Report of the JSME Research Committee on the Great East Japan Earthquake Disaster

Chapter 3

Damage to Machines and Equipment, and Good Practices for Seismic Countermeasures

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Abstract

Based on the investigations conducted by the JSME, it was found that the damage to mechanical structures resulting from the 2011 Great East Japan Earthquake was due to the movement of the ground, soil deformation and subsequent tsunami. Damage caused by the ground motion, such as that at the base of machines, the failure of pipe supports, the buckling of tanks and the failure of hook bolts in crane rails was found to be widespread. The soil deformation caused buried pipes to break and gantry crane rails to misalign. The tsunami also caused various damages, such as broken equipment due to collisions with floating objects and damage to tanks caused by the water pressure. Power system damage caused by electrical short circuiting also occurred. Although the earthquake caused a great deal of damage, seismic countermeasures taken in advance mitigated damage at some facilities. In this section, an overview of the damage to industrial facilities caused by the Great East Japan Earthquake is presented and the effectiveness of the countermeasures that were in place is summarized.

Keywords : Damage investigation, Industrial facilities, Damage due to strong seismic motion, Damage due to soil deformation, Tsunami damage, Seismic countermeasure

1. Introduction

A devastating earthquake of Mw 9.0 hit the Tohoku region, the north-eastern part of Japan, on March 11, 2011 (The 2011 Great East Japan Earthquake, hereinafter referred to as the GEJE). The earthquake and subsequent tsunami killed approximately 16,000 people and 3,000 more are still missing. The economic damage was estimated to be about 16.9 trillion yen not including the costs associated with the nuclear accident at Fukushima Daiichi Nuclear Power Plant (Cabinet Office, 2012). Industrial facilities, power plants, and research facilities were damaged, as were various kinds of mechanical equipment located at these facilities. The Japan Society of Mechanical Engineers (JSME) formed an investigative committee to study the seismic damage to mechanical equipment at these facilities to elucidate in detail the mechanisms through which the damage occurred and improve the level of preparedness for future earthquakes.

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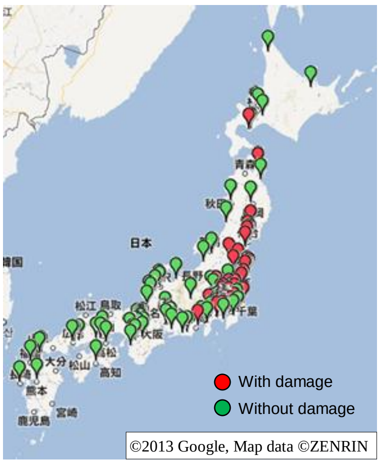
Working Group 1 (WG1) of the committee mainly conducted damage surveys of industrial facilities, including on-site investigations. In this section, an overview of the damage to industrial facilities and mechanical structures caused by the GEJE is presented and the effectiveness of the countermeasures employed is described.

2. Overview of the seismic damage to industrial facilities caused by the 2011 Great East Japan Earthquake

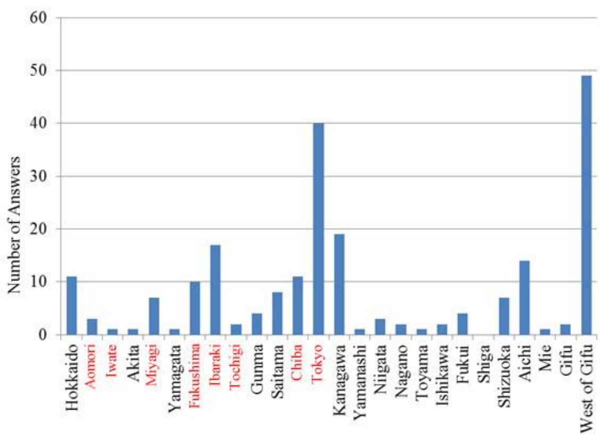
The JSME distributed a questionnaire to investigate the influence of the earthquake on industrial facilities about two months after the earthquake. The questionnaire was sent to about 1,000 organizations, and around 200 of them responded. Figure 1(a) shows a map of Japan and the questionnaire answers, and Fig. 1(b) shows the number of questionnaire answers for each prefecture. In Fig. 1 (a), the red marks denote damaged facilities and the green marks denote facilities that did not sustain damage. In Fig. 1 (b), the prefectures shown in red characters were the "disaster-stricken regions" where the Disaster Relief Act was applied. Although the questionnaire responses were mainly from the Kanto region and the numbers of answers obtained from the seriously tsunami-damaged areas in Iwate, Miyagi, and Fukushima were relatively small, some features of the seismic damage caused by the GEJE and other important knowledge was obtained from the various answers.

Based on the questionnaire and investigations of many sites, it was found that the damage to industrial facilities was mainly caused by one of the following causes or a combination thereof: strong seismic motion, soil deformation, and the tsunami. As for the damage caused by the movement of the ground, there were many cases at bases and supporting members of structures, pipes, cranes, shutters, and lifting machines such as elevators. Some damage was caused by the sloshing of liquids such as molten solder and spillage from liquid storage tanks. Troubles were reported that arose from machines slipping from fixed locations or being titled or disturbed from their upright/flat positions, even if they were not actually broken as a result. Such machines had to be adjusted and recalibrated after the earthquake. In addition, there were some cases in which evacuation was hampered by scattered tools, even when equipment damage did not occur. As for the effects of soil deformation, many cases of foundation damage due to liquefaction and damage to buried pipes were reported. In areas not devastated by the tsunami, problems mainly affected the vulnerable equipment or parts that had insufficient seismic capacity. In the tsunami-affected areas, however, all equipment, regardless of type, was damaged.

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 problems continuing operation because both their primary and backup facilities suffered. Many facilities that were



(a) Seismic damage distribution for industrial facilities (as of June 15, 2012)



(b) The number of questionnaire responses by region

Fig. 1 Results of the JSME questionnaire

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relied upon to repair damaged machines or produce replacement machines also suffered from the earthquake, so a long time was needed for industrial operation to fully resume. In addition, the rapid recovery of industries was hindered by the stoppage and shortages of electrical power, water and fuel supplies. The questionnaire answers showed that the disruption of the supply-chain affected production activities in western Japan that were not directly affected by the earthquake. Large aftershocks frequently occurred after the main shock of March 11, most notably on April 7 and April 11, and often caused additional damage to industrial facilities. Several facilities suffered more severe damage due to the aftershocks than from the main shock.

It took from one to several days to determine the extent of the damage to many facilities in the disaster-stricken region. Though the questionnaire was distributed about two months after the earthquake, several organizations answered that they had not yet determined the full extent of the damage sustained. In addition to the damage to facilities, most organizations said that their employees had trouble commuting to work by both car and train after the earthquake, because of the low availability of gasoline in the first one or two weeks after the earthquake, and because of the disruption to public transportation caused by the planned blackouts.

Communication interruptions/convergence and electrical power outages occurred as a result of the earthquake. As a result many organizations said that securing means of communication was an important future task. Mobile phones and mobile text-messaging helped organizations contact their staff during the electrical power outage. It seems that private lines worked well as a way to maintain contact between main offices and branch offices, although some systems that relied on an electrical power supply were ineffective due to the blackouts. About 60% of the organizations who answered the questionnaire had prepared an emergency manual, and about 80% said that this manual was helpful to a greater or lesser extent in responding to the disaster, although a few of them said it was not helpful at all. The problems with the manuals were related to the estimated scale of the disaster, maintaining stocks of food, water and fuel, long-term power outages or shortages, and disaster training. Many organizations that did not have a manual answered that it was necessary to prepare such a manual soon.

The damage caused by the GEJE was varied in type and widespread as described above. In the following sections, the most common types of damage sustained by mechanical structures are discussed.

3. Damage to mechanical structures

3.1 Damage due to the strong seismic motion

Figure 2 shows the damage at the base of a circulation pump. The concrete base 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. In many cases, equipment installed on the roofs of buildings, such as air conditioning units, had collapsed or failed because the seismic response of buildings tends to be amplified at the top. Figure 5 shows examples of such damage. This kind of damage, which is related to bases and anchors, mainly occurred due to a lack of consideration of earthquake resistance when installing the equipment. Figure 6 shows damage to the anti-vibration bar of a boiler. The boiler was suspended from the upper position only in order to allow for heat expansion during operation; consequently the seismic response was large and the body of the boiler collided with the anti-vibration bar, damaging it.

Figure 7 shows the failure of pipe supports and Fig. 8 shows damage to 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 to books and documents or problems with electrical equipment. To prevent such secondary damage, it is necessary to consider the facility layout in the planning stage as well as the seismic resistance of the piping system. Another pipe-failure mode was related to soil deformation and is described in section 3.2. Figure 9 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.

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The buckling failure of tanks has been reported after previous earthquakes, such as the 1995 Kobe Earthquake and the 2007 Niigata-ken Chuetsu-oki Earthquake; this failure mode was also found to result from the GEJE. Figure 10 shows the buckling failure of a 2,000 m^3 water tank (Thermal and Nuclear Power Engineering Society, 2011). This


Fig. 2 Damage at the base of a pump


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


Fig. 4 Deformation of the steel base of a FRP tank


Fig. 5 Failure of a water tank installed on a roof


Fig. 6 Damage to the anti-vibration bar of a boiler

Fig. 7 Failure of a pipe support (in-house hanging pipe)


Fig. 8 Failure of a utility pipe and water leakage (Provided by JAXA)


Fig. 9 Damage to inner walls by pipes (Provided by JAXA)

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failure was caused by the aftershocks on April 11 and 12. There were some tanks that did not sustain damage, despite being located in the same prefecture as the failed tanks. Thus, it is necessary to investigate the cause of these failures taking into account the characteristics of the seismic motion along with other factors. The damage investigations at hazardous material facilities were conducted and summarized by the National Research Institute of Fire and Disaster. According to their report, the damage caused by sloshing liquids 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 and damage investigations were conducted by the Japan Crane Association (JCA) (Japan Crane Association, 2011). Figure 11 shows the number of damaged cranes with respect to crane type, revealing that it was mainly overhead cranes that were damaged by the seismic motion. Figure 12 shows a typical failure of an overhead crane. The hook bolts that 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.

Fig. 10 Buckling failure of a 2,000 m^3 water tank (Thermal and Nuclear Power Engineering Society, 2011)

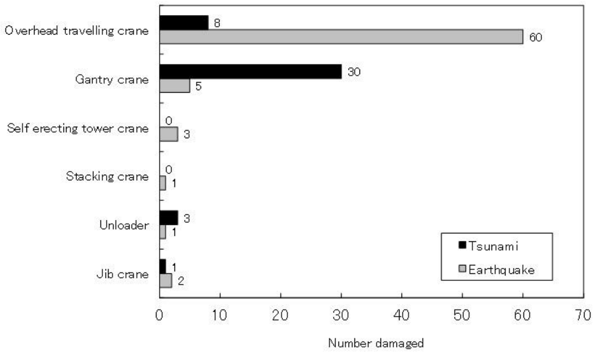

Fig. 11 Number of damaged cranes by type

Fig. 12 Elongation of a hook bolt

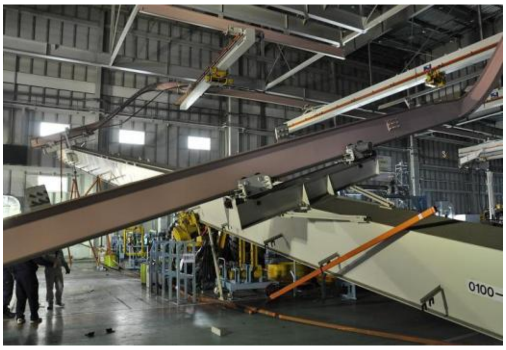

Fig. 13 Failure mode of an overhead crane (fallen rail)

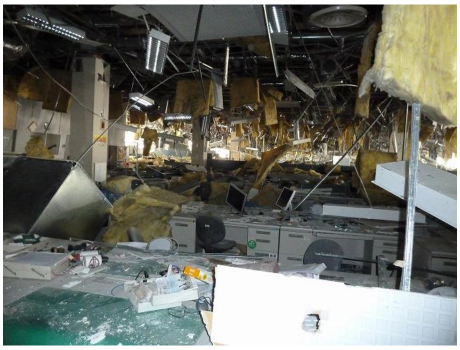

Fig. 14 Fallen ceiling materials

Fig. 15 Failure of cable racks

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Elevators are mechanical structures that require a high level of seismic safety. Typical damage to elevators included the jamming of cables, the deformation of rails, and derailing. The damage to elevators was investigated by the Japan Elevator Association (JEA) (Miyata, 2012) and the relation between the percentage of elevators damaged (damage ratio) and the applied seismic design guideline was analyzed. It was found that the damage ratio was about 3% for elevators constructed in accordance with the guidelines used before 1981, but only 2.36% for elevators constructed in accordance with the guidelines used from 1981-1998. The damage ratio of elevators constructed in accordance with the latest revision in 2009 was just 1.13%. It is clear that the damage was mitigated to some extent by both the previous and latest revision to the seismic design guidelines. In addition, an escalator reportedly collapsed, that is, became detached from its fixings in a large shopping centre in Miyagi Prefecture, but a detailed investigation of the incident has not yet concluded.

The ceilings and walls of factory buildings and equipment hung from the ceilings such as cable racks and air-conditioning units were also damaged. Figures 14 and 15 show some examples of these types of damage. Such incidents led to human injuries, secondary damage to machines, and hindered the resumption of business operations.

3.2. Damage due to soil deformation

During the GEJE, liquefaction was observed in many areas (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 of the damage caused by soil deformation was observed in industrial facilities. Figure 16 shows a 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 buildings into the surrounding soil were often damaged by the relative displacement between the building and the soil. Figure 17 shows pipes fractured at the point of connection of the building and soil, due to the subsidence of the soil. Figure 18 shows a deformed quay wall and the misalignment of the unloader rail. In this case, the crane was unserviceable after the earthquake because it could not

Fig. 16 Uplift of a pipe support base due to ground subsidence

Fig. 17 Pipes fractured at the connection point of the building and soil

Fig. 18 Quay wall deformation and misalignment of the unloader rail

Fig. 19 Damage to road due to ground subsidence

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run on the deformed rail, although the crane itself was undamaged. There were many cases in which damage was observed at smaller facilities that surrounded larger or more important sites. This is mainly because the satellite facilities are set on different bases from the main facilities, for which less consideration is given to seismic countermeasures. Such instances were common in previous earthquakes also. Although not a mechanical structure, damage to a road in a research facility is shown in Figure 19. In this case large soil deformation slowed recovery, because the heavy machines necessary for making repairs could not be transported to the facility via the damaged road.

3.3. Damage caused by the tsunami

Many factories and plants are located on the coast because of the numerous advantages such a location offers in terms of the transportation of materials or products and access to coolant water. For this reason, however, many facilities were devastated by the tsunami, forcing the suspension of operation for a long time after the disaster. Although the number of cases investigated by the JSME committee was small, common types of damage caused by the tsunami were identified.

Typical occurrences were the breakage of equipment through collisions with floating objects, tanks being damaged or swept away (water, oil, gas), buckling failure of tanks due to buoyancy, and unloader wheels derailing. Power system damage resulting from short-circuiting of electrical lines also occurred due to tidewater flooding. Figure 20 shows the lifting-damage sustained by a 60-ton LPG tank (manufactured in 1974) due to its buoyancy. The sea was located at the left side of Fig. 20, and it seems that the anchor bolt was stretched by buoyancy and then deformed by the force of 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. 20 may be mitigated in the future by an adequate anti-tsunami design. Figure 21 shows tanks washed away by the tsunami and Fig. 22 (Tokyo Electric Power Company, 2011) shows the buckling failure of a water tank due to the pressure of the water. Figure 23 also shows the failure of a FRP tank supposedly caused by water pressure. An example of damage due to collisions with floating objects is shown

Fig. 20 Lifting damage to LPG tank by tsunami

Fig. 21 Tanks washed away by tsunami

Fig. 22 Buckling failure of a water tank due to the water pressure (Provided by TEPCO)

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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 tidewater flooding. In many cases, electrical systems and devices including power panels required inspection, cleaning, and replacement after the tsunami. In addition, the large amount of rubble left after the tsunami hindered the disaster-relief at industrial facilities (Thermal and Nuclear Power Engineering Society, 2011). The tsunami affected near-sea level facilities, but no damage was sustained by elevated sites. Thus, it is effective to install essential equipment in elevated areas.

Fig. 23 Failure of a FRP tank caused by the tsunami

Fig. 24 Damage due to collisions with floating objects (Provided by TEPCO)

3.4. Good practice

Although many industrial facilities and mechanical structures were damaged by this earthquake, the damage sustained by some facilities was mitigated by seismic countermeasures put in place before the earthquake. Many organizations took safety precautions such as fixing machines and furniture to the floor or building walls and preventing objects from falling from racks. Anchor bolts of a diameter sufficient to withstand seismic motion were effective for securing machines. As described in section 3.2, many pipes were damaged by the relative displacement between buildings and the surrounding soil. In such cases, flexible pipes such as those shown in Fig. 25 effectively overcame the problem. The application of base isolation systems or vibration control devices was also effective for reducing the movement of mechanical structures. Figure 26 shows an example of a vibration control brace in a facility building.

Many organizations said in their answers to the questionnaire that they had troubles due to the blackouts. In a factory that WG1 investigated, seismic shutoff valves were installed in flammable gas lines. These valves were designed to work mechanically, not requiring an electrical control, for such seismic events followed by electrical power outages. These valves worked effectively following the GEJE. The design of this factory also incorporated features that

Fig. 25 Flexible pipes

Fig. 26 Vibration control brace

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shutoff the flammable gas and vent the nitrogen gas in seismic events. Accommodating such features at the planning stage of future industrial facilities could prevent disasters to come.

Another good example of planning was seen in factories with raised walkways running along the outside of the buildings. The walkways prevented fractured wall materials from falling on persons and machines, and provided evacuation routes in addition to the corridors in the building. The additional access provided by the walkways aided in the resumption of operation at the factories. Of course, seismic designs in the initial facility construction plans are both essential and effective for mitigating the damage to mechanical structures caused by seismic motion, as are the elevator guidelines described in section 3.1. Equipment that was designed well in this sense sustained overall less damage during the GEJE. Reviewing past seismic damage and continuously rechecking the state of a facility is necessary and effective for improving seismic safety.

4. Recommendations for the seismic safety of mechanical structures

Based on the investigations into the damaged caused by the GEJE, the following recommendations have been made for mitigating the seismic damage to mechanical structures caused by earthquakes in the future.

(1) Promotion of seismic countermeasures
In order to prepare for possible future earthquakes such as the Tokai, Tonankai, and Nankai trough earthquakes as well as those occurring directly beneath the Tokyo metropolitan area, it is necessary to promote the implementation of seismic countermeasures in mechanical structures. It is also important to prepare emergency manuals and carry out emergency drills based on the manuals.

(2) Take measures to mitigate the damage caused by soil deformation
A lot of damage occurred to the bases of machines and buried pipes due to soil deformation resulting from liquefaction or subsidence. It is necessary to take measures to mitigate this damage.

(3) Preparation for tsunamis
A fundamental and effective countermeasure to tsunami damage is simply to install essential equipment at elevated locations. In addition to such countermeasures, it is also important to consider safety operations that are put into action when a does occur tsunami, for example, the safe evacuation of staff from the facilities.

(4) Preparations for electric power outages
Electric power failure can occur on a large scale as a result of earthquakes. It is important to stock fuel for emergency power generators. With the assumption that there will be no power in emergency situations, fail-safe designs for emergency shutdown valves that contain hazardous or flammable material must not require electricity. It is also important to improve the reliability of the electric power grid and power stations during seismic events.

(5) Continuation of disaster prevention research for mechanical structures and ensuring damage survey data accessibility
Investigations into the damage sustained by mechanical structures due to natural disasters are fairly uncommon in the field of mechanical engineering. The JSME should support the members conducting disaster prevention research to foster young researchers in this field and ensure the data obtained by the damage survey is maintained and kept easily accessible.

5. Conclusion

The damage sustained by industrial facilities and mechanical structures in the 2011 Great East Japan Earthquake was summarized. From a questionnaire and many on-site investigations, we can conclude that the damage to industrial facilities was mainly caused by one or a combination of the following: strong seismic motion, soil deformation, and the

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tsunami. Although a great deal of damage occurred, seismically well-designed equipment did sustain less damage overall. In their questionnaire answers, many organizations said that their means of communication and provisions for electrical power outages/shortages should be improved in the future.

Though the damage caused by this earthquake was spread over a very wide area and various kinds of damage were observed, the authors focused on the damage to mechanical structures in the present work. In order to clarify the causes of this damage in detail, the relationships between the seismic motions, locations, structural characteristics and damages should be investigated in future work.

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