TSUNAMI DAMAGE TO OIL STORAGE TANKS

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ABSTRACT :

The giant Indian Ocean tsunami of December, 2004 caused damage to oil storage tanks in Aceh Province of Sumatra Island. Some of them collapsed and others floated and moved several hundreds of meters. The author investigated the damaging of these tanks. Conclusions are as follows: 1) Storage tanks containing little oil can be easily floated and moved by a tsunami. The floating tank may then collide with adjacent tanks, causing leakage of oil. A fire may then be triggered, causing massive environmental destruction. 2) Similar widely spreading tsunami could simultaneously damage a number of oil storage stations and cause serious disruption to the world economy. 3) An effective countermeasure against floating is to place a cylindrical wall around the tank or an impermeable liner around the base plate of the tank. 4) It would be advantageous for piping to uncouple from the side valve of a tank when a tsunami flow force is applied to the piping. 5) In tsunami-prone areas, oil leakage prevention dikes should also be designed against tsunami pressure from the outside.

KEYWORDS: tsunami, tank, floating, piping, dike

1. INTRODUCTION

On December 26, 2004, there was a giant tsunami resulting from a huge earthquake of Mw 9.3 off the west coast of Sumatra, resulting in a great deal of damage and over 200,000 dead or missing people in countries with coasts on the Indian Ocean. While a huge number of lives were lost, there was also serious damage to roads, water supplies, energy supply facilities and so on. In Aceh province in the northwest of the Sumatra island of Indonesian, large oil storage tanks suffered damage, and some were dislodged and floated considerable distances. There are many petroleum storage tanks along seashores all over the world. A similar widely spreading tsunami could simultaneously damage a large number of oil storage tanks, thus causing serious disruption to the world economy and environment.

2. HISTORY OF TSUNAMI-INDUCED DAMAGE TO OIL STORAGE TANKS

2.1 1964 Alaska Earthquake[1)]

On March 27, 1964, a giant earthquake of Mw 9.2 struck the south coastal area of Alaska, USA. The epicenter was in the Northern part of Prince William Sound, about 120 km east of Anchorage. The earthquake generated two types of tsunami: a tectonic tsunami by tectonic uplift of the sea floor and at least five local tsunamis by earthquake-induced landslides slumping into the bay. The tectonic tsunami damaged harbors, boats and houses, and killed 16 people along the west coast of Canada and the USA, and in Hawaii several hours after the earthquake. The local tsunamis occurred within minutes after the shaking began, and they severely damaged several Alaskan cities. In Valdez, 88 km east of the epicenter, the shaking caused massive failures of an unstable, water-saturated silty delta containing sand seams, which slid into sea. The slide generated a wave, which penetrated two blocks into the town. It also destroyed oil tanks and spread the oil, which ignited. Five or six hours after the earthquake, unusually high waves occurred. These last waves inundated the downtown section of Valdez, ruining almost all the merchandise in the stores. The maximum run-up was 9.1 m. The fires lasted two weeks and burned out the town. In Seward, 113 km south-west of the epicenter, a section of the waterfront slid into the bay. At the time of the earthquake, a tanker was moored at an oil company dock taking on petroleum products. About 30 seconds after the shaking, the ship heeled, listed and rose suddenly, breaking the hose connections or pulling them out with pipelines. Fire followed almost immediately. 14 storage tanks were completely destroyed by the slumping and ensuing fire, and four more were badly damaged, leaving just five of the original 23 tanks intact. An 80-car train on railroad tracks was caught in the wave and fire. Tank cars and boxcars were moved as far as a quarter of a mile from the track by the tsunami. The last 40 cars were filled with petroleum products. They exploded sequentially toward the tanks of another oil company. The tanks continued to burn for two days. In Whittier, about 48 km west of the epicenter, within 45 seconds of the onset of the earthquake, an oil storage tank failed as its bottom moved away. Fire continued for three days. The maximum local tsunami height reported in Whittier was 13 m.

2.2 1964 Niigata Earthquake[2)]

On June 16, 1964, an earthquake of JMA magnitude (Mj) 7.5 occurred off Niigata prefecture, north of middle Japan. The earthquake caused widespread destructive liquefaction in Niigata city, one of the biggest cities in northwest Japan. Large amplitude sloshing occurred in oil storage tanks due to the long-period component of the earthquake wave, and oil in several tanks overflowed and caught fire. Then, a tsunami 4 m high entered the lowlands of the city through slumped dikes. The coastal oil industry area was flooded both by the tsunami and by the water that came up from liquefied ground. The blazing oil spread over the water, and ignited neighboring tanks and residential houses. 149 tanks and 290 houses were burned out. The tsunami itself did not damage the tanks, but it spread the fires and hampered effective disaster mitigation activities.

2.3 1993 Southwest-of-Hokkaido Earthquake[3)]

On July 12, 1993, an earthquake of Mw 7.7 occurred in the sea 50 km north of Okushiri Island, 20 km off the southwest coast of Hokkaido, Japan. A tsunami arrived within 4 minutes after very strong shaking. The highest run-up on the island was 30.6 m. 198 of about 4,400 inhabitants lost their lives, most due to the tsunami. Aonai village, the largest community on the island and comprising 504 houses, was struck by a series of tsunami about 10m high, and lost 385 houses. Aonae also caught fire less than half an hour after the first shock. A propane tank was ignited by the tsunami, and oil tanks for individual houses caught fire. 190 houses were burned out.

2.4 2005 Hurricane Katrina Storm Surge[4)]

Storm surge has also damaged oil storage tanks. On August 29, 2005, Hurricane Katrina made landfall near New Orleans, Louisiana, USA, recording winds of 180-210 km per hour and accompanying a storm surge of 8.2 m along the Northern Gulf Coast. It caused massive failures along the Mississippi River Gulf Outlet levee, and the storm surge inundated low land along the river, where there were many oil refineries and oil storage tanks. The storm surge lifted and dislodged many tanks, which were split and released oil. More than 28,000 kl poured into the Gulf Coast region's waterways. According to the US Coast Guard, there were about 44 oil spills in the area affected by Hurricane Katrina. Most of these occurred in areas of Plaquemines Parish, which does not have a large population. However, one of the oil spills hit the residential area of Chalmette, St. Bernard Parish. A 29,000 kl storage tank was dislodged, lifted and damaged in the flooding. The tank contained 7,600 kl of mixed crude oil, and approximately half of this was released. The released oil polluted approximately 1700 homes in Chalmette, a few miles southeast of New Orleans.

3. TANK DAMAGE ON SUMATRA ISLAND DUE TO 2004 INDIAN OCEAN TSUNAMI

There were four oil tank yards in the area affected by the tsunami and all of them suffered heavy damage. In Meulaboh of Aceh Barat district, there were 4 oil tanks about 16 m in diameter and one of them was dislodged and moved 1 km inland by the tsunami, which was more than 5 m high. In Kuala Budon, 16 km northwest of Meulaboh, there were two palm oil tanks about 22 m in diameter. One of them was empty at the time of the tsunami and was dislodged and moved 3 km inland. The other was almost full of oil and was not dislodged, but it was split and all of the palm oil was lost. In a cement factory at Lho'nga of Aceh Besar district, 13 km southwest of Banda Aceh, capital city of Aceh province, three large tanks 23 m in diameter and eleven rather small tanks were dislodged or crushed by the tsunami. The fourth yard was an oil delivery terminal located at Krueng Raya of Aceh Besar district, 24 km east of Banda Aceh. Three tanks 17 m in diameter were dislodged and moved several hundred meters by the tsunami. Fortunately none of these tank yards caught fire. The author visited Lho'nga and Krueng Raya three times and investigated the damage to the tanks.

3.1 Damage in cement factory at Lho'nga

This factory comprises modern integrated mills for cement manufacture consisting of a kiln, silos, a port of shipment, a power generation plant, quarries etc.

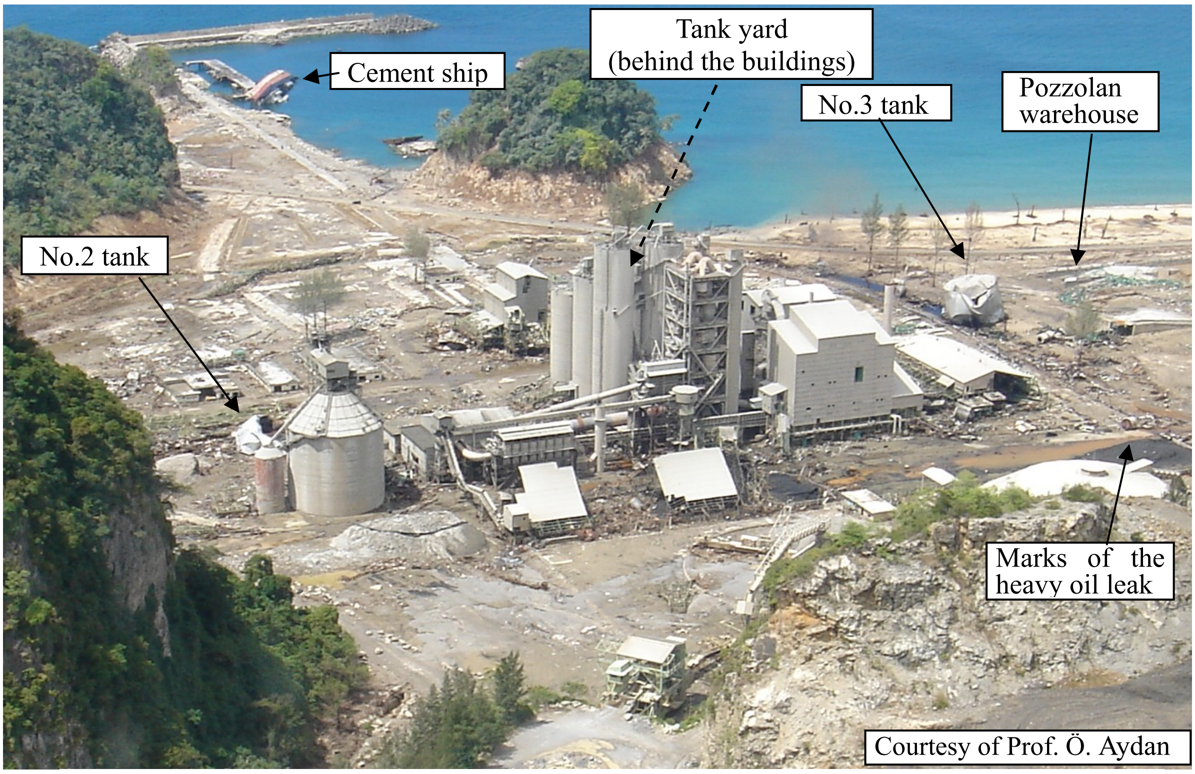

Photo 1 Factory after suffering calamity as seen from ridge

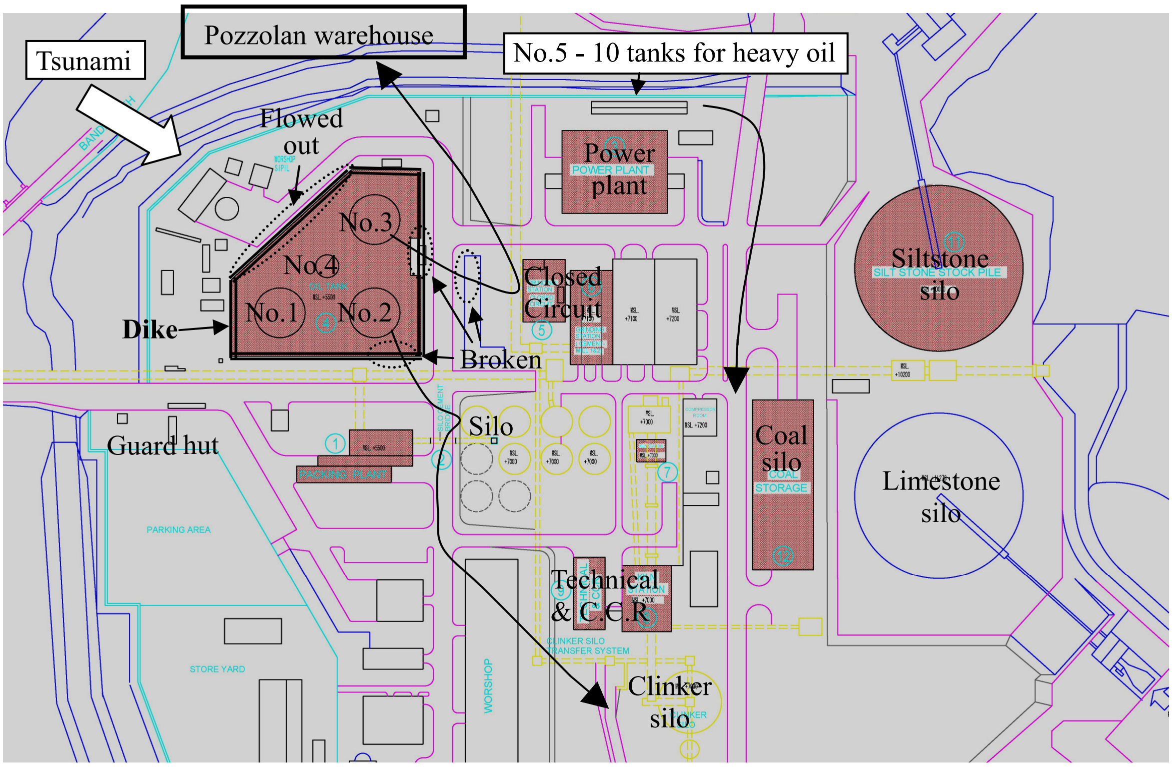

Figure 1 Central part of cement factory and movement locus of tanks

Table 1 Dimensions of oil storage tanks in cement factory

No. of tank	Specification				Liquid level at the tsunami	Instal-lation year	Criteria applied	Damage notes
	Applica-tion	Dia. m	Height m	Capa. kl				
Tank 1	Water	23.30	14.62	6,000	100%	1981	API650	Smashed and flattened within diked enclosure.
Tank 2	Distillate	23.30	14.62	6,000	75%	1981	API650	Broke through dike and collided with neighboring structures. Original shape lost.
Tank 3	Distillate	23.30	14.62	6,000	50%	1981	API650	Broke through dike, collided with neighboring structures and seriously deformed.
Tank 4	Distillate	11.65	10.98	1,000	50%	1981	API650	Dislodged and deformed.
Tank 5 -10	Heavy fuel oil	3.05	5.719	25	?	1981	Un-known	Dislodged. Factory ground partially polluted by leaked heavy fuel oil.

The layout of No.1-No.4 tanks and the configuration of the spilled oil containment dike are shown in Figure 1. No.5-No.10 tanks had been located beside the power generation plant. The spilled oil containment dike was a reinforced concrete structure, height 2.25 m, base width 250 mm, and crest width 160 mm. The main reinforcement was DΦ13 mm 0.1 m pitch and comprised single reinforcement located at the tank yard side in the wall section. Distribution bars were Φ9 mm. There was no tide embankment.

3.1.1 Damage features

Spilled-oil containment dikes are designed to resist hydraulic pressure from the interior, but not usually from the exterior. As a result, the side exposed directly to the run-up wave toppled off its base, and was sucked out by the receding tide. No.2 and No.3 tank rode on the tsunami, and collided with and broke through the dike. They collided with silos and steel framed buildings, and were moved about 80 and 200 m from their original location, and were badly deformed. Although No.1 had been filled with water and remained inside the dike, the incoming tide crashed into it and flattened it. A cement ship had also moored in the harbor and was loading. It capsized, and a part of the pier was damaged by its impact.

3.1.2 Tsunami inundation height

The tsunami along the coastline of Lho'nga was estimated to be about 20 m high according to the investigation by Professor Tsuji of the Seismic Research Institute of the University of Tokyo[5)]. Tsunami traces on the silo wall indicated that the surge rose to about 10 m above the ground in the factory yard. According to survivors, the tsunami mainly rolled in from the the right-hand side when viewed from the factory, and reached a limestone silo and a siltstone silo on the hillside.

3.1.3 Survivor's report

The following was witnessed by an engineer who was in the factory.

“Two strong earthquakes, mainly with horizontal shake, were felt. The 2nd came 15 minutes after the first and was larger. The inside of the factory was filled with dust due to the shaking. Powder of raw materials that had piled up on steel frame members of the building etc. seemed to fall. In-house power generation stopped. The tsunami came about 30 minutes after the 2nd earthquake. The wave crashed onto the sea side wall of the pozzolan warehouse nearest the sea, and a large spray splashed upward. There were three tsunamis; the 2nd was the largest. There was about 5 minutes between the 1st and the 2nd tsunami. Many facilities were destroyed by the 1st and then moved by the 2nd. However, the 1st one started to move the tanks. The tanks floated and collided with various other facilities, and in particular caused the elevated belt conveyor bridges to collapse. After No.3 tank broke the dike, it tore the wall of the material yard and collided with a building. It was then carried in the direction of the pozzolan warehouse. No.2 tank also broke the dike. After it collided with a silo, it was carried toward the side of the clinker silo. No.5-No.10 heavy fuel oil tanks floated and were carried in the direction of the coal silo. Part of the factory yard was polluted with leaked heavy fuel oil. Fire did not occur, maybe because of the early power failure”.

The engineer in the factory who witnessed these events was on the second floor of a building, named Technical & C.C.R, in the factory when the earthquake occurred. About 5 minutes after the 1st earthquake, he went outside to observe the situation. He then returned and went outside again after the 2nd earthquake. He was not sure about the exact timings. After a while, since one guard came running to escape from a guard hut located on the marine side, he also escaped in the direction of higher ground with 15 other persons. It was not known how the guard had noticed the tsunami. When the tsunami inundated the area, there were about 100 persons in the factory. About 50 of them escaped to higher ground etc. and survived. Almost none of the people had any knowledge about tsunami.

3.1.4 Restoration

The amount of damage was probably more than one hundred million USD. Restoration work was urgently required to open the harbor. It was necessary for cement-transport ships from outside the factory to enter the harbor and stow the shipment there. 1,600 ton of cement a day needed to be sent down to various parts of Aceh province. Restoration of the harbor was being performed in August of 2005. According to the HP of LAFARGE dated June 23 (http://www.bkpm.go.id/en/node/2256), 2008, resumption of factory operation was planned for 2009. It will have a production capacity of 1.6 million tons of cement per year, up from 1.3 million before the tsunami.

Photo 2 No.3 tank. 50% full of distillate

Photo 3 No.1 tank remained inside the dike
(Courtesy of Penta-Ocean Construction Co., Ltd)

Photo 4 This part of the dike was broken through by No.2 tank.

Photo 5 The part where No.3 tank broke through the dike viewed from outside.

3.2 Damage to Oil Delivery Terminal at Krueng Raya

The owner of the terminal is PERTAMINA (an Indonesian public oil corporation). It is managed by a branch office in Band Aceh. The spilled oil containment dike was made from earth fill. As shown in Figure 2, it encloses the tank yard. It is 317 m long and has 2.5 m trapezoid base width, 0.8 m trapezoid surface length, and 1.2 m height. There was no tide embankment.

Photo 6 Three tanks drifted about 300 m and one moved 0.7 m

Table 2 Dimensions of oil storage tanks in oil delivery terminal

No. of tank	Specification			Liquid level at the time of the tsunami		Installation year	Criteria applied	Damage notes
	Application	Diameter m	Height m	Oil storage kl	Height of Oil			
1	Gasoline	17.07	11.11	250	1.1	1986	API	Moved several hundreds of meters
2	Distillate	17.07	11.11	600	2.6	1986	API	
3	Distillate	17.07	11.11	0	0	1986	API	Moved several hundreds of meters
4	Kerosene	17.07	11.11	1,500	6.6	1986	API	
5	Jet fuel	10.98	6.23	200	2.5	1986	API	Moved 0.70 meters
6	Jet fuel	10.98	6.23	413	5.3	1986	API	
7	Gasoline	18.10	10.98	250	1.1	1990	API	Moved 314 meters
8	Kerosene	18.10	10.98	1,600	7.0	1990	API	
9	Distillate	18.10	10.98	549	2.4	1990	API	

3.2.1 Appearance of tsunami inundation

The height of the tsunami in the Krueng Raya area was assumed to be 4-6 m. Dr. Tomita of the Port and Airport Research Institute reported that the height showed a variation[6)]. It was 4.8 - 5.7 m for No.2 tank, about 5.1 m for No.5 tank, and about 4.9 m for No.6 tank. Since the mound height was 1.0-1.1 m from foundation level, when calculating the buoyant force that had acted, it is necessary to deduct the height. Although the pier had been inundated, it did not suffer damage. Moreover, the pump hut on the pier was not washed out. The dynamic pressure of the tsunami in this area had the impression of being smaller than that in the cement factory.

3.2.2 Witnesses of damage

When Dr. Sugano of the Port and Airport Research Institute investigated in March 2005[6], an engineer at the site testified to the following. "10 minutes after the earthquake, the sea receded, and then the tsunami surged three times, each progressively higher. However, it was unclear which tsunami had caused the tanks to float. No.1 tank moved in the direction of No. 4 tank. No.3 tank collided with No. 5 tank and a dent was made in the side wall of No.5 tank. No. 7 tank was moved 314 m". The author got information about the oil storage levels at the time of the tsunami and about the structural details of the tanks, together with the following information from an engineer of PERTAMINA. Intake and outlet pipelines placed on the ground were moved by the tsunami, and flexible joints attaching piping to the tank were torn off. However, since the valve in the side of the tank was shut, there was no outflow of oil from the tank. No apparent unusual deformation was observed at the valve attachment area of the tank side wall.

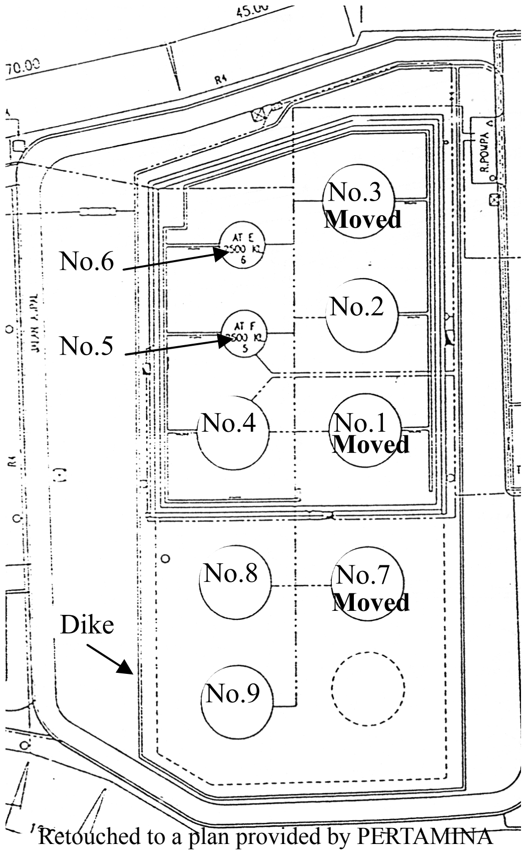

Figure 2 Tank layout

3.2.3 Secondary damage, total damage amount, and restoration situation

All of the oil in the ground piping, about 10 kl, leaked out. No gasoline leaked from No.7 tank, even though it moved a large distance. Neighboring residents gathered and took the gasoline away for their own use. Estimated damage was 30 million USD. Although No.5 tank moved about 0.7 m, since no oil leak was seen, it was being used as it was. This terminal was an important oil supply base for the Banda Aceh area. Fuel for airplanes that were carrying out rescue operations had to be sent to the Banda Aceh airport in a hurry.

Emergency restoration was performed as follows: 1) Shipment of kerosene started on January 14. 2) Shipment of jet fuel started on January 15 (30 kl/day). 3) Shipment of distillate started on January 16. 4) A ship arrived at the pier on February 2. The pipeline had been reconstructed before that, so oil could be landed.

3.2.4 Consideration of floatation

It is easy to calculate the total weight of a tank including its contents if the oil level and structural details are known. For a cylindrical tank, it is also easy to calculate the flood depth that balances the buoyancy and the total weight. Table 3 shows that tanks of more than 2 m of the value of "flood depth to balance buoyancy and weight" could have survived. However, the tsunami height in the terminal was estimated to have been about 4 m above mound level. The difference between this 4 m and the 2 m is the point of interest. Although the accuracy

Table 3 Depth of flood to balance buoyancy and total weight

No. of tank	Self-weight ton	Liquid weight ton	Total ton	Diameter m	Area m^2	Depth of flood to balance buoyancy and weight	Actual damage
1	57.7	186	244	17.07	229	1.04 m	Moved
2	57.7	492	550	17.07	229	2.35 m	
3	57.7	0	57.7	17.07	229	0.25 m	Moved
4	57.7	1,185	1242	17.07	229	5.30 m	
5	15.1	156	171	10.98	94.6	1.77 m	Moved a little
6	15.1	322	337	10.98	94.6	3.48 m	
7	62.7	186	249	18.1	257	0.95 m	Moved
8	62.7	1,264	1,327	18.1	257	5.05 m	
9	62.7	450	513	18.1	257	1.95 m	

of the oil depth is one of the problems, it was presented by PERTAMINA. Calculated self-weight may contain some error, but it is not a major factor. The following two points emerge: 1) The 4 m tsunami height was an instantaneous value; the average height might be lower. 2) It might have taken some time for the tsunami to permeate to the bottom of the sole plate, to push the sole plate up, and to generate the perpendicular component of membrane force in the sole plate to raise the side wall of the tank. Significant time may have been required for Archimedes' principle force to act. This time lag can be a factor in developing a countermeasure.

Photo 7 Side wall of No.5tank caved in a little
（Courtesy of Mr. Furukawa of Kajima）

Photo 8 Pipe attachment part. The intake side pipe separated and a temporary pipe was attached.

4. CONCLUSIONS

1) There are petroleum storage tanks all over the world, and many are located near the seashore. Fortunately, neither a fire nor serious environmental destruction occurred in the tsunami of December 26, 2004, but it was shown that storage facilities near the seashore can easily suffer damage from a tidal wave.
2) Countermeasures against floatation are required for tanks in areas with a high risk of tsunami and/or a high tidal wave. One of the ways is to fill empty tanks with water before a tsunami comes. This may be effective against transoceanic tsunamis. Another way is to construct a high cylindrical dike around the tank.
3) It is hard to prevent piping on the ground surface from being moved by a tsunami. It is more effective to provide a flexible joint that enables piping to be broken off the tank side valve when an unusually large force is applied to a tank from the piping. The flexible joint serves as a fuse. However, when a tsunami warning is received, even during cargo work, a mechanism is required for positively shutting the valve on the tank side.
4) Conventional oil-spillage prevention dikes are designed for hydraulic pressure from the inner side. However, in the tsunami danger zone they should also be designed for tsunami pressure from the outer side.
5) It seems that tanks do not instantly float and move even if the calculated buoyancy from the highest tsunami height exceeds the total weight of the un-anchored tanks. We therefore need to investigate the time required for the tsunami pressure to permeate under the sole plate of a tank of large diameter.

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