Seismic damage of mechanical structures by the 2011 Great East Japan Earthquake

S. Fujita
Tokyo Denki University, Tokyo, Japan

I. Nakamura
National Research Institute for Earth Science and Disaster Prevention, Ibaraki, Japan

O. Furuya
Tokyo City University, Tokyo, Japan

T. Watanabe
Saitama University, Saitama, Japan

K. Minagawa
Saitama Institute of Technology, Saitama, Japan

M. Morishita
Japan Atomic Energy Agency, Ibaraki, Japan

T. Kamada
Tokyo University of Agriculture and Technology, Tokyo, Japan

Y. Takahashi
Iwaki Meisei University, Fukushima, Japan

SUMMARY:
In the 2011 Great East Japan Earthquake, serious damage occurred in power plants and industrial plants due to the strong ground motion, soil deformation and tsunami. .Many kinds of damage caused by strong motion, such as the buckling of tanks, the failure of hook bolts, or the falling of overhead cranes, and the dropping of over-hanging pipes were commonly observed. The tsunami also caused various kinds of damage, such as broken equipment due to collisions with floating objects and damage of tanks due to water pressure. Power system damage caused by electrical short circuiting also occurred. Although the earthquake caused a great deal of damage, seismic measures taken before the earthquake could mitigate damage of some facilities. This paper provides an overview of the damage of mechanical facilities caused by the 2011 Great East Japan Earthquake, their typical damage cases, and the effects of the earthquake resisting methods.

Keywords: Damage investigation, Industrial facilities, 2011 Great East Japan Earthquake

1. INTRODUCTION

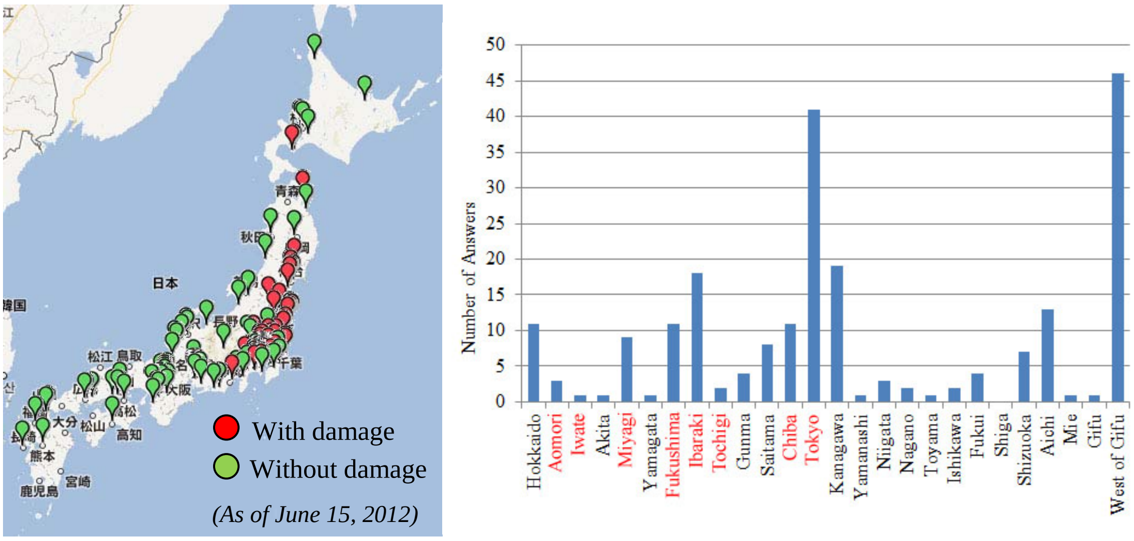
A devastating earthquake of Mw 9.0 hit the Tohoku district in the north-eastern part of Japan on March 11, 2011 (The 2011 Great East Japan Earthquake, hereinafter referred to as the GEJE). Approximately 16,000 people died and 3,000 people went missing due to the strong motion and tsunami, and the economic damage was estimated at about 16.9 trillion yen except for the influence by the nuclear accident at Fukushima Daiichi Nuclear Power Plant (Cabinet office, 2012). Industrial facilities, power plants, and research facilities were damaged in this earthquake, and various kinds of mechanical equipment located in these facilities were also damaged. The Japan Society of Mechanical Engineers (JSME) has set up an investigation committee and investigated the seismic damage of mechanical equipment in these industrial facilities for the purpose of understanding the situation and causes of the damage in such facilities and improving of preparedness for the future earthquakes. This paper provides an overview of the damage of industrial facilities and mechanical structures caused by the GEJE and the effects of earthquake-resistance methods mainly based on the JSME investigation.

2. OVERVIEW OF THE SEISMIC DAMAGE OF INDUSTRIAL FACILITIES BY THE 2011 GREAT EAST JAPAN EARTHQUAKE

The JSME carried out a questionnaire to investigate the influence of the earthquake on industrial facilities about two months after the earthquake. The questionnaire was sent to about 1,000 organizations, and about 200 of them responded. Figure 1(a) shows a map of Japan and the questionnaire answers, and Fig. 1(b) shows the number of questionnaire answers for each prefecture. In Fig.1 (a), the red marks denote the facilities with damage, and the green marks denote the facilities without damage. In Fig.1 (b), the prefectures shown in red characters were the "disaster-stricken regions" to which the Disaster Relief Act was applied. Although there were regional biases e.g., a relatively small numbers of answers were obtained from the seriously tsunami-damaged area, we can find some features of the seismic damage caused by the GEJE and other important knowledge from the various answers.

Based on the questionnaire and many site investigations, the damage of industrial facilities was mainly caused by one of the following causes or a combination of thereof: "strong seismic motion", "soil deformation", and "tsunami". As for damage caused by the ground motion, there were many damage cases at basements and supporting members, pipes, cranes, shutters, and lifting machines such as elevators. Some damage was caused by sloshing behaviours, for example, overflow of liquid storage tanks, or molten solder. Many troubles on machines such as slipping from a fixed position and the deviation of the flatness were also reported, even if the machines themselves were not broken. Such machines had to be adjusted and calibrated after the earthquake. In addition, there were some cases in which safe evacuation was made difficult by scattered tools, even if equipment damage did not occur. As for damage caused by soil deformation, many cases of settling of basements due to liquefaction and damage of buried pipes were reported. In the area where the tsunami did not strike, the problems mainly affected the vulnerable equipment or parts which had insufficient seismic capacity. But in the tsunami-affected area, all of the equipment was damaged by the tsunami, regardless of the type of equipment.

Very large areas in Japan were simultaneously affected by the GEJE. The total area of the "disaster-stricken region" to which the Disaster Relief Act applied amounted to more than 12% of the total area of Japan. Many organizations had to face the problem to continue their activities, because their alternative facilities also suffered. Many facilities which were expected to repair damaged machines or fabricate the alternative machines in times of disaster also suffered from the earthquake,



(a) Seismic damage distribution of industrial facilities (As of June 15, 2012) (Add on the Google map)

(b) The number of the questionnaire responses by region

Figure 1. Result of JASME questionnaire

so it took a lot of time to recover the industrial activities. In addition, the early recovery of the industrial activities was affected by the stoppage or shortage of the electrical power supply, water supply, and oil supply. The questionnaire answers showed that the disruption of the supply-chain affected production activities in western Japan, which were not directly affected by the earthquake. Large aftershocks frequently occurred after the main shock of March 11 in GEJE, and they often damaged the industrial facilities again, especially the aftershocks on April 7 and April 11 again destroyed that had just recovered from the main shock. Several facilities suffered more severe damage due to those aftershocks than to the main shock.

It took from one to several days to determine the extent of the damage for many facilities in the disaster-stricken region. Though the questionnaire was administered about two months after from the earthquake, several organizations answered that they had not determined the full extent of their damage. In addition to the damage of facilities, most of the organizations said that their employees had trouble both car commuting and train commuting to work after the earthquake, because of the lack of gasoline arising immediately after the earthquake and lasting about one or two weeks and because of the disruption of public transportation due to the planned blackouts.

Because the communication interruptions/convergence and the electrical outage occurred just after the earthquake, many organizations responded that securing the means of communication was an important future task. Mobile phones and mobile text-messaging helped organizations to contact their staffs during the electrical outage. It seems that private lines worked well as a way to maintain contact between a main office and the branch offices, though some systems which required an electrical power supply did not work well during the blackout after the earthquake. About 60% of organizations who answered the questionnaire had prepared an emergency manual, and about 80% of them said that this mannual was helpful to a greater or lesser extent in responding to this earthquake disaster, although a few of them said it was not helpful at all. The problem points of the manuals were the scale of the assumed disaster, maintaining stocks of food, water and fuel, long-term power outages or shortages, and disaster training. Many without the manual answered that it was necessary to prepare such a manual soon.

The damage caused by the GEJE shows various aspects as described above. In particular, the authors would focus in the following sections on the structural damage of mechanical structures.

3. DAMAGE OF MECHANICAL STRUCTURES

3.1. Damage due to strong seismic motion

Figure 2 shows the damage at the base of a circulation pump. The concrete basement and cast iron base were broken, and the anchor bolts were deformed by the seismic motion. Figure 3 shows an example of the deformation of an anchor bolt, and Fig. 4 shows the deformation of a steel base of a FRP tank. Equipment installed on the roof of the building, such as air conditioning equipment, was often tumbled or failed because the seismic response of the building tends to be amplified at the tops of buildings. Figures 5 and 6 show examples of such damage. This damage related to basements or anchors mainly occurred due to a lack of consideration of earthquake resistance in setting and fixing the equipment. Figure 7 shows damage of the anti-vibration bar of a boiler. The boiler was suspended only at the upper position in order to release the heat expansion during the operation, so the response grew during the seismic motion, and the body of the boiler collided with the anti-vibration bar and broke it.

Figures 8 shows the failure of pipe supports and Fig. 9 shows damage of utility pipes. The failure of the pipes occurred mainly at the pipe supports or connections with other equipment. The leakage of water from the damaged pipes often caused secondary damage such as moisture damage of books and documents or problems with electrical equipment. To prevent such secondary damage, it is necessary to consider well the facility layout design in the planning stage as well as the seismic design of the piping system. Another failure mode of pipes was related to soil deformation. This kind of failure is described in section 3.2. Figure 10 does not show pipe failure itself, but rather failure related to a pipe's seismic response. The different seismic responses of the pipes and the building caused damage at the inner wall.

Figure 2. Damage at the base of a pump

Figure 3. Deformation of an anchor bolt (Provided by JAXA)

Figure 4. Deformation of the steel base of FRP tank

Figure 5. Failure of a water tank installed on the roof

Figure 6. Tumbled equipment set on the roof

Figure 7. Damage of the anti-vibration bar of a boiler

(a) In-house hanging pipe

(a) Pipe on the roof

Figure 8. Failure at pipe supports

Figure 9. Failure of utility pipe and water leakage (Provided by JAXA)

Figure 10. Damage of inner walls by pipes (Provided by JAXA)

Figure 11. Buckling failure of 2,000 m^3 water tank (Thermal and Nuclear Power Engineering Society, 2011)

Figure 12. Failure mode of overhead crane (Damage of hook bolts, provided by JAXA)

Figure 13. Failure mode of overhead crane (Fallen crane rail)

Figure 14. Failure of ceilings (Provided by JAXA)

Figure 15. Failure of cable racks

The buckling failure of tanks was reported in past earthquakes, such as in the 1995 Kobe Earthquake and in the 2007 Niigataken Chuetsu-oki Earthquake, and this failure mode was also found in the GEJE. Figure 11 shows the buckling failure of a 2,000 m^3 water tank (Thermal and Nuclear Power Engineering Society, 2011). This failure was caused by the aftershocks on April 11 and 12. There were some tanks without damage, though they were located in the same prefecture as the failed tanks. So it is necessary to investigate the cause of these failures taking into account the characteristics of the input motion, and other factors. The damage investigations of hazardous material facilities were conducted and summarized by the National Research Institute of Fire and Disaster. According to this report, the damage due to sloshing behaviour occurred in the Tokyo Bay area and the Sea-of-Japan side of North Japan (Nishi, 2012). Cranes and unloaders were also damaged by the earthquake. From the result of the damage investigation by the Japan Crane Association (JCA) (Japan Crane Association, 2011), overhead cranes were mainly damaged by seismic motion. Figure 12 shows one typical failure of an overhead crane. The hook bolts which held the crane rail deformed or fractured. Figure 13 shows another failure mode of an overhead crane. The failure occurred at the welding point at the suspension of the crane rail.

Elevators are one of the mechanical structures which require high seismic safety. Typical damage related to elevators included the jamming of cables, the deformation of rails, and derailing. Damage of elevators was investigated by the Japan Elevator Association (JEA) (Miyata, 2012). In the investigation, the relation between the damage ratio of the elevators and the applied seismic design guideline for elevators was analysed. As a result, the damage ratio was about 3% for elevators constructed in accordance with the guideline before 1981, but it decreased to 2.36% for elevators constructed in accordance with the guideline used from 1981-1998. The damage ratio of elevators constructed in accordance with the latest revision in 2009 decreased to 1.13%. It was therefore clarified that the damage was mitigated by the latest revision of the seismic design guideline, and the past revisions of the guideline were also effective to mitigate the seismic damage. Regarding escalators, fall-off damage was reported in a large-scale shopping centre in Miyagi Prefecture, but the details of the damage are still under investigation.

The ceilings and walls of factory buildings and equipment hung from the ceilings such as cable racks and air-conditioning machines were also damaged. Figures 14 and 15 show examples of these types of damage. Such damage led to human suffering and secondary damage of machines, and it has been an obstacle to business recovery.

3.2. Damage due to soil deformation

In the GEJE, liquefaction was observed in a very wide area (Yasuda and Harada, 2011). Ports and embankments were also severely damaged by liquefaction, seismic motion, and the tsunami (Yoshida, et al, 2011, Murakami, et al, 2011). Much damage caused by soil deformation was observed in industrial facilities. Figure 16 shows the pipe support hanging from a pipe due to the subsidence of the surrounding soil. In this case, the pipe did not fail because the strength of the pipe itself was sufficient. Pipes which run out from a building into the surrounding soil were often damaged by the relative displacement between the building and the soil. Figure 17 shows broken buried utility pipes, and Fig. 18 shows pipes fractured at the point of connection of the building and soil, due to the subsidence of the soil. Figure 19 shows the deformed quay wall and the rail misalignment of unloaders placed at a port. In this case, the crane was not available after the earthquake because it could not run on the deformed rail, although the crane itself was not damaged. Overall, damage was often observed at facilities that surrounded the large or important facilities with strong basements. This is mainly because the surrounding facilities are set on different basements from the main facilities, and less seismic consideration is paid to such surrounding facilities' basements. This kind of failure repeatedly occurred in past earthquakes. Although it is not damage of a mechanical structure, the damage of a road in a research facility is shown in Figure 20. This is a case in which the large soil deformation became an obstacle to recovery, because the heavy machines necessary for early recovery could not be carried to the facility via the deformed road.

Figure 16. Pipe support hanging from a pipe due to subsidence of the soil

Figure 17. Buried utility pipes broken due to soil deformation

Figure 18. Pipes fractured at the connection point of the building and soil

Figure 19. Quay wall deformation and misalignment of the unloader rail

Figure 20. Damage of a road in a research facility

Figure 21. Lifting damage of LPG tank by tsunami

Figure 22. Tanks washed away by the tsunami

Figure 23. Buckling failure of a water tank due to the pressure of the water (Provided by TEPCO)

3.3. Damage due to the tsunami

Many factories and plants are located on the coast line because of the many advantages of such a location in terms of the transportation of materials or products and access to coolant water. For this reason, however, many facilities suffered major damage in this earthquake disaster due to the tsunami, and they were forced to cease their activities for a long time after the disaster. Although the number of cases investigated by the JSME committee is not many, some typical damages by tsunami could be obtained by the site investigations.

The tsunami caused various types of damage, such as breakage of equipment by collisions with floating objects, damage/missing of tanks (water, oil, gas), buckling failure of tanks due to buoyancy, and dropping of unloader wheels. Power system damage due to short-circuiting of electrical lines also occurred due to flood of tidewater. Figure 21 shows the lifting damage done to a 60-ton LPG tank (manufactured in 1974) due to buoyancy. The sea was located at the left side of Fig. 21, and it seems that the anchor bolt was stretched by buoyancy and then deformed by the force due to the tsunami arriving from the left. A 50-ton tank (manufactured in 1992) near the damaged tank was not damaged due to the larger diameter of its anchor bolts. The failure mode shown in Fig. 21 may be reduced in the future with adequate anti-tsunami force design. Figure 22 shows tanks washed away by the tsunami, and Fig. 23 (Tokyo Electric Power Company, 2011) shows the buckling failure of a water tank due to the pressure of the water. An example of damage due to collisions with floating objects is shown in Fig. 24 (Japan Crane Association, 2011). This container crane had an isolation system at the bottom and was not damaged by the seismic motion. However, wreckage hit the cover of the device and deformed it. Salt damage also occurred due to the flood of tidewater. In many cases, the electrical system devices including power panels required inspection, cleaning, and replacement after the tsunami. In addition, the large amount of rubble left after the tsunami disturbed the disaster-relief activity of industrial facilities (Thermal and Nuclear Power Engineering Society, 2011). Basically, the tsunami affected facilities at low-altitude sites, and no damage occurred at high-altitude sites. Thus, it is effective to install significant equipment at a high-altitude area of a site considering the damage scenario.

3.4. Good Practice

Although many industrial facilities and mechanical structures were damaged by this earthquake, the damage of some facilities could be mitigated by seismic countermeasures taken before the earthquake. Many organizations took safety precautions such as fixing machines and furniture to the floor of the building walls, and to prevent objects from falling from racks. Anchor bolts of a diameter sufficient to withstand seismic input were effective in fixing machines. As described in section 3.2, many pipes were damaged by the relative displacement between buildings and soil. In such cases, the flexible

Figure 24. Damage due to collisions with floating objects (Provided by JCA)

Figure 25. Flexible pipes

pipes such as those shown in Fig. 25 were effective.

A person affiliated with one of the sites we investigated said, "All of our problems began with the power outage". Indeed, many organizations responded to the questionnaire by saying that they had troubles due to the blackout. In this individual's factory, seismic shutoff valves were installed in the flammable gas line. These valves were designed to work mechanically, not by an electrical control, in a seismic event in case there was no electrical power. These valves worked effectively in this earthquake. This factory was also designed so that the flammable gas would be shutoff and the nitrogen gas vented in a seismic event. Such attention in the planning could prevent seismic disasters in industrial facilities.

Another good example of planning was in factory buildings with balconies. The balconies prevented the fractured wall materials from falling on persons and machines in the factory, and provided two-way evacuation routes in addition to the corridors in the building. The additional access permitted by the balcony aided in the recovery activities at the factory.

Of course, seismic design from the initial plan of facility construction is essentially effective in mitigating the seismic damage of mechanical structures, as with the guidelines for elevators described in section 3.1. Equipment that was seismically designed well was damaged less by the seismic motion as a whole in the GEJE. Reviewing past seismic damage and continuously rechecking the state of a facility is necessary and effective for improving the seismic safety of the facility.

4. CONCLUSION

The outline of the damage of industrial facilities and mechanical structures in the 2011 Great East Japan Earthquake were summarized. From the questionnaire and many site investigations, we can conclude that the damage of industrial facilities was mainly caused by one or a combination of the following: strong seismic motion, soil deformation, and the tsunami. Though a great deal of damage occurred, well-seismically designed equipment was less damaged by the seismic motion as a whole. In the questionnaire investigation, many organizations mentioned that the means of communication and provisions for electrical outages/shortages should be improved in the future tasks.

Though the damage caused by this earthquake was spread over a very wide area and various kinds of damage were observed, the authors just listed the cases of damage of mechanical structures at the current moment. In order to clarify the causes of this damage in detail, the relations among the input motions, conditions of location, structural characteristics and damage should be investigated in future work.

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