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TSUNAMI DAMAGE TO OIL STORAGE TANKS IN THE MW9.0 2011 TOHOKU, JAPAN EARTHQUAKE

K. HATAYAMA[1]

[1] *Chief Researcher, National Research Institute of Fire and Disaster, hatayama@fri.go.jp*

Abstract

The Mw9.0 2011 Tohoku, Japan earthquake tsunami damaged 418 oil storage tanks located along the Pacific coast of the Hokkaido, Tohoku, and Kanto Districts of Japan. A wide variety of damage was observed, including movement and deformation of the tank body, scouring of the tank base and ground, sediment runoff from the tank mound, movement or structural fracture of the pipe, cracking of the oil-retaining perimeter wall, and scouring of the perimeter wall base and ground. In total, 157 of the 418 tanks were moved by the tsunami. The moved tanks were distributed in the Aomori, Iwate, Miyagi, and Fukushima Prefectures of the Tohoku District. In the Fukushima Prefecture, the tsunami with an inundation depth of 13 m moved two 9,800-m^3 tanks with 7,400-m^3 and 6,000-m^3 heavy oil stored, respectively, causing a large amount of heavy oil to leak out of the tanks.

In this study, by comparing the severity of damage with the inundation depths of the tsunami experienced by the oil storage tanks, a fragility curve projecting the damage rate (P) for the piping of the tank was presented in terms of an inundation depth (η in m): $\mathrm{P}(\eta) = \Phi((\ln \eta - 0.98) / 0.48)$, where Φ is the standard normal cumulative distribution function. A rough but easy-to-use method of predicting tsunami damage to an oil storage tank from a given inundation depth was also presented: (i) for inundation depths of less than 2 m, most tanks are safe, although some might suffer minor damage, (ii) for inundation depths of 2–5 m, tanks suffer damage to their piping, small tanks (capacity < 100 m^3) and empty larger tanks may be moved, but non-empty larger tanks are not moved, and (iii) for inundation depths of greater than 5 m, most tanks are moved.

The validity of the previously-proposed tsunami tank-movement prediction method was first examined. A comparison of the method's predictions with the actual damage data from the 2011 Tohoku earthquake tsunami indicated a hit rate of 76%. The method was also observed to overestimate tank movement. Almost every misprediction was a safe error (a tank that did not actually move was predicted to be moved). Because of the high accuracy and the tendency to provide safe predictions, the method has potential applications in practical prediction of movement caused to oil storage tanks by tsunamis resulting from future earthquakes.

Keywords: tsunami damage; oil storage tank; the 2011 Tohoku, Japan earthquake; tank-movement prediction method

1. Introduction

The Mw9.0 2011 off the Pacific coast of Tohoku, Japan earthquake (hereafter, the 2011 Tohoku earthquake) that occurred on March 11, 2011 created a huge tsunami off the Pacific coasts of the Hokkaido and Tohoku Districts in northeastern Japan and the Kanto District in central Japan, as well as strong ground motions in the Tohoku and Kanto Districts; this event caused 19,418 casualties, and 2,592 people are still reported to be missing (Fire and Disaster Management Agency (FDMA), Japan, 2016). The maximum run-up height of the tsunami was 40 m in the Iwate Prefecture, Tohoku District [1]. Most of Japan's large oil storage tanks are located in coastal areas, and many oil storage tanks in the Tohoku District that were exposed to the tsunami suffered various types of damage. Although it is believed that the damage due to the 2011 Tohoku earthquake is the largest-scale one caused by a tsunami to oil storage tanks worldwide, the 2011 event is not the first in which a tsunami caused severe damage to oil storage tanks (e. g., [2-6]).

One of the most serious types of tsunami-induced damage to oil storage tanks is movement of a tank such as sliding, floating, and drifting; emphasis should be placed on prevention of tank movement because of the high risk of leakage of large amounts of oil from damaged shells and pipes attached to the tanks. The first step toward preventing or mitigating movement-induced damage to tanks is to predict the risk of movement for each tank that is likely to be hit by a tsunami in future earthquakes. [7] presented a method for making such a prediction (tsunami tank-movement prediction method). The method consists of equations developed from their hydraulic model experiments to evaluate horizontal and vertical forces exerted by a tsunami on a cylindrical tank (tsunami force equations). These equations were then modified by [8] to better reproduce the experimental data. The tsunami tank-movement prediction method was presented without validation because data on actual tank movement caused by tsunamis were not sufficient. The accuracy of the tsunami tank-movement prediction method requires assessment, and validation is possible because the 2011 Tohoku earthquake left a large number of moved and unmoved tanks that were exposed to the tsunami.

After the 2011 Tohoku earthquake, FDMA conducted semi-nationwide questionnaire investigations to survey the damage caused by the strong ground motions and tsunami at facilities where flammable materials such as oil are used, produced, or stored (hazardous-material facilities). The questionnaires were distributed to and collected from the municipal fire-services headquarters that were responsible for the disaster areas. The author conducted on-site reconnaissance with his colleagues and complementary questionnaire investigations to survey the tsunami-induced damage to oil storage tanks.

The tsunami-induced damage to oil storage tanks are briefly summarized in the third section based on the questionnaire investigations and the on-site reconnaissance. The fourth section discusses the correlation between tsunami inundation depth and severity of damage to tanks on the basis of the actual damage data, where a fragility curve is first presented for tsunami damage to the piping of affected tanks. A rough but fact-based method is also presented to predict damage to a tank from a given maximum inundation depth. The fifth section examines the validity of the previously-proposed tsunami tank-movement prediction method [7, 8] on the basis of the actual damage data. The model examination is followed by conclusions. The tanks discussed in this paper are basically vertical cylindrical metal tanks (cylindrical tanks whose axis direction is vertical). The third and fourth sections partly include transverse cylindrical metal tanks (cylindrical tanks whose axis direction is horizontal). The fifth section discusses vertical cylindrical metal tanks only.

2. Data

The semi-nationwide questionnaire investigations conducted by FDMA took place from May to August 2011. The questionnaires were presented to the municipal fire-services headquarters in 16 prefectures in which damage to hazardous-material facilities was likely to have occurred in the 2011 Tohoku earthquake. In Japan, the safety of hazardous-material facilities is regulated by the Fire Service Act, and FDMA is in charge of implementation of the act. The municipal fire-services headquarters were requested to provide information about the following items for each of the damaged hazardous-material facilities: the specifications of the facility, including the use and size or capacity, the amount of hazardous material stored at the time of the earthquake, and the assessment of damage and the possible cause of the damage (ground motion or tsunami).

When the semi-nationwide questionnaire investigation was conducted by FDMA, the author distributed his questionnaire to the municipal fire-services headquarters together with FDMA's questionnaires. The author's questionnaire requested the respondents to indicate the maximum inundation depth not only for oil storage tanks that suffered tsunami damage but also for tanks that were inundated but not damaged by the tsunami. Data on the maximum inundation depth were collected for some damaged and non-damaged tanks, although the collection rate of the author's questionnaires was lower than that of FDMA.

FDMA conducted an additional questionnaire investigation to obtain the maximum-inundation-depth data at headquarters in the Aomori, Iwate, and Miyagi Prefectures after their semi-nationwide questionnaire investigation.

The detailed tsunami-induced damage data including maximum inundation depths for the tanks were also collected through the author's on-site reconnaissance.

3. Summary of Damage

Table 1 lists the damage situations caused by the 2011 Tohoku earthquake tsunami to oil storage tanks that were picked up from the collected questionnaires. Although it could be difficult to judge whether the damage was caused by the tsunami or strong ground motions in some cases, the damage that was reported to be caused by the tsunami was regarded as tsunami damage. The tsunami caused different types and severity of damage to different parts of oil storage tanks, including movement of tank (Fig. 1), structural fracture of the pipe (Fig. 2) and scouring of the tank base and ground (Fig. 3).

In this study, the number of damaged oil storage tanks was recounted by rearranging and reviewing the raw questionnaire data of FDMA as well as combining data from the on-site reconnaissance and from the author's questionnaire investigation. Table 2 lists the number of tanks that suffered tsunami damage irrespective of the type and severity of damage. In total, 418 tanks were damaged by the tsunami in Japan during the 2011 Tohoku earthquake, and most of the damaged tanks were distributed in the Iwate, Miyagi, and Fukushima Prefectures, where the height of the tsunami was higher than that observed in the other areas [1].

The number of tanks that suffered movement such as washing away, sliding, and falling was also recounted. Table 3 shows that 157 tanks were moved in the Aomori, Iwate, Miyagi, and Fukushima Prefectures. The largest one of the moved tanks had a capacity of 22,000 m^3 and was located in Sendai City, Miyagi Prefecture. According to the property owner, the tank was empty at the time of the earthquake and floated temporarily when exposed to the tsunami with the maximum water level (maximum inundation depth) of 2.7 m, measured from the top of the tank mound. The largest of the non-empty tanks moved by the tsunami were two tanks with a capacity of 9,800 m^3 located in Minami-Soma City, Fukushima Prefecture and they stored 7,400 m^3 and 6,000 m^3 of heavy oil, respectively, at the time of the earthquake. The tsunami with the maximum inundation depth of 13 m moved the one that stored 7,400 m^3 16 m away and the other 32 m away from the original position. The tank that was moved farthest was located in Onagawa Town, Miyagi Prefecture. The 980 m^3-tank was almost empty at the time of the earthquake and drifted 5 km away across the Onagawa bay.

Table 1 – Tsunami damage to oil storage tanks during the 2011 Tohoku earthquake

Damaged Part	Situation of Damage
Tank Body	- Washing away, Sliding, or Falling - Deformation
Base and Ground	- Scouring - Sediment runoff from the mound - Caving or Cracking at the berm (narrow annular passage between the side plate and the concrete ring of the base)
Piping	- Washing away or Moving - Fracture, Bend, or Break
Oil-retaining Perimeter Wall	- Cracking or Breaking - Scouring at the base and ground
Other	- Peeling of the rainwater-repelling seal at the flared portion of the bottom plate - Washing away, Flooding, or Breaking of the accessory equipment such as pumps, valves, and fire extinguishers - Inflow of rubble or mud into the tank yard - Scouring at the tank yard

Fig. 1 – Oil storage tanks moved by tsunami in Kesennuma City, Miyagi Prefecture. (Images taken by Dr. Kiminori Araiba of NRIFD on April 7, 2011.)

Fig. 2 – Pipe fractured by tsunami in Sendai City, Miyagi Prefecture. (Image taken by Dr. Haruki Nishi of NRIFD on June 6, 2011.)

Fig. 3 – Tank base and ground scoured by tsunami in Sendai City, Miyagi Prefecture.

Table 2 – Number of oil storage tanks damaged by the 2011 Tohoku earthquake tsunami

Capacity (C) Class (m^3)		$C <$ 500	500 $\le C <$ 1,000	1,000 $\le C <$ 10,000	10,000 $\le C <$ 50,000	50,000 $\le C$	Unknown	Sum
By Capacity Class		262	64	51	21	15	5	418
By Prefecture	Hokkaido	2	1	0	0	0	0	3
	Aomori	22	4	12	0	0	0	38
	Iwate	60	8	8	0	0	0	76
	Miyagi	125	38	28	19	15	4	229
	Fukushima	49	11	2	2	0	1	65
	Ibaraki	3	2	1	0	0	0	6
	Chiba	1	0	0	0	0	0	1

Table 3 – Number of oil storage tanks moved by the 2011 Tohoku earthquake tsunami with respect to storage capacity (capacity class)

Capacity (C) Class (m^3)		$C <$ 500	500 $\le C <$ 1,000	1,000 $\le C <$ 10,000	10,000 $\le C <$ 50,000	50,000 $\le C$	Unknown	Sum
By Capacity Class		110	30	16	1	0	0	157
By Prefecture	Aomori	3	0	0	0	0	0	3
	Iwate	40	4	0	0	0	0	44
	Miyagi	55	19	14	1	0	0	89
	Fukushima	12	7	2	0	0	0	21

4. Correlation Between Inundation Depth and Damage

As a result of reviewing the raw questionnaire data of FDMA and combining data from the on-site reconnaissance and from the author’s questionnaire investigation, maximum-inundation-depth data were collected for 337 tanks and compared with the severity of damage.

Fig. 4 shows the correlation between maximum inundation depth and severity of damage. Squares (n = 158) indicate tanks that were not moved and whose piping was also safe. Triangles (n = 85) indicate tanks that were not moved but whose piping was damaged. Circles (n = 94) indicate tanks that were moved and consequently whose piping was most likely to be damaged. For maximum inundation depths less than 2 m, most tanks were safe, although some might have suffered minor damage. Most of the tanks that experienced a maximum inundation of 2 to 5 m suffered damage to their piping but were not moved, although some of the moved tanks were also included in this class. At maximum inundation depths of greater than 5 m, most tanks were moved. This chart provides a rough but easy-to-use method of predicting damage caused by a tsunami to an oil storage tank from a given maximum inundation depth.

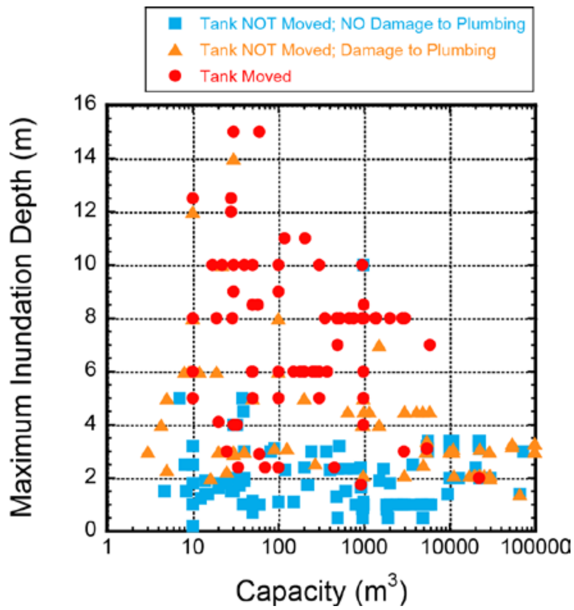

Fig. 4 – Correlation between maximum inundation depth and severity of damage to oil storage tanks due to the 2011 Tohoku earthquake tsunami.

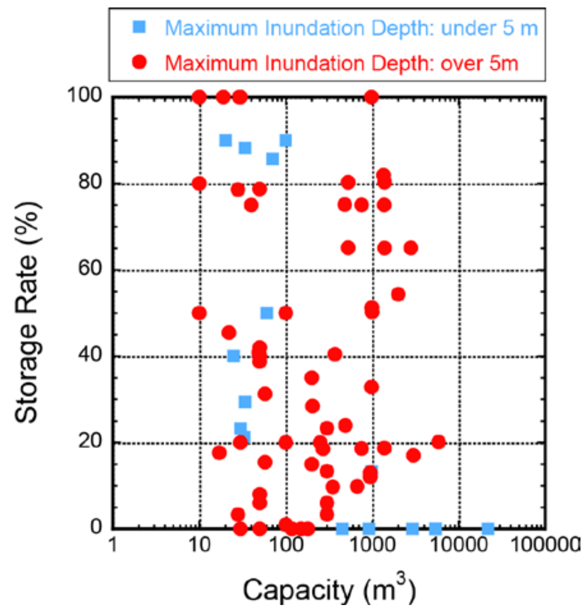

Fig. 5 – Correlation between oil storage rate (proportion of tank capacity used) and movement of oil storage tanks.

Fig. 5 shows the relationship between tank movement and oil storage rate (the ratio of the quantity of oil stored at the time of the earthquake to the tank capacity) for 90 moved tanks. Squares (n = 20) and circles (n = 70) indicate tanks that were inundated to depths of less and greater than 5 m, respectively. Small (capacity < 100 m^3) and large (capacity > 500 m^3) empty tanks were moved to a maximum inundation depth of less than 5 m. Large non-empty tanks were not moved by this class of tsunami. To maximum inundation depths of greater than 5 m, both small tanks and large non-empty tanks were moved. This chart again provides a rough but easy-to-use method of predicting tank movement caused by a tsunami from a given maximum inundation depth and a given oil storage rate.

Fig. 6 shows the rate of damage to the piping in relation to maximum inundation depth. Moved tanks are most likely to suffer damage to their piping, so the rate of damage to the piping was calculated by dividing the sum of the number of tanks that were moved and the number of tanks that suffered damage to their piping but were not moved by the total number of tanks. For maximum inundation depths of greater than 6 m, the damage rate was almost 100%. These observed damage rates were modeled by the log-normal cumulative distribution function. As a result, the model of the fragility curve is presented as follows:

$$P(\eta) = \Phi\left(\frac{\ln\eta - 0.98}{0.48}\right) \tag{1}$$

where P is the damage rate, η is the maximum inundation depth in meters, and Φ is the standard normal cumulative distribution function. The fragility curve model is also shown in Fig. 6. Damage rate data for the class $9.5 \le \eta \le 10.5$ was omitted from the regression analysis.

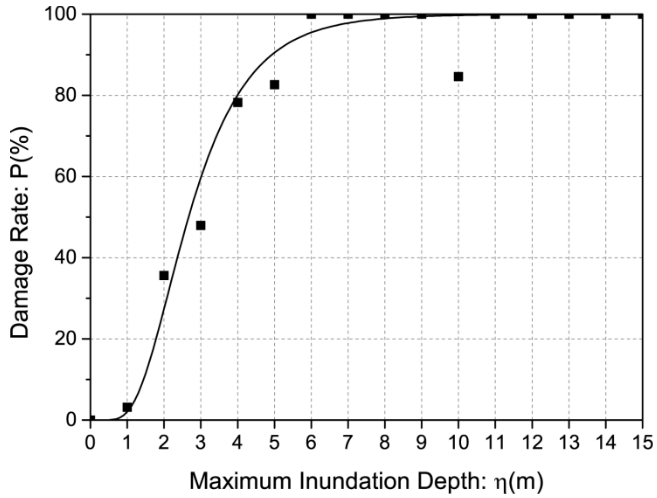

Fig. 6 – Rate of damage sustained by the piping of oil storage tanks in the 2011 Tohoku earthquake tsunami (squares) and the fragility curve (solid line) modeled by the log-normal cumulative distribution function.

5. Validation of Tsunami Tank-Movement Prediction Method

In this section, the validity of the tsunami tank-movement prediction method [7] with the modified version [8] of the tsunami force equations is examined by verifying the predictions obtained using the method against the actual damage data from the 2011 Tohoku earthquake tsunami. First, the method is outlined, and then its validity is discussed.

5.1 Tsunami Tank-Movement Prediction Method

Using the method presented by [7], the risk of sliding and floating for a vertical cylindrical tank exposed to a tsunami is evaluated by the sliding safety factor F_{sS} and the floating safety factor F_{sF}, which are defined by the following equations:

$$F_{sS} = \mu(W_T + W_L - F_{tV}) / F_{tH} \tag{2}$$

$$F_{sF} = (W_T + W_L) / F_{tV} \tag{3}$$

where W_T and W_L are the weights of the tank and stored liquid, respectively; F_{tH} and F_{tV} are the horizontal and vertical forces exerted on the tank by the tsunami, respectively; μ is the coefficient of static friction between the tank bottom and the base. Let the numerator of the right-hand side of Eq. (2) be referred to as the resistance force for sliding. When the resistance force for sliding is larger than the horizontal tsunami force, i.e., $F_{sS} \geq 1$, the tank is assumed to neither slide nor float. When $F_{sS} < 1$, it is assumed to slide, and when $F_{sS} < 0$, which is equivalent to $F_{sF} < 1$, the tank is assumed to float.

The tsunami force equations to calculate F_{tH} and F_{tV} were empirically developed from the hydraulic model experiments by [7] and their original forms are as follows:

$$F_{tH} = \frac{1}{2}\int_{-\pi}^{\pi} \rho g \left[h_H(\theta)\right]^2 R\cos\theta d\theta \tag{4}$$

$$F_{tV} = 2\int_{0}^{\pi} \rho g h_V(\theta) R^2 \sin^2\theta d\theta \tag{5}$$

where

$$h_H(\theta) = \alpha \eta_0 \sum_{m=0}^{3} p_m \cos(m\theta) \tag{6}$$

$$h_V(\theta) = \beta \eta_0 \sum_{m=0}^{3} q_m \cos(m\theta) \tag{7}$$

In Eq. (4), the horizontal force exerted on the tank by the tsunami is modeled by the integration of the hydrostatic pressure for a hypothetical water-height distribution over the tank side plate. The hypothetical water-height distribution is denoted by $h_H(\theta)$, θ being the azimuth angle with respect to the center of the tank bottom, and θ is 0 for the direction from which the tsunami propagates. R, ρ, and g are the radius of the tank, density of tsunami water, and acceleration due to gravity, respectively. $h_H(\theta)$ is described by Eq. (6), where η_0 is the maximum inundation depth that would be observed in the case where a tank was absent. The θ-dependency of $h_H(\theta)$ is modeled as a series of cosine function and the expansion coefficients p_m were determined from the water-height data measured at the side plate of tank models in the hydraulic model experiments, where a model tank was exposed to a simulated tsunami wave: $p_0 = 0.68$, $p_1 = 0.34$, $p_2 = 0.015$, and $p_3 = -0.035$. These p_m values give a normalized distribution. α controls the amplitude of $h_H(\theta)$ and the value of α was determined to be 1.8 so that the peak values of the horizontal force exerted on various model tanks that were exposed to simulated tsunamis with different water velocities would be included.

The vertical tsunami force is modeled by Eq. (5) in the similar manner to that for the horizontal tsunami force. In Eq. (5), the hydrostatic pressure for a hypothetical water-height distribution $h_V(\theta)$ is integrated over the tank bottom, and $h_V(\theta)$ is described by Eq. (7) like $h_H(\theta)$, where the expansion coefficients q_m give a normalized distribution and β controls the amplitude. Values of q_m were determined from the water-pressure data measured at the bottom of tank models in the hydraulic model experiments: $q_0 = 0.72$, $q_1 = 0.308$, $q_2 = 0.014$, $q_3 = -0.042$. The value of β was determined to be 1.2 by the same approach as that used for α.

Eqs (4) to (7) do not require water velocity for determination of the tsunami force. This is the result of α, β, p_m, and q_m having been determined so that the values predicted by the equations would not fall below the peak values of the tsunami force measured from the simulated tsunamis with different water velocities. The lack of need for water velocity is convenient in practice because water velocity has not been predicted in most of the tsunami hazard assessments conducted in Japan. A shortcoming of excluding water velocity is that the tsunami force and the consequent damage are likely to be overestimated. To improve the accuracy of evaluating the tsunami force by taking the water velocity into account in a simplified manner, [8] presented a modification for α and β given by the following equations:

$$\alpha = \begin{cases} 1 & for \quad F_r \le 0.9 \\ 2.0F_r - 0.8 & for \quad 0.9 \le F_r \le 1.3 \\ 1.8 & for \quad F_r \ge 1.3 \end{cases} \tag{8}$$

$$\beta = \begin{cases} 1 & for \quad F_r \le 0.9 \\ 0.5F_r + 0.55 & for \quad 0.9 \le F_r \le 1.3 \\ 1.2 & for \quad F_r \ge 1.3 \end{cases} \tag{9}$$

where F_r is the Froude number, which is dependent on water velocity. F_r is calculated by the following equation:

$$F_r = V_{\max} / \sqrt{g\eta_{\max}} \tag{10}$$

where $V_{\max}$ is the maximum water velocity. For a supercritical flow whose F_r is over 1.3, the values of α and β are the same as those proposed by [7]. On the other hand, for a slower flow whose F_r is under 1.3, α and β are reduced. Fig. 7 compares the force calculated from Eqs (4) to (9) with the force measured in the hydraulic model experiments. The equations reproduce the measured force well, although they are likely to overestimate the force in the case where the oil-retaining perimeter wall withstands a tsunami.

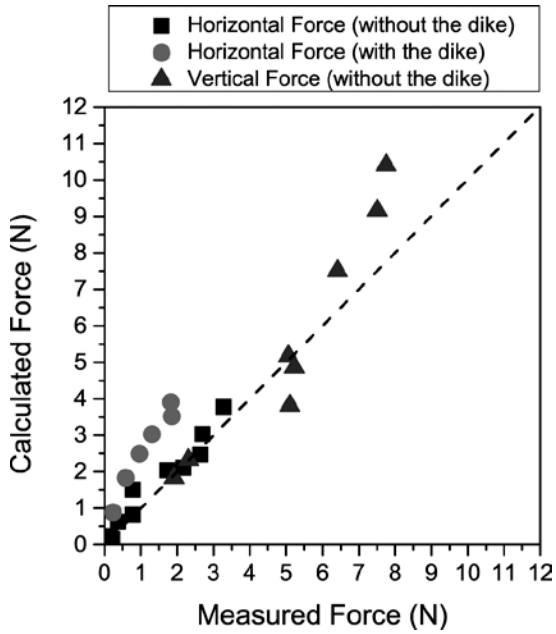

Fig. 7 – Comparison between the tsunami force measured in the hydraulic model experiments an that calculated from Eqs (4) to (9).

5.2 Validation of Tsunami Tank-Movement Prediction Method

The tsunami tank-movement prediction using Eqs (2) to (7) require the data of the weight of the tank and the stored oil, the radius of the tank, and the maximum inundation depth of tsunami at the tank. The data from the questionnaire investigations and the on-site reconnaissance included 194 tanks that were given the data needed for the prediction, and the movement predicted for these 194 tanks was compared with the actual damage situation. In the prediction, tanks for which the values of F_{sS} was less than 1 were assumed to be moved. It was not possible to obtain data on water velocity from the questionnaire investigation. Therefore, F_r was assumed to be less than 0.9, so α and β were set to be 1. For solving Eqs (6) and (7), the maximum inundation depth (η_0) in the absence of tanks is required, which could not be known. The variable η_0 was replaced by η, which is the maximum inundation depth in the presence of tanks. The variables μ and ρ were assumed to be 0.6 and 1.02 × 103 kg/m^3, respectively.

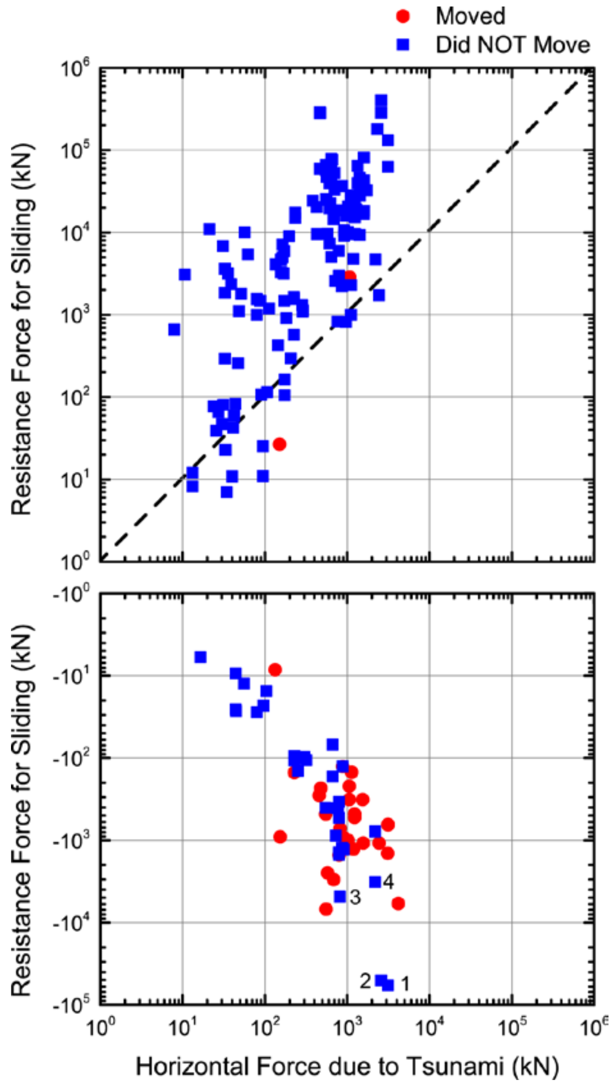

Fig. 8 – Comparison between the predicted and actual movement of oil storage tanks due to the 2011 Tohoku earthquake tsunami.

Fig. 8 shows the resistance force for sliding with respect to the horizontal tsunami force. When the resistance force for sliding is larger than the horizontal tsunami force (the upper triangular portion of the upper panel), it is predicted that tanks would not move. The prediction was accurate for 118 tanks that were not moved, while the damage for one tank that was moved was mispredicted by the calculations. When the horizontal tsunami force exceeds the resistance force for sliding and the resistance force is not negative (the lower triangular portion of the upper panel), it is predicted that a tank would slide but would not float. Movement of one tank was successfully predicted, but 12 tanks that were not moved were predicted to move, indicating a misprediction for these tanks. When the resistance force for sliding is negative (the lower panel), it is predicted that the tanks would float. Movement of 28 tanks was successfully predicted, but 34 tanks that were not moved were predicted to move, indicating a misprediction again.

Of the 30 tanks that were actually moved, 29 were predicted to be moved, while damage to one tank was mispredicted. Of the 164 tanks that were not actually moved, 118 were predicted not to be moved and the remaining were predicted to be moved, with their damage being overestimated. As a whole, the prediction for 147 tanks whose predicted damage was compared with the actual damage was successful, indicating a hit rate of 76%.

6. Conclusions

The 2011 Tohoku earthquake tsunami damaged 418 oil storage tanks located along the Pacific coast of the Hokkaido, Tohoku, and Kanto Districts of Japan. A wide variety of damage was observed, including movement and deformation of the bodies of the tanks, scouring of the tank base and ground, sediment runoff from the tank mound, movement or structural fracture of the pipe, cracking of the oil-retaining perimeter wall, and scouring of the perimeter wall base and ground. In total, 157 of the 418 tanks were moved by the tsunami.

By comparing the severity of damage with the maximum inundation depth of the tsunami experienced by an oil storage tank, a fragility curve projecting the damage to the piping of the tank was presented in terms of a maximum inundation depth (Eq. (1)). A rough but easy-to-use method of predicting tsunami damage to an oil storage tank from a given maximum inundation depth was presented: (i) for maximum inundation depths of less than 2 m, most tanks are safe, although some might suffer minor damage, (ii) for a maximum inundation depth of 2–5 m, tanks suffer damage to their piping, small tanks (capacity < 100 m^3) and empty larger tanks may be moved, but non-empty larger tanks are not moved, and (iii) for maximum inundation depths of greater than 5 m, most tanks are moved.

The validity of the tsunami tank-movement prediction method [7] with the modified version [8] of the tsunami force equations (Eqs (2) to (9)) was examined. A comparison of the method's predictions with the actual damage data from the 2011 Tohoku earthquake tsunami indicated a hit rate of 76%. The method was also observed to overestimate tank movement. Almost every misprediction was a safe error (a tank that did not actually move was predicted to be moved). Because of the high accuracy and the tendency to provide safe predictions, the method has potential applications in practical prediction of movement caused to oil storage tanks by tsunamis resulting from future earthquakes.

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