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WATER TANK DAMAGE DUE TO THE 2011 EAST JAPAN EARTHQUAKE IN CONSIDERATION OF STRONG GROUND MOTION AND DESIGN CODES

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Abstract

The 2011 Great East Japan Earthquake caused severe damage to on-ground and elevated water tanks in broad areas. First the authors conducted a detailed survey on the damage of water tanks in the areas mainly affected by the earthquake. Through the survey, 167 damage data concerning rectangular water tanks were obtained, and the characteristics of the damage are discussed. Next the authors compare the damage locations with the contour maps of the response spectra obtained from the strong ground motion records at 1,249 stations. The results show that the characteristics of the damage can be well explained from the viewpoint of the bulging damege by short-period responses and the sloshing damege by longer-period responses to the earthquake respectively. Finally, by comparing with the response spectra from the 1995 Great Hanshin-Awaji Earthquake, on which the current design codes of water tanks have been based, the authors consider the current design codes. These results will be useful for discussing the countermeasures against the vulnerability of water tanks hereafter.

Keywords; The 2011 Great East Japan Earthquake; water tank; bulging; sloshing; strong ground motion

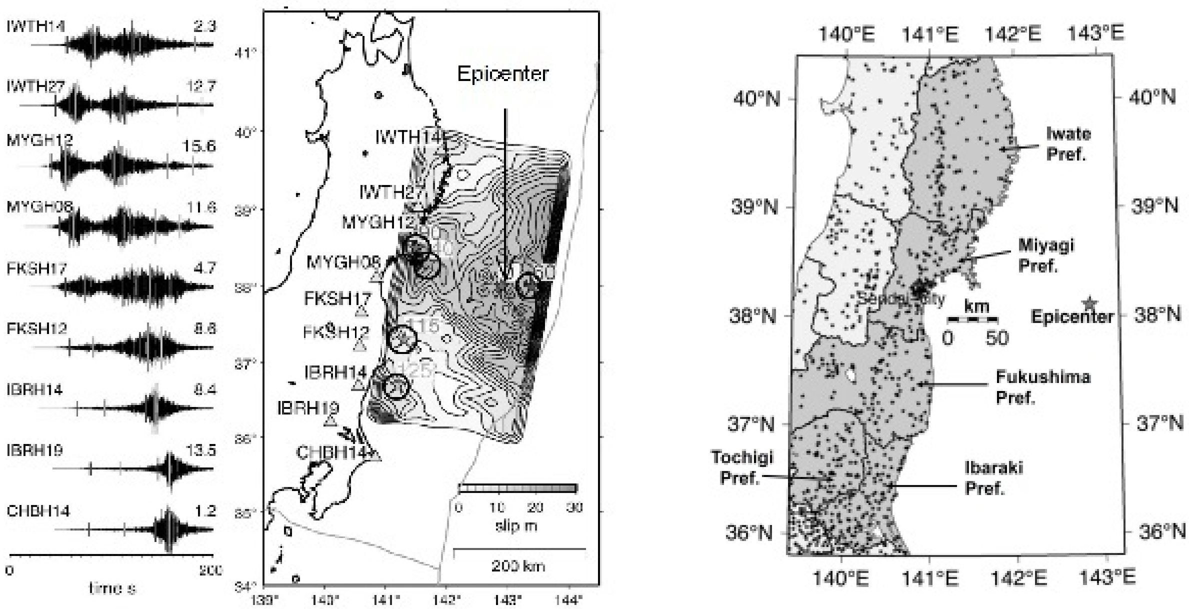
1. Introduction

The 2011 Great East Japan Earthquake (M_w=9.0), the death toll of which mainly caused by the huge tsunami was over 10,000, also did severe damage to on-ground and elevated water tanks important for the lifeline facilities in broad areas. Fig. 1 shows the gigantic fault plane of the 2011 Great East Japan Earthquake and the locations of the five prefectures of Miyagi, Iwate, Fukushima, Ibaraki and Tochigi, mainly affected by the earthquake.

This megathrust subduction zone earthquake occurred off the northeastern Pacific coast of Japan, which was one of the largest earthquakes in the history of Japan. For example, according to Ide et al. [1], as shown in Fig. 1(a), it has been explained that the size of the fault plane was 400km-500km in length and 200km in width, and that the slip at the eastern shallower part generated the huge tsunami, whereas several small area slips (○ in the figure) at deeper parts mainly along the western edge radiated short-period strong seismic waves. Fig. 1(b) shows the locations of the five prefectures and their surroundings. In the figure the locations of dense observation networks in the areas are also plotted with black points in the figure, from which a number of strong-motion acceleration records were obtained.

The authors, as one of the activities of the Earthquake Engineering Committee of JSCE, first conducted a detailed questionnaire survey on water tanks damaged by the earthquake. The objects were water tanks mainly used for schools and large hospitals in the five prefectures. From the result of the survey, it can be found that the damage is characterized by the two damage patterns, those are the bulging type damage and the sloshing type damage, and that the number of the former type damage is overwhelmingly more than the latter one.

Next the authors made the contour maps of response spectra obtained from the strong ground motion



(a) Gigantic fault plane and sources of short-period seismic waves

(b) Locations of the five prefectures and Sendai City

Fig. 1 - The 2011 Earthquake and mainly affected areas

Footnote: (a) was modified from Fig.2 of Ide et al., Science 2011, 332, 1426-1429 and reprinted with permission from AAAS and the authors

records in the broad areas, to compare the locations of the damaged water tanks, and the result indicates that the characteristics of the damage very well correspond to the predominant areas on the contour maps in the short-period range and longer-period range respectively.

These results have already been reported partly as the authors' previous papers [2,3], and this paper is an extension of them including the supplement of data and consideration.

2. Water Tanks

2.1 Water tanks treated

It has been reported that on-ground and elevated water tanks were severely damaged due to the earthquake in broad areas including Miyagi Pref. (for example [4]). The objects discussed in this paper are small-scaled water tanks with the volume of at most about 100m^3, which are used in facilities such as hospitals, schools (which are used as evacuation places) and so on, closely related with civilian life. In Japan almost all of such tanks have been rectangular-shaped, and from the viewpoint of a variety of tank material, fiber-reinforced plastics tanks (hereafter we will abbreviate to FRP tanks), welded steel tanks (steel tanks) and stainless steel panel tanks (stainless tanks). Besides them, there have been cylindrical- or spherical-shaped, or reinforced concrete ones, but those are too few to discuss in this paper.

2.2 Water tank specifications

In Japan at present there has been a respective specification for the seismic design corresponding to FRP, steel and stainless tanks. These specifications were revised many times in the past, and especially have been greatly revised, based on the heavy damage due to the 1995 Great Hanshin-Awaji Earthquake (Fiber-Reinforced Plastics Association [5]; Welded Steel Tank Industrial Association [6]; Japan Stainless Tank Industrial Association [7]).

For example, according to the 1996 version of the FRP tank specification, for on-ground tanks it is regulated that the maximum design value of the horizontal seismic coefficient is 1.0, in other words the maximum design value of the absolute acceleration response spectrum SA is 1,000cm/s/s, which is used for the calculation of tank wall pressure by using the Housner's equation [8], and the maximum design value of the pseudo velocity response spectrum PSV is 150cm/s, which is used for the calculation of sloshing wave height and accompanying sloshing impact to the top panel. For elevated tanks, the former one and the latter one are regulated to be 1,500cm/s/s and 375cm/s respectively.

3. Survey of Water Tank Damage

3.1 Questionnaire survey

The questionnaire survey started in September of 2013 from elementary and junior-high schools in Miyagi Pref., and gradually has been extend to large hospitals and to the other prefectures. As of March, 2016, the total number of significantly damaged water tanks has been 167.

Among the damaged tank data in the answers we will deal with significantly damaged FRP, stainless and steel rectangular tanks only, although the damage of few spherical and cylindrical tanks and a reinforced concrete tank was included in the answers. Also the damage defined in this paper excludes the one caused by the tsunami, and although the damage by ground deformation or liquefaction was included in the survey items, there were almost no answers applicable to it. Therefore, it can be said that the tank damage obtained from the survey was directly caused by the vibration of tank itself through the strong ground motion during the earthquake.

3.2 Results of survey

Table 1 shows the number of the damaged tanks classified by area, among which the number in Miyagi

Table 1 – The number of damaged tanks classified by area

Area / Type	**Miyagi**		**Iwate**	**Fukushima**	**Ibaraki**	**Tochigi**	**Sum (ratio)**
	Sendai	**others**					
On-ground	38	12	1	11	30	18	110 (65.9%)
Elevated	20	12	2	6	11	6	57 (34.1%)
Sum (ratio)	58 (34.7%)	24 (14.4%)	3 (1.8%)	17 (10.2%)	41 (24.6%)	24 (14.4%)	167 (100%)

Pref. is 49.1%, especially that in Sendai City is very remarkable. This is because that the number of the questionnaire objects was much larger in the city with a large population, and that the influence of the earthquake was much stronger, as it is very near the sources of short-period seismic waves.

Table 2 shows the number of the damaged tanks classified by tank material and by completion year, in which the tanks are classified by material into FRP, stainless and steel ones. Most of the damaged tanks were FRP tanks, the rest were stainless tanks, and there were no damage data with respect to steel tanks.

Also, as almost all of the tanks with the unknown completion year are considered to be completed in old days, most of the damaged tanks (about 87%) had already been constructed before 1997, in other words they had been designed before the specifications were revised on the basis of the damage from the 1995 Great Hanshin-Awaji Earthquake (M_J=7.3). The number of the damaged tanks constructed after 1997 is 21 and occupies 12.6%, in which the numbers of FRP tanks and of stainless tanks are 9 and 12 respectively, and the latter is rather increasing than before.

Table 3 shows the number of the damaged tanks classified by damage pattern, in which the damage patterns are separated by the mode of tank collapse into side wall, roof, inside wall, anchor bolt, base frame, pipe-connected part, base plate and inside reinforcement types. In Fig. 2 the examples of side wall collapse.and roof collapse are shown In Table 3 we duplicate the number of the damaged tanks in the case with plural collapse modes. From Table 3, we can see that the number of the tanks damaged with side wall collapse mode overwhelms the one with the other collapse modes, and that many tanks with the other collapse modes are accompanied with side wall collapse mode at the same time. Thus, one of the characteristics of the damage of water tanks during the earthquake is that the damage with side wall collapse mode is very predominant.The

Table 2 – The number of damaged tanks classified by material and completion year

Footnote: OG and EL show the cases of on-ground and elevated tanks

<table>
<tr><th colspan="2">Completion year
Material</th><th>Before 1981</th><th>1982-1996</th><th>After 1997</th><th>Unknown</th><th>Total sum</th></tr>
<tr><td rowspan="3">FRP</td><td>On-ground</td><td>29</td><td>38</td><td>6</td><td>23</td><td>96</td></tr>
<tr><td>Elevated</td><td>16</td><td>22</td><td>3</td><td>10</td><td>51</td></tr>
<tr><td>Sum</td><td>45(26.9%)</td><td>60(35.9%)</td><td>9(5.4%)</td><td>33(19.8%)</td><td>147(88.0%)</td></tr>
<tr><td rowspan="3">Stainless</td><td>On-ground</td><td>0</td><td>3</td><td>9</td><td>1</td><td>13</td></tr>
<tr><td>Elevated</td><td>0</td><td>1</td><td>3</td><td>3</td><td>7</td></tr>
<tr><td>Sum</td><td>0(0%)</td><td>4(2.4%)</td><td>12(7.2%)</td><td>4(2.4%)</td><td>20(12.0%)</td></tr>
<tr><td rowspan="3">FRP + Stainless</td><td>On-ground</td><td>29</td><td>41</td><td>15</td><td>24</td><td>109</td></tr>
<tr><td>Elevated</td><td>16</td><td>23</td><td>6</td><td>13</td><td>58</td></tr>
<tr><td>Sum</td><td>45(26.9%)</td><td>64(38.3%)</td><td>21(12.6%)</td><td>37(22.2%)</td><td>167(100%)</td></tr>
<tr><td rowspan="2">Max design value</td><td>SA(cm/s/s)</td><td>OG: 200
EL: 300</td><td>OG: 667
EL: 1,000</td><td>OG: 1,000
EL: 1,500</td><td>?
?</td><td></td></tr>
<tr><td>PSV(cm/s)</td><td>No spec.</td><td>No spec.</td><td>OG: 150
EL:375</td><td>?
?</td><td></td></tr>
</table>

Table 3 – The number of damaged tanks classified by damage pattern

Footnote: (1) The numbers in the parentheses indicate the cases accompanied with side wall collapse mode. (2) M indicates the number of roof collapse tanks in Miyagi-Pref.

Damage pattern / Tank	Side wall	Roof	Inside wall	Anchor bolt, Base frame	Pipe-connect	Base plate/ Inside Reinforcement
On-ground	93	26 (17)	1	8 (5)	15 (9)	12 (8)
		M: 18				
Elevated	32	8 (4)	1	11 (2)	18 (5)	7 (4)
		M: 8				
Sum	125	34 (21)	2	19 (7)	33 (14)	19 (12)
		M: 26				

(a) On-ground stainless tank (Tsukuba, Ibaraki Pref., 1985)

(b) On-ground FRP tank (Sendai, 1988)

Fig. 2 – Examples of side wall collapse and roof collapse

number of tanks with roof collapse mode is 34 in total, among which the number in Miyagi Pref. is 26 and predominant. Another one of the characteristics of the damage of water tanks during the earthquake is that the roof collapse mode damage is not so dominant, and is concentrated in Miyagi Pref.

4. Analysis of Relationship with Strong Ground Motion of the 2011 Earthquake

4.1 Damage with side wall collapse and other collapses by bulging

The main cause of side wall collapse including inside wall collapse in Table 3 is considered to be the dynamic water pressure acting upon side and inside walls during the earthquake. Also, other collapses other than the roof collapse are considered to be mainly caused by the increase of the dynamic water pressure or of the horizontal force due to the earthquake. In this case we should not only consider the impact pressure (Housner, [8]) generated by the tank rigid movement, but also the fluid-elastic pressure generated by the interactive vibration between the tank wall and the contained liquid (Sakai et al., [9],[10].[11]; Housner and Haroun, [12],[13]), in other words, we should make much of the “bulging” response (Sakai et al.).

In order to estimate the bulging response to the earthquake, we need to know the first natural period of bulging T_B, but it cannot be obtained without detailed calculation for each tank. Here, for general water tanks we estimate roughly that T_B lies between 0.15sec and 0.4sec from the experimental results by Minowa [14]. Thus, the bulging response can be seen to be the one in the short-period range.

4.2 Damage with roof collapse by sloshing

The cause of roof collapse is considered to be the impact pressure upon tank roofs acted by sloshing with excessive wave height over the clearance (Yamamoto [15], Minowa [16]). In order to estimate how high sloshing wave response, we need to know the first natural period of sloshing T_s given by the following equation (Senda and Nakagawa [17]):

$$T_s = 2\pi\sqrt{\frac{L}{g\pi}\coth\left(\frac{\pi H}{L}\right)} \tag{1}$$

Here we define H, L and g as the water depth, the tank width in the direction of ground motion and the gravity acceleration, respectively.

By using Eq.(1), we calculated T_s for 51 damaged tanks in Miyagi Pref., the dimensions of which are assumed to be typical, as shown in Table 4. From the results we estimated that T_s for general water tanks lies between 1.4sec and 4.0sec. Thus, the sloshing response can be seen to be in the longer-period range.

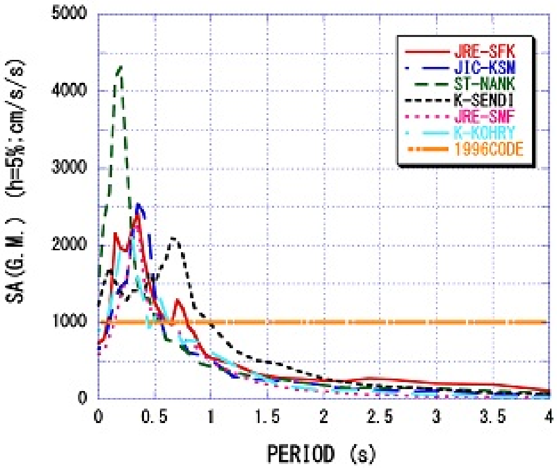
Table 4 – The first natural period of sloshing of 51 tanks in Miyagi Pref.

	On-ground tank	Elevated tank	Total
Number of tanks	38	13	51
Max. of T_s (s)	3.73	3.17	3.73
Min. of T_s (s)	1.60	1.44	1.44
Average of T_s (s)	2.23	1.94	2.15

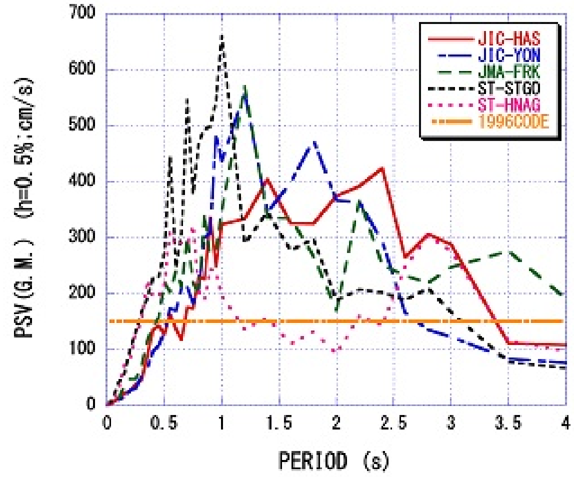
4.3 Response spectra and contour maps for the 2011 Earthquake

During the main shock of the 2011 Earthquake on March 11, a lot of strong ground motion records were observed. In this paper, we collected a total of 1,249 earthquake records observed in the five prefectures and their surroundings, Fig.3 (a) and Fig. 3(b) show SA and PSV for the horizotal components of the records (the geometric means for the two horizontal directions), under the conventional assumption of the damping ratio 5% and 0.5% respectively.

Fig.3(a) shows the curves of typical response spectra SA at 7 stations in Miyagi and Fukushima Prefectures, in which the SA level for T_B around 0.15 to 0.4sec is dominant and the locations of which are near the sites of bulging-damaged tanks. Fig.3(b) shows the curves of typical response spectra PSV at 5 stations in



(a) Absolute accelaration response spectra at 7 stations located nearby bulging damaged tanks.



(b) Pseudo velocity response spectra at 5 stations located nearby sloshing damaged tanks.

Fig.3 – Typical response spectra from the 2011 Earthquake

Miyagi Pref., in which the PSV level for T_S around 1.4 to 4.0 sec is domonant and the locations of which are near the sites of sloshing-damaged tanks.

In both figures, the orange horizontal lines show the maximum design values for on-ground tanks in the current specifications, i.e., SA=1,000cm/s/s and PSV=150cm/s, respectively, and it can be found that the SA level in the period range of 0.15-0.40sec reaches about 1500-4000 cm/s/s and remarkably exceeds 1,000cm/s/s the maximum design value, and that the PSV level in the period range of 1.4-4.0s reaches about 200-500 cm/s and distinctly exceeds the maximum design value, and that these facts lead us to the origins of the bulging and sloshing collapse in the tanks located nearby the stations.

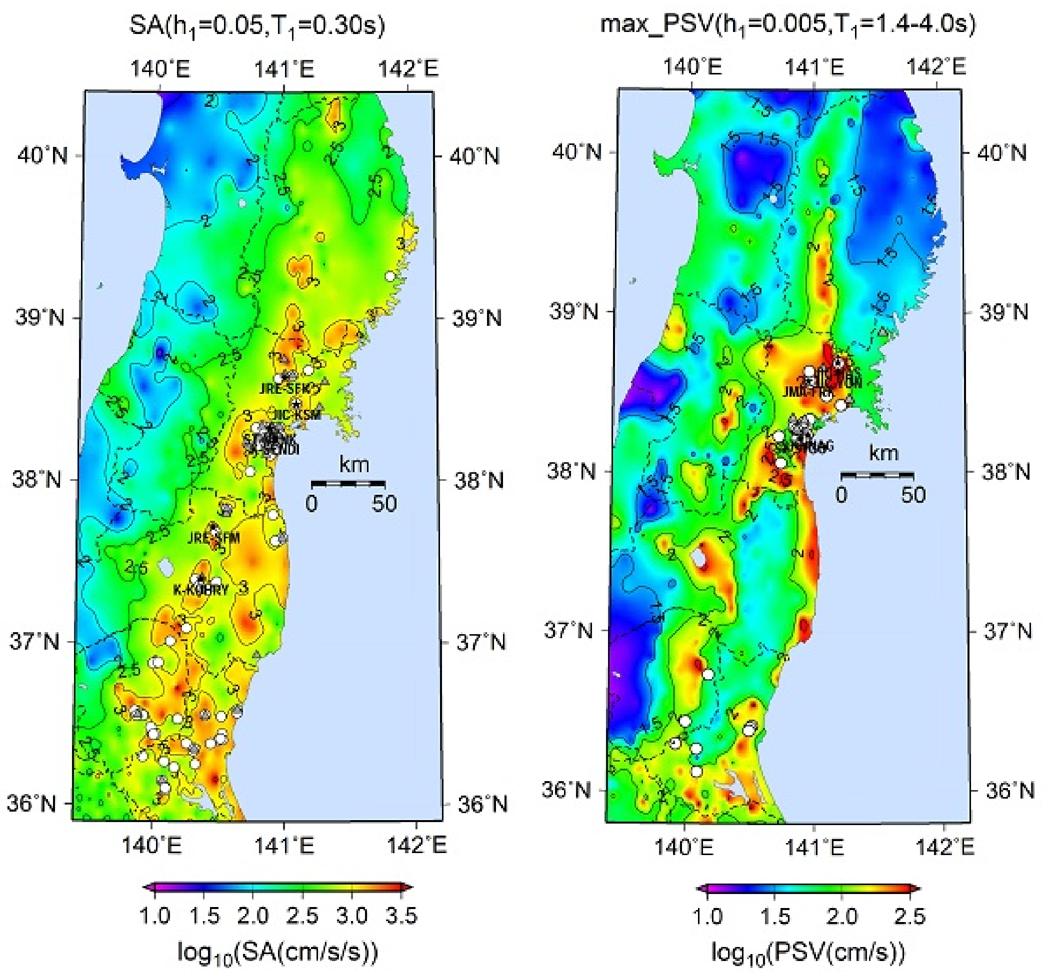
In order to grasp how much the earthquake response of each location in the broad areas is, the authors made the contour maps of the response spectra, based on the geometric mean of the response spectra obtained from each record at the 1,249 stations. For making the contour maps, the Generic Mapping Tools were used (Wessel & Smith [18]). The details of the procedure are described in the authors' previous paper [2].

4.4 Relationship between damage locations and response spectra on contour maps

Fig.4 shows two examples of the contour maps, in which (a) does the curves of the absolute acceleration response spectra with T_B=0.3sec, for the short-period of bulging, and (b) does the curves of the pseudo velocity response spectra between Ts=1.4sec and 4.0sec (using the maximum values between them), for the longer-period of sloshing.

In Fig. 4(a) the location of each tank damaged with collapse by bulging is plotted, from which it can be seen that the areas with the SA level between 1,000cm/s/s and 2,000cm/s/s exist broadly in the five prefectures and that almost all of the bulging- damaged tanks are located in such areas.

In Fig. 4(b) the location of each damaged tank with collapse by sloshing is plotted, from which it can be seen that the areas with the PSV level spectra between 200cm/s and 300cm/s are distributed dispersively in the five prefectures and that almost all of the sloshing-damaged tanks are located in such areas.



Footnote:
○: On-ground tanks,
▲: Elevated tanks.

The yellow areas correspond to the maximum design values:
SA=1,000cm/s/s
PSV=150cm/s
respectively.

(a) The contour map of SA and locations of water tanks with bulging damage.

(b) The contour map of PSV and locations of water tanks with sloshing damage.

Fig. – 4 Contour maps of response spectra and locations of damaged water tank

5. Comparison with response spectra from the 1995 Great Hanshin-Awaji Earthquake

5.1 Response spectra and contour maps for the 1995 Earthquake

Similarly to the above-mentioned analysis, we obtained the response spectra from the strong-motion records of the 1995 Great Hanshin-Awaji Earthquake, on which the current design codes of water tank specifications are based. This crustal strike-slip earthquake (M_J=7.3) occurred on Janualy 17, 1995 in the southern part of Hyogo Pref., and caused heavy damage in densely populated region of southern Hyogo Pref. (included in the hatched zone in Fig.5, which shows the mailly affected area in the Kinki District by the 1995 Earthquake). The fatalities mainly caused by collapse of wooden houses were about 4,400 and also many water tanks were damaged. For example, according to the reference [19], it was reported that among 20,000 water tanks designed after 1981 the number of damaged water tanks was around 120 (the bulging-damaged ones and the sloshing-damaged ones were 82 and 35 respectively).

By using 50 strong-motion records available at that time (e.g., [20],[21]), we calculated SA and PSV at each station for the same period ranges and damping factors as mentioned in Subsection 4.3. Fig. 6(a) and (b) show the curves of SA and PSV for the records at 7 typical stations.

From Fig. 6(a) it can be seen that the SA level in the short-period range between 0.15sec and 0.4sec is about 500-2000cm/s/s and at most two times larger than the maximum design value 1000cm/s/s. On the other hand, From Fig 6(b) it can be seen that the PSV level in the period range between 1.4 and 4.0sec reaches up to 600-700 cm/s, and remarkably exceeds the maximum design value 150cm/s, and that it is clearly larger than the level of the 2011 Earthquake shown in Fig. 3(b).

Similarly to the Subsection 4.3, we made the contour maps of response spectra, and Fig. 7 shows the contour map of pseudo velocity response spectrum. From Fig. 7 it can be found that the area with very high level of PSV spreads broadly from Kobe to Osaka, and the facts are consistent with that during the 2011 Earthquake we can see much more bulging-damaged tanks than sloshing-damaged tanks (with the ratio of about 4:1), on the other hand during the 1995 Earthquake we can see only comparatively more bulging-damaged tanks than sloshing-damaged tanks (about 2:1).

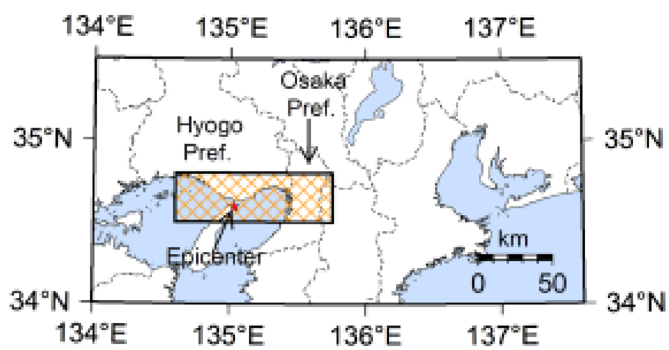
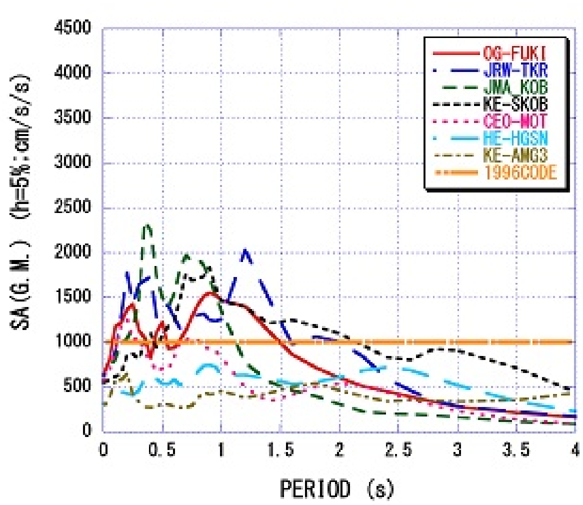
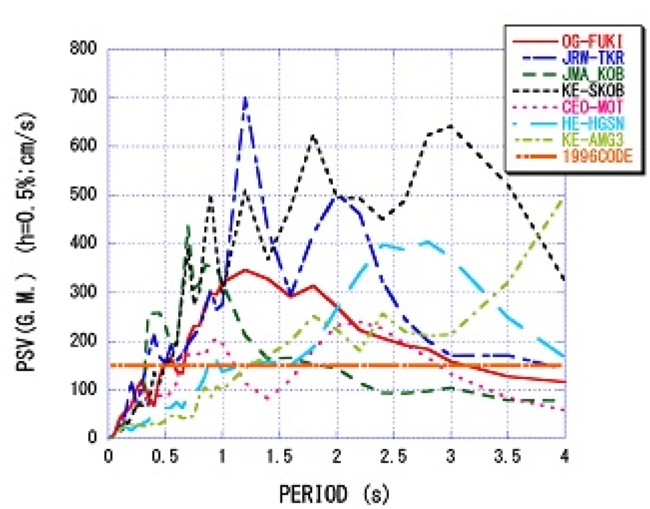


Fig.5 – The mainly affected areas (the hatched zone) in the Kinki District by the 1995 Eartquake



(a) Absolute accerelation response spectra at 7 stations.



(b) Pseudo velocity response spectra at 7 stations.

Fig.6 – Typical response spectra at the 7 stations in the southern Hyogo Pref.

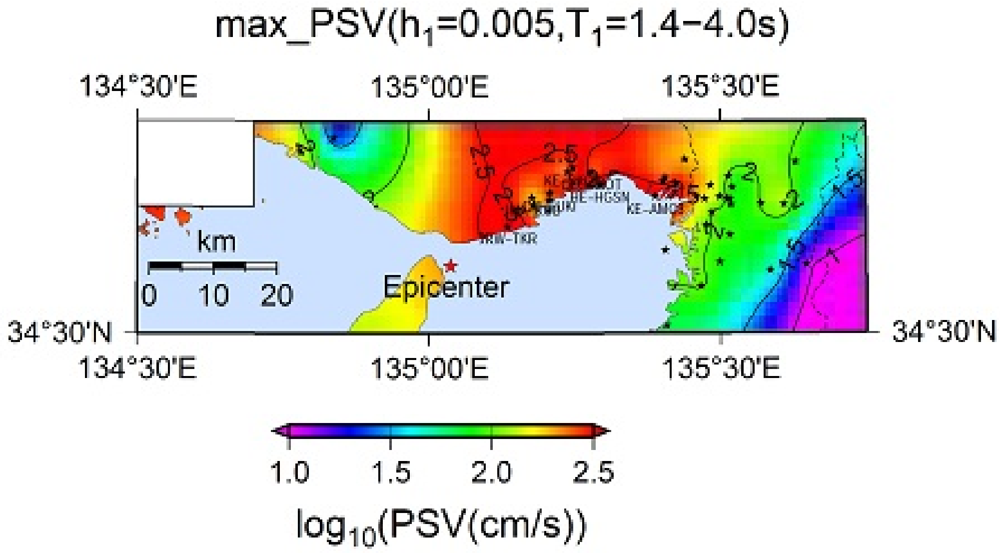


Fig. 7 – The contour map of PSV in the hatched zone in Fig.5 from the Earthquake

7. Conclusions

Through the survey of the water tank damage in broad areas during the 2011 East Japan Earthquake and the analysis of the damage characteristics including the relationship with the strong ground motion from the 2011 Earthquake and the 1995 Great Hanshin-Awaji Earthquake, we come to the following conclusions.:

1. As many as 167 damage data were collected from the broad areas of the mainly affected five prefectures, where about a half of them were from Miyagi Pref., and the damage in Sendai City was remarkable.

2. Among the damage data, the damage of old tanks completed before 1996 were overwhelming (87.4%) and that of FRP tanks were remarkable (82.6%). The damage of tanks completed after 1997 were less, but the damage of stainless tanks was rather increasing.

3. With respect to the damage patterns, the authors classify them into two types of damage mode, i.e., bulging collapse for the short-period response and sloshing collapse for the longer-period response, and the number of the former type damage was over four times more than that of the latter type damage.

4. By using the strong ground motion records at 1,249 sites, we obtained the response spectra in broad areas, from which it can be seen that the values of predominant response spectra SA and PSV exceed significantly the maximum design values in the present specifications revised after the 1995 Great Hanshin-Awaji Earthquake.

5. The locations of the tanks damaged by bulging and sloshing respectively correspond very well to the areas where the short-period and longer-period response are predominant on the contour maps of the response spectra. The area where SA for T_B=0.15-0.4sec is predominant exist broadly in five prefectures, but the areas where PSV for T_S=1.4-4.0sec is predominant are distributed sparsely. This is the reason why in the 2011 Earthquake the bulging damge was overwhelmingly more than the sloshing damage (with the ratio of about 4:1).

6. Comparing the SA curves for T_B=0.15-0.4sec from typical records of the 2011 Earthquake with those of the 1995 Earthquake, the former level is much larger than the latter one. On the other hand, with respect to the PSV curves, the result is reverse. This is the reason why in the 1995 Earthquake the bulging damage was not so remarkable than the sloshing damage (with the ratio of about 2:1).

These results indicate the validity of the authors' approach to analyze the damage from the viewpoint of sloshing and bulging, and will be useful for discussing the countermeasures against the vulnerability of water tanks hereafter.

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