DAMAGES CAUSED BY 3/11 GREAT EAST JAPAN EARTHQUAKE ON COASTAL DRAINAGE PUMPING STATIONS ALONG SENDAI BAY

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ABSTRACT: On March 11, 2011, a tsunami struck low-lying land along Sendai Bay, where no tsunami had hit in the past 200 years. These coastal lowlands were equipped with drainage pumping stations for paddy areas, but the pumping stations were destroyed by the tsunami, thus preventing drainage of the sea water inundation.There are two kinds of pumps, motor and diesel pumps. Even diesel pumps need electricity to start up and control their power. If a pump is inundated by salt water, all electric parts will be short-circuited. Although the diesel mechanisms can be reused after being washed by fresh water, the electric parts of both types of pump must be replaced. The switchboard for the pumps must also be replaced. If damages are caused only by salt inundation, the electric parts of both types of pump must be replaced. Temporary recovery was done by manually controlling the pumps because the automatic pump control system was difficult to restore. The mean recovery time was one month for electric pumps and two months for diesel pumps. For pumps that were broken by external force, quick recovery was abandoned.Past studies on tsunami have shown that concrete structures are strong enough to withstand tsunami surges. In the present study, a few concrete pumping stations located near the coast were damaged. The damages to buildings were mainly governed by the type of material and location on the coast. At some pumping stations, the tank for desorption prevented external forces from acting on the buildings.These results show that the tsunami safety of drainage pumping stations could be improved by increasing the resistance to salt inundation and appropriately locating the tank for desorption.

Keywords: Drainage pumping stations, tsunami, inundation, salt water, safety design

OBJECTIVE OF STUDY

In 2011, the tsunami caused by the Great East Japan Earthquake struck low-lying land along Sendai Bay, destroying buildings and infrastructure. These coastal lowlands were equipped with drainage pumping stations (DPS) for urban areas and paddy areas, which were inundated by sea water. Photo 1 shows a view of the inundation of Fujisone pumping station on March 18, 2011. Although many dead bodies remained in the inundated areas, at that time the top priority to recover from the tsunami disaster was to drain the inundated areas. Normally, urban areas are located on higher ground than paddy areas, so the final drainage of inundation depends on pumping stations for paddy areas. However, all pumping stations in inundated areas were destroyed. Attempts were made to use small mobile pumps to reduce the inundation, and it took several weeks to remove the water from inundated areas.

Drainage pumping stations are designed for pumping inundation caused by rainfall in a basin; inundation caused by water intrusion from outside areas is not considered. The buildings of pumping stations were not designed to withstand the external force caused by tsunami, and so the drainage pumping stations were too weak. Based on this experience, the design of drainage pumping stations along the coast should take damage by tsunami into consideration.

There have been many studies on tsunami damage to buildings, but few studies on drainage pumping stations. The authors consider that drainage pumping stations are particularly important for recovery from tsunami damage. This paper summarizes the damage to drainage pumping stations to identify which structures resisted the tsunami.

PAST STUDIES

Tsunami damage to buildings has been widely studied, particularly the relation between damage and inundation height. Hatori (1984) was the first study based on data on damage caused by the 1986 to 1933 Sanriku Tsunami, and 1960 Chilean Tsunami. Shuto (1993) deduced the relation between the damage ratio of housings and tsunami height in past tsunami in Japan by numerical analysis and proposed a “tsunami intensity and damage table”. Koshimura et al. (2007) developed fragility functions “by an integrated approach using the numerical modeling of tsunami inundation and GIS analysis of post-tsunami survey data” for Banda Aceh Indonesia, but did not consider building structures because of the limited satellite image data available on damage. Kimura et al. (2006) proposed vulnerability functions through an investigation in Matara. Murao et al. (2010) developed fragility curves by type of building structure based on damage in Sri Lanka caused by the 2004 Indian Ocean Tsunami.

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Photo 1 Inundation after the tsunami

After the 2011 Great East Japan Earthquake, NILIM and BRI (2011) conducted various research on damaged buildings. Suppasri et al. (2012) developed fragility functions.

STUDY METHOD

Selected drainage pumping stations along Sendai Bay located in Miyagi and Fukushima prefectures were studied. Figure 1 shows the locations of the studied drainage pumping stations (DPS). Damage conditions were checked by several field surveys from March to July 2011. The locations of pumping stations were measured by GPS. Distances from the coast were measured by GIS based on the position data by GPS. Tsunami heights near pumping stations were selected from data of "The 2011 Tohoku Earthquake Tsunami Joint Survey Group".

Damage was analyzed based on the tsunami intensity scale shown in Table 1 proposed by Shuto (1993). The influence on this scale was evaluated by tsunami height and distance from the coast in consideration of studies on tsunami damage to buildings.

Photo 2 Hanagasa 2 DPS
(RC)

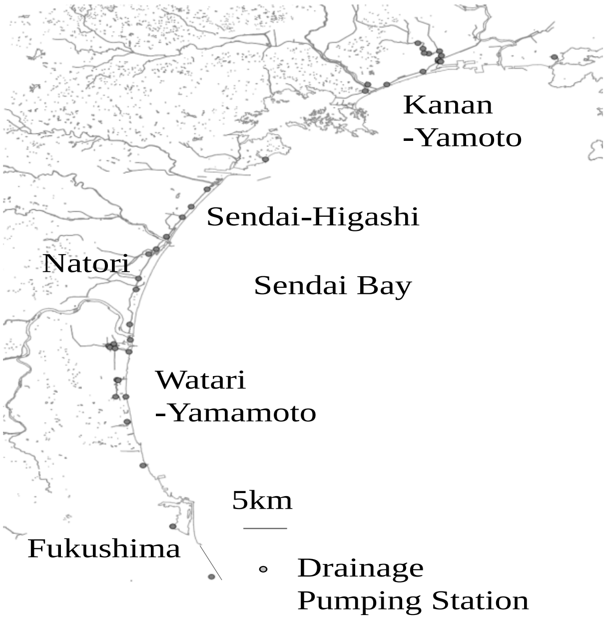

Fig. 1 Location of studied drainage pumping stations

Photo 3 Fujisone DPS
(RC)

RESULTS

Situation of basins

The low-lying land along Sendai Bay was historically tidal flats and lagoons, with the land in some areas lying below sea level, particularly around the Kitakami River and reclaimed land. Figure 1 shows the Jyo River (Kanan-Yamoto area) basin below sea level. In Fukushima Prefecture, the Yasawaura land reclamation area is below sea level. The DPS of Yasawaura is shown at the southern end in Fig. 1.

The earthquake in 2011 caused land subsidence of some low lands, of up to 100 cm. This subsidence increased the inundation damage and made drainage more difficult. In Fig. 1, the Kanan-Yamoto area suffered land subsidence of 60 cm.

Situation of damages

Shuto (1993) stated that RC buildings are relatively strong against tsunami damage. Shuto classified building structures into RC, masonry and wood. In the present study, the drainage pumping stations were RC, panel and wood structures.

RC is basically strong against tsunami. Some damage to RC occurred at Hanagasa 2 DPS shown in Photo 2. This DPS is located just behind a coastal bank, which is located just to the right of the DPS in Photo 2. This photo is taken from the land side facing toward the sea. DPSs in RC buildings are relatively strong because a DPS is equipped with a crane for pumps and the structure is relatively strong for a simple RC building. Photo 3 shows damage to Fujisone DPS. This RC DPS remained standing even though all neighboring buildings were destroyed.

Another type of DPS structure is the panel structure. In a panel structure, a steel frame is constructed first and then panels are added onto the frames. These panels are weak against tsunami. Photo 3 shows tsunami damage at Ohori DPS. Except the ceiling boards, all panels were swept away and only the steel frame remained. A panel structure can be constructed quickly and easily, and so even new DPSs such as the Fujitsuka DPS are panel structures.

Wood structures are popular for private homes but are rarely used for a DPS. Before the tsunami, some DPSs made of wood remained, which had been constructed

Photo 4 Oohori DPS
(Panel)

fields. DPSs for a government drainage project are designed to allow less than 30 cm of inundation in case of heavy rainfall. DPSs are only a single-story structure with floor dimensions of less than 10m x 10m, with a pump capacity of less than 1 m^3/s. Since 1970, because of overproduction of rice, inundation by rainfall cannot be allowed. Many RC or panel DPSs were constructed by the local government because the loss of paddy area by urbanization meant that not enough drainage area remained for the government project. However, no effort was made to reorganize the DPSs in the drainage project design, and so wood DPSs remained.

Relation between tsunami height and distance

Based on Asakura et al. (2000), the tsunami force acting on a building is three times the height of hydrostatic pressure of tsunami inundation. Therefore, tsunami inundation height is an index of the tsunami force acting on a building. Past researchers used this relation to derive fragility functions for buildings.

Table 1 Tsunami intensity scale

Scale	Name	Specification
5	Total destruction	Beams and entire building destroyed.
4	Major destruction	Most of the walls and beams destroyed.
3	Moderate destruction	Beams remain. Some walls destroyed.
2	Minor destruction	Windows are broken but walls remain.
1	Flooding only	No mechanical damage.

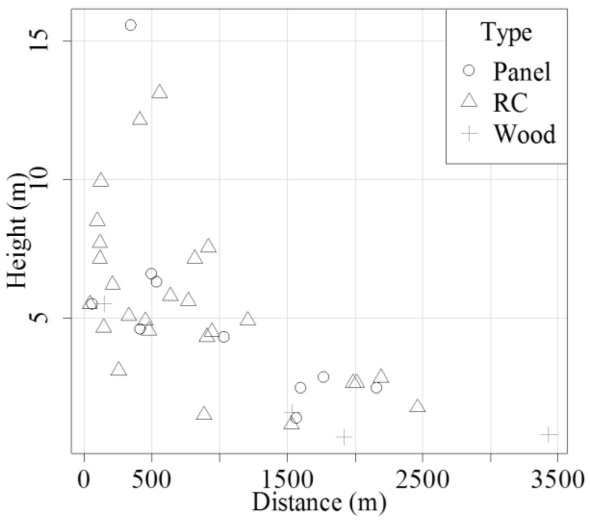

Fig. 2 Relation between tsunami height and distance.

Table 2 DPSs along Sendai Bay

Area	DPS name	Distance	Height	Damage	Type
Kanan -Yamoto	Nakaku-2	3432	0.80	2	Wood
	Akai	2460	1.77	2	RC
	Yanaginome-2	1531	1.15	2	RC
	Minamiku	1535	1.59	2	Wood
	Gomikura	1919	0.71	2	Wood
	Yanaginome	882	1.49	1	RC
	Omagari	147	5.50	5	Wood
	Omagari-2	327	5.06	2	RC
	Kama	40	5.50	1	RC
	Shimokaidou	475	4.56	1	RC
	Tatenuma	254	3.09	2	RC
	Hamichi	145	4.66	2	RC
Natori	Yuriage	916	7.55	2	RC
	Terano	1205	4.91	2	RC
	Ainokama	940	4.50	2	RC
	Fujisone	767	5.60	2	RC
	Kamasaki	450	4.90	1	RC
Watari -Yamamoto	Arahama	1770	2.85	3	Panel
	Arahama-2	2189	2.85	2	RC
	Nagatorohama	2160	2.48	5	Panel
	Ohatahama	1596	2.48	3	Panel
	Yoshida	209	6.20	2	RC
	Ushibashi	905	4.31	3	RC
	Ushibashi-new	816	7.14	2	RC
	Hanagasa	1032	4.31	3	Panel
	Hanagasa-2	114	7.14	4	RC
Sendai -Higashi	Takasagonambu	636	5.79	3	RC
	Ohori	498	6.59	4	Panel
	Nigouhori	413	4.59	5	Panel
	Fujitsuka	533	6.30	5	Panel
Other Miyagi	Arahama-rain	123	9.93	2	RC
	Udagawa	1568	1.38	3	Panel
	Kama-small	57	5.50	4	Panel
	Nakashita	114	7.70	3	RC
	Agawanuma	94	8.50	2	RC
	Ooyachi	410	12.14	2	RC
Fukushima	Ootohama	345	15.56	5	Panel
	Souma	1984	2.67	2	RC
	Shinden	2011	2.67	2	RC
	Yasawaura	557	13.12	2	RC

Distance is an index of the location of a DPS. DPSs are located at the downstream end of a drainage canal or the lowest point in the basin, and so are located along rivers or on the coast. Figure 1 shows a few DPSs located along the coast: Agawanuma, Yoshida, Hanagasa 2 and Ooyachi. Typical DPSs are located along Teizanbori canal, Torinoumi lake and Ushibashiga lagoon. Because of fishing rights, direct drainage to Sendai Bay is difficult. These off coast locations may decrease the damage caused to DPSs by tsunami. Teizanbori canal is located on the coast. Although the tsunami destroyed coastal banks, the Teiaznbori canal remained. This canal helped reduce inundation by using mobile pumps. Distance is measured from the coast. DPSs are located along rivers, canals and lakes. Therefore, the distances are the lengths from the coast to rivers, canals and lakes.

Figure 2 shows the relation between distance and tsunami inundation height. If the distance is longer than 750 m, the relation is linear, but if the distance is less than 750 m, the tsunami height is unstable and the relation is complex. Tsunami height may change depending on the local landform and topography of the sea floor.

Table 2 shows details of DPSs. “Area” means a government drainage project or similar size basin.

Table 3 Tsunami intensity scale and damage (based on Shuto 1993)

Tsunami intensity	1	2	3	4	5
Tsunami height (m)	2	4	8	16	32
Damage: Wooden house	partly damaged	complately damaged			
Damage: masonry house	withstand	no data	complately destroyed		
Damage: rainforced concrete	withstand		no data		complately destroyed

Remarks on tsunami damage on DPSs

Studies on tsunami damage to buildings tend to focus on whether the building structure remains or not. But in the present study, the authors considered the recovery of drainage capability after the tsunami. In the study of DPSs, the resistance of the drainage capacity of pumps and the recovery capability should be considered.

There are two types of drainage pump: the diesel pump and the motor pump. Motor pumps are easy to maintain, but if there is a power failure in a flood, the pumps cannot work. Diesel pumps are difficult to maintain. They run on oil, but when starting up, small motors are powered by electricity. As a countermeasure in case of a power failure, diesel pumps use a private power generator. Based on these characteristics, diesel pumps are typically used for flood drainage and motor pumps are used for ordinary drainage. The procedure for starting a diesel pump is complex. Diesel pumps have a control box nearby and a central control desk in a control room. After inundation by the tsunami, salt water destroyed the electric parts, and all power supply boxes failed. Even if there is no mechanical damage, to restore the pumps, a new temporary power box and a control box were installed. The mechanical parts of a diesel pump can resist salt water; they can be reused by flushing them with fresh water, whereas electric parts must be replaced by new ones. Because of this complexity, it takes about one month to restore a motor pump and about one and a half months to restore a diesel pump.

Based on this experience, electric parts should be placed at higher elevations. A waterproof structure to prevent salt intrusion into a building is an effective countermeasure against tsunami.

Shuto (1993) showed that the windows of a building are weak points against tsunami. This tendency applies to DPSs too. In Photo 3, the windows were broken by the tsunami. To protect against tsunami damage, the structure of windows should be strengthened.

Relation between tsunami damage and distance

Figure 3 shows the relation between tsunami damage (intensity score) and distance. Severe damage (4 or 5 on Shuto’s scale) occurred within 500 m from the coast. Only one data of grade 5 is located more than 2000m from the coast. This pumping station is located at a lagoon of Torinoumi Lake. The distance shows that from the coast. But the actual tsunami struck Trinoumi Lake. Many DPSs are classified into scale 2. This shows that the strength of window structures is a key factor.

Relation between tsunami damage and height

Table 3 shows Shuto’s tsunami intensity scale. Wood buildings are very weak against tsunami because they easily float. Figure 4 shows the relation between tsunami damage as intensity scale and tsunami inundation height. For wood, damage occurs even for buildings lower than 2 m. This tendency is similar to Table 3.

This study has a bias to derive fragility functions, because only damaged DPSs were studied and no damaged DPSs were surveyed. For fragility functions, data for both damaged cases undamaged cases must be prepared. The data of Table 2 contains bias for deriving

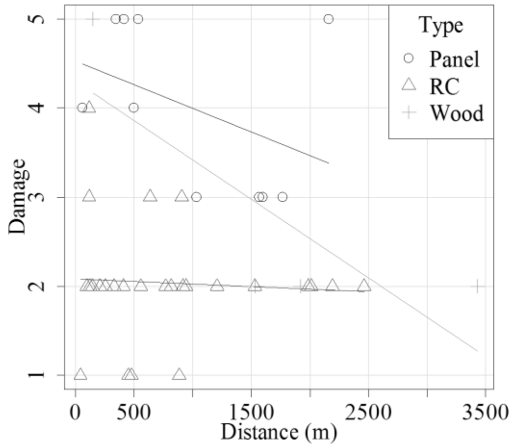

Fig. 3 Tsunami damage and distance.

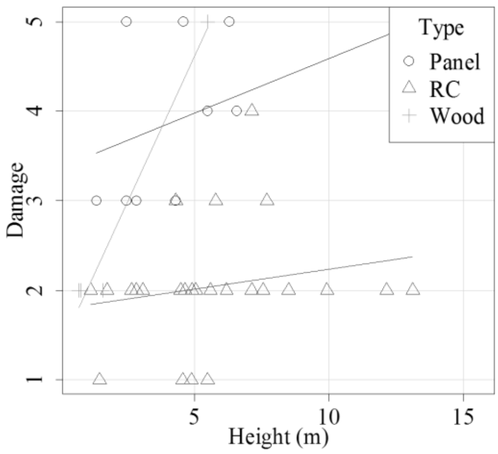

Fig. 4 Tsunami damage and height.

Photo 5 New Ushibashi DPS

fragility functions. Even considering this bias, Fig. 4 shows severe damage for small inundation height of less than 1 m for wood and panel structures.

The aim of this study was to clarify the tsunami height resistance of DPSs. From Fig. 4, an RC structure is strongly recommended for a DPS. Recently, to reduce the cost and construction period, some DPSs are panel structures. However, for resistance to tsunami, panel structures should be avoided.

Other remarks for designing a DPS

Photo 5 shows the new Ushibashi DPS. The control room is on the third floor. On March 11, the tsunami reached the second floor. About 20 persons took refuge on the third floor. This DPS acted as a shelter from the tsunami.

When designing a DPS, if there is no nearby shelter, the additional function of the DPS as a shelter should be considered.

CONCLUSIONS

For increasing tsunami resistance, the design of a DPS should consider the following:

1) An RC structure is recommended.
2) The strength of windows should be considered.
3) For decreasing electric damage by salt water inundation, a waterproof DPS should be considered. Another solution is to locate the pumps and electric parts as high as possible.
4) If there is no tsunami shelter near a DPS, such a function should be added.

ACKNOWLEDGEMENTS

In the field survey, the authors were supported by Miyagi Prefecture, Kanan-Yamoto WUA, Natori WUA and Watari WUA.

REFERENCES

Asakura, R. et al. (2000) An Experimental Study on Wave Force Acting on Shore Structures, Proc. of Coastal Engineering, JSCE, Vol. 47, pp. 911–915 (in Japanese)

Hatori, T. (1984), “On the damage to houses due to tsunami”, Bull. Earthq. Res. Inst., Vol. 59: 433–439 (in Japanese).

Kimura, K., Ishimi, K., Sato, S., Fukuda, T., Mikami, T., and Kikuchi, S. (2006), “Verification of tsunami wave source model and formulation of a vulnerability function for buildings based on the investigation of actual damage due to the Sumatran earthquake and tsunami: subject area being the damage at Matara city, Sri Lanka”, Coastal Engineering Committee, Vol. 53: 301–305 (in Japanese).

Koshimura, S., Oie, T., Yanagisawa, H., and Imamura, F. (2009), “Developing fragility functions for tsunami damage estimation using numerical model and post-tsunami data from Banda Aceh, Indonesia”, Coastal Engineering Journal, Vol. 51, No. 3: 243–273.

NILIM and BRI (National Institute for Land and Infrastructure Management and Building Research Institute: Summary of the Field Survey and Research on “The 2011 off the Pacific Coast of Tohoku Earthquake” (the Great East Japan Earthquake) http://www.kenken.go.jp/english/contents/topics/20110311/0311summaryreport.html

Shuto, N., 1993. Tsunami Intensity and Disasters, Tsunami in the World, 197–216.

Suppasri, A., Mas, E., Koshimura, S., Imai, K., Harada, K. and Imamura, F., 2012b. Developing tsunami fragility curves from the surveyed data of the 2011 Great East Japan Tsunami in Sendai and Ishinomaki plains, Coastal Engineering Journal, 54 (1), Special Issue of 2011 Tohoku tsunami.

The 2011 Tohoku Earthquake Tsunami Joint Survey Group. http://www.coastal.jp/tsunami2011/