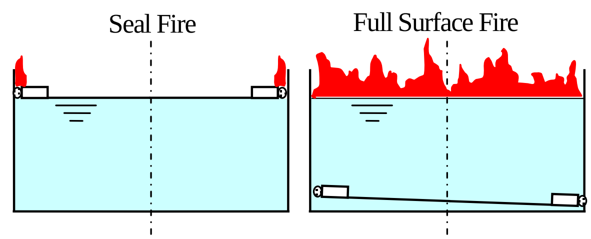


Figure 8. Fire in floating roof tanks

4. 1964 Niigata Earthquake

The 1964 Niigata Earthquake occurred on June 16, 1964 with a moment magnitude 7.6. The epicenter was located on the continental shelf off the northwest coast of Honshu Island about 50 km north of Niigata as shown in Fig. 3. 26 people lost their lives, 1,940 residential houses were completely destroyed, and 6,640 residential houses were severely damaged.

Full surface fires of 12 ASTs occurred at a refinery of Showa Oil, Inc. in Niigata due to the 1964 Niigata Earthquake. The fires lasted two weeks. The cause of the fires was considered the soil liquefaction at first. The low frequency earthquake was not recognized at that time. The cause was concluded to be the sloshing due to the low frequency earthquake later. Two large external floating roof tanks with nominal capacity 45,000 m^3 were included into the burned tanks. The fires were extinguished when oil burned out.

All floating roofs have an annular space between a sidewall and a floating roof to permit smooth travel of the roof within the tank. A rim seal is used to seal the annular space. A mechanical shoe seal came into collision with the sidewall due to this sloshing in the earthquake. An ignition of flammable vapors occurred. The mechanical shoe seal was the cause of the tank fire. A foam-filled fabric seal is currently used instead of the mechanical shoe seal to prevent an ignition inside the tanks in Japan.

It was not clear whether the floating roofs sank before the fire occurred. The fires finally became a full surface fire in several floating roof tanks and they spread to other tanks.

It was the 1968 Tokachi Oki Earthquake that the low frequency earthquake has been recognized for the first time. This earthquake occurred on May 16, 1968, and its moment magnitude was 8.3. The ground motion wave was recorded in Hachinohe, northern city of Honshu Island, and it included a low frequency component. No major damages of ASTs occurred in the 1968 Tokachi Oki Earthquake.

5. 1978 Miyagi Earthquake

The 1978 Miyagi Earthquake (the 1978 Miyagi-Ken Oki Earthquake) occurred on June 12, 1978 with a surface wave magnitude 7.7. The epicenter was located off the northeast coast of Honshu Island about 100 km east of Sendai as shown in Fig. 3. It caused 28 deaths and 1,325 injures. Approximately 4,400 residential houses were completely destroyed, and 86,000 residential houses were partially destroyed in City of Sendai.

A refinery of Tohoku Oil, Inc. was located near Sendai. An uplifting occurred at the sidewall-to-bottom joints in three large fixed roof tanks due to the high frequency earthquake in this refinery. Two of them had the same size and stored heavy fuel oil. Their diameter was 43.6 m, the height was 21.9 m, the nominal capacity was 31,500 m^3, the sidewall thickness of the lowest course was 19 mm and the annular plate thickness was 9 mm. The other tank stored diesel oil and the diameter was 37.8 m, the height was 21.9 m, the nominal capacity was 23,700 m^3, the sidewall thickness of the lowest course was 16 mm and the annular plate thickness was 8 mm.

The uplifting caused large plastic strain in the sidewall-to-bottom fillet weld. The fracture started at the toe of the fillet weld, and it led to catastrophic tank failure. The three tanks lost their contents which then spilled over a dike, inundated much of the refinery area and spilled into the port. Black area in Fig. 9 shows the spilled oil. Fortunately, no fire broke out.

6. 1983 Sea of Japan Earthquake

The 1983 Sea of Japan Earthquake (the 1983 Nihonkai Chubu Earthquake) occurred on May 26, 1983 with a moment magnitude 7.8. The epicenter was located off the northwest coast of Honshu Island in the Sea of Japan about 120 km northwest of Akita as shown in Fig. 3. 104 people lost their lives. 100 of them were the victims of tsunami, which struck communities along the coast. The tsunami warning was issued 14 minutes after the earthquake, but many parts of the nearby coast were struck before any action could be taken.

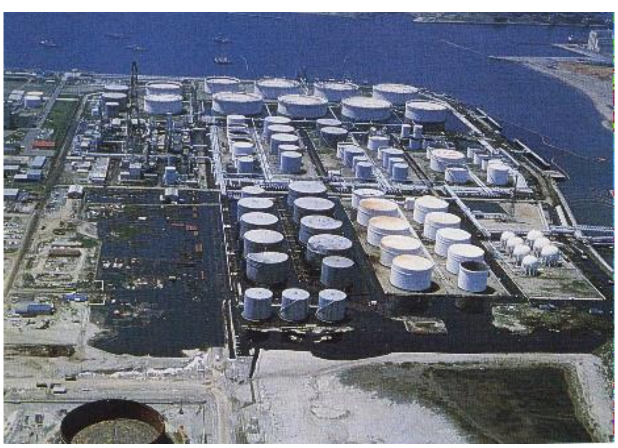


Figure 9. Spilled oil inundated a refinery area in Sendai at the 1978 Miyagi Earthquake (Courtesy of Kahoku Simpo Publishing Co.)

A seal fire broke out in a 35,000 m^3 external floating roof tank with crude oil storage at a thermal power plant of Tohoku Electric Power Company in Akita, and it was extinguished 2 hours later. A projection which was welded at a peripheral upper part of the double-deck floating roof had collided with a sidewall due to the sloshing, and the collision generated sparks. The diameter was 50 m and the height was 20 m in this AST.

Two external single-deck floating roofs of large ASTs ruptured due to the sloshing and oil spilled on the roof in Niigata. Niigata is located 220 km south of Akita. These floating roofs did not sink and no fire broke out.

7. 1995 Kobe Earthquake

The 1995 Kobe Earthquake occurred on January 17, 1995 with a moment magnitude 6.8. The epicenter was the Nojima Fault on the northern end of Awaji Island, 20 km away from Kobe as shown in Fig. 3. 6,434 people lost their lives, and approximately 44,000 people were injured.

The high Frequency earthquake was predominant in Kobe, because the epicenter was near. The buckling of sidewalls in small ASTs occurred due to the rocking motion in Kobe. Figure 10 shows the diamond-shape buckle, and Figure 11 shows the elephant foot bulge of the sidewall in ASTs. The soil liquefaction also occurred everywhere in Kobe. Small ASTs were inclined by the soil liquefaction as shown in Fig. 12. Although a leak occurred in a water storage tank and many resident houses were burned, no oil leak and no fire occurred in ASTs.

Figure 10. Diamond-shape buckle of a sidewall in a small AST in Kobe at the 1995 Kobe Earthquake (Courtesy of National Research Institute of Fire and Disaster, Japan)

Figure 11. Elephant foot bulge of a sidewall in a small AST in Kobe at the 1995 Kobe Earthquake (Courtesy of National Research Institute of Fire and Disaster, Japan)

Figure 12. Inclination of small ASTs due to the soil liquefaction in Kobe at the 1995 Kobe Earthquake (Courtesy of National Research Institute of Fire and Disaster, Japan)

8. 2003 Hokkaido Earthquake

The 2003 Hokkaido Earthquake (the 2003 Tokachi Oki Earthquake) occurred on September 26, 2003 with a moment magnitude 8.3. The epicenter was located about 60 km offshore of Hokkaido Island as shown in Fig. 3. Tsunami attacked to two persons who were fishing on a river, one person was dead and the other was missing.

A refinery of Idemitsu Kosan Co., Ltd. is located in Tomakomai, 220 km northwest of the epicenter. A seal fire of an external single-deck floating roof tank with 30,000 m^3 crude oil storage broke out immediately after the earthquake, and was extinguished 7 hours later. The diameter was 42.7 m, the height was 24.4 m in this AST.

In this tank, crude oil spilled over the floating roof by the sloshing, and it evaporated. The cause of the ignition was presumed a collision of the apparatus at the upper sidewall with the floating roof, or a fall of the gauger's platform which installed at a top of sidewall to the floating roof. The floating roof did not sink in this AST.

There was another external single-deck floating roof tank with 30,000 m^3 naphtha storage near the crude oil tank at the same site. The tank size was the same as the crude oil tank. The floating roof was ruptured due to the sloshing, and it sank into oil completely one day after the earthquake. A full surface fire broke out in this tank two days after the earthquake, and continued 44 hours [1]. The fire was extinguished when naphtha burned out. The cause of ignition was unknown. Both Figure 13 and Figure 14 show this full surface fire.

Figure 13. Full surface fire in a 30,000m^3 naphtha storage tank in Tomakomai at the 2003 Hokkaido Earthquake (Courtesy of National Research Institute of Fire and Disaster, Japan)

Figure 14. Aerial photo of full surface fire in a 30,000m^3 naphtha storage tank in Tomakomai at the 2003 Hokkaido Earthquake (Courtesy of National Research Institute of Fire and Disaster, Japan)

Other 6 ASTs had experienced sinking failures of single-deck floating roofs in this refinery. The pontoons and the deck plates were ruptured, and the floating roofs lost buoyancy due to the sloshing. The roofs sank into oil slowly taking several days. Figure 15 and Figure 16 show the sunken floating roof of an AST with 100,000 m^3 crude oil storage. These photos were taken several months after the earthquake when the oil was drained from the floating roof and the tank was cleaned. The large deformation and failure of the floating roof is presumed to be caused during the sinking process. This roof remained afloat without collapse for 1.5 days after the earthquake according to aerial photos.

Though floating roofs had been designed under the load of rain water, snow and buoyancy, the earthquake sloshing had not been taken into consideration. This full surface fire and the sinking failures led to an establishment of the seismic design method of floating roofs. The regulation for

Figure 15. Deck plate of a sunk single-deck floating roof of a 100,000 m^3 crude oil storage tank at the 2003 Hokkaido Earthquake

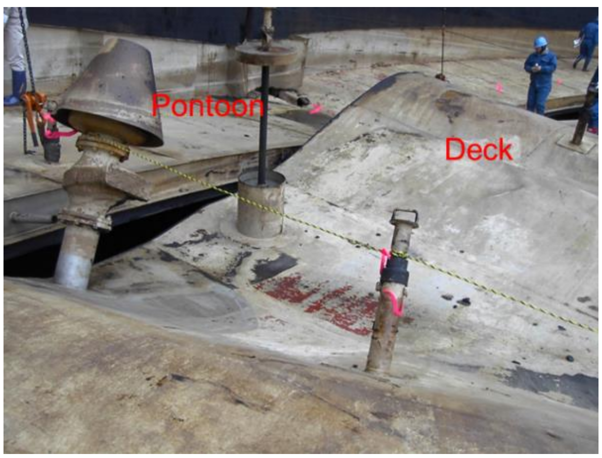


Figure 16. Deck plate and pontoon of a sunk single-deck floating roof of a 100,000 m^3 crude oil storage tank at the 2003 Hokkaido Earthquake

a floating roof design was issued on January 14, 2005 by the Fire Service Law of Japan [2].

9. 2011 Great East Japan Earthquake

The 2011 Great East Japan Earthquake occurred on March 11, 2011 with a moment magnitude 9.0. The epicenter was off the northeast coast of Honshu Island as shown in Fig. 3. It was the most powerful earthquake ever to have hit Japan, and it was the fourth most powerful earthquake in the world since 1900. Powerful tsunami attacked to the northeast coast, and it caused nuclear power plant incidents in Fukushima. 15,883 people lost their lives, 2,640 people were missing and 6,150 people injured in this earthquake.

There are many fishing ports along the coastline of northeast Honshu Island. Several small ASTs were installed at the fishing ports. The ASTs had stored the fuel for fishing boats. Tsunami moved the tanks and overturned them. Some of them sank to sea. Leaked oil from ASTs made massive fire. Figure 17 shows an AST moved to higher ground and overturned by the tsunami.

Figure 17. AST moved to higher ground and overturned by the tsunami at the 2011 Great East Japan Earthquake (Courtesy of National Research Institute of Fire and Disaster, Japan)

An external single-deck floating roof in Kawasaki near Tokyo sank to oil due to the sloshing. Several aluminum internal floating roofs also sank in Sakata, northwest coast of Honshu Island. Fortunately, no fire broke out in these ASTs. Except for the overturning accidents of ASTs by tsunami and the sinking accidents of floating roofs mentioned above, there were few accidents in ASTs in this earthquake.

A spherical LPG storage tank at a refinery of Cosmo Oil Co., Ltd. in Chiba near Tokyo was being used for a hydrostatic test during this earthquake. The hydrostatic load was twice larger than usual load, and it was collapsed by the earthquake. This tank destroyed an adjoining LPG tank when it collapsed, and gas leaked. As a result, a massive fire broke out.

10. Disaster Prevention of ASTs

10.1. High frequency earthquake

The uplift of sidewall-to-bottom joint due to high frequency earthquake easily occurs in large AST, resulting in extremely large plastic strains at the toe of fillet weld. If this part is broken, it will become a catastrophic oil spill and the risk of fire will increase. In the disaster prevention measures, it is important to perform the safety management of ATS, that is the internal inspection on corrosion of bottom plate and defects of weld at proper interval.

10.2. Low frequency earthquake

In the low frequency earthquake, the maximum liquid height is important to set so that the sloshing wave does not reach the upper limit of the sidewall to prevent both the overflow of content and the buckling of sidewall-to-roof joint. However, it is very difficult to determine the reasonable design sloshing height, and often sloshing that exceeds the assumption is occurring.

The floating roof is installed to prevent emission of hydrocarbon vapors to the atmosphere. It is not a pressure resistant member. Even if the floating roof sinks, oil does not leak outside the tank, but a full surface fire may occur. It is not practical to make the floating roof stiff in strength as the pressure resistant member. Floating roofs designed with current concept can be damaged by sloshing due to low frequency earthquake.

It is important that the floating roof does not sink in order to prevent the full surface fire of AST. If a full surface fire breaks out, it will be extinguished when oil burns out a few days later and air pollution will occur while burning. In recent years, unsinkable floating roof which is made of FRP has been developed as shown in Fig. 18. In addition, it is also important to develop a foam extinguishing agent that extinguishes in a short time when the full surface fire occurs.

10.3. Tsunami

From the Great East Japan Earthquake, countermeasures against tsunami in ASTs also became an important issue. It is not realistic to make individual ASTs resistant to tsunamis. If possible, it is desirable to transfer ASTs to a high place not subject to the tsunami or a place far from the coast. However, when it cannot be done, it is necessary to think in the framework of disaster prevention measures for the entire local area or the AST base.

Figure 18. Unsinkable FRP floating roof (Courtesy of HMT Inc.)

11. Conclusion

Earthquake damages of ASTs which occurred for the last several decades in Japan are reviewed. These are damages in the 1964 Niigata Earthquake, the 1978 Miyagi Earthquake, the 1983 Sea of Japan Earthquake, the 1995 Kobe Earthquake, the 2003 Hokkaido Earthquake, the 2011 Great East Japan Earthquake.

A massive earthquake with an epicenter at Nankai Trough off the south coast of Honshu Island is due in not-too-distant future. In this earthquake, ASTs in the industrial area in Tokyo, Osaka, and Nagoya are expected to suffer damage. There is an urgent need for disaster prevention and mitigation of ASTs for these earthquakes.

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