Post Earthquake Field Investigation of the M_w9.0 Tōhoku Earthquake of 11th March 2011

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SUMMARY:
A reconnaissance was conducted by the UK-based Earthquake Engineering Field Investigation Team (EEFIT) to study the effects of the recent M_w9.0 Tōhoku earthquake. The purpose of the mission was to assess the damage on buildings and infrastructure caused by the earthquake and tsunami. The consequent effects of the catastrophe on the local community were also one of the mission's key interests. This paper presents a wide coverage of the earthquake event, comprising the damage observed on residential, commercial and industrial buildings and facilities, geotechnical failures such as ground settlement, liquefaction and landslides, the effectiveness of coastal defences, vertical evacuation facilities and the use of geospatial tools after experiencing the nation's largest earthquake event since the beginning of instrumental seismology circa 1900. The observations on ground motion and shaking damage are discussed in the accompanying paper.

Keywords: structural damage, geotechnical failures, coastal defences, vertical evacuation facilities, geospatial tools

1. INTRODUCTION

On 11th March, 2011, a M_w9.0 earthquake occurred in the Japan Trench off the coast of Tōhoku in north-east Japan. Ground shaking was felt as far as western Japan and lasted for almost four minutes (220 seconds), generating large, unprecedented tsunami toppling sea defences and destroying entire settlements and towns along the coastline. This M_w9.0 earthquake was the largest event that has been recorded in Japan since the beginning of instrumental seismology circa 1900. The government of Japan (GoJ, 2011) announced the estimated total direct loss to be around ¥23 trillion (US$297bn), making this the world's costliest earthquake. Japan is exposed to some of the world's most extreme natural hazards and is considered to be one of the most prepared countries in terms of earthquake and tsunami. Early warnings systems for earthquakes and tsunami were in place; sea defences were erected along coastlines; frequent evacuation drills took place in these coastal communities. Strict seismic building codes have also been implemented. However, an earthquake and tsunami of such magnitude was not expected. Considering the significance of the event, the UK Earthquake Engineering Field Investigation Team (EEFIT) deployed a multidisciplinary team of 9 to conduct a 6-day field mission in the Tōhoku region in May last year. A summary of observations and findings from the mission are presented in this paper. Further details can be obtained from EEFIT (2011) and Fraser *et al.* (2012).

2. THE 11TH MARCH 2011 EARTHQUAKE

The 11th March 2011 earthquake occurred at the Japan Trench where the lithosphere of the Pacific Plate subducts under the Okhotsk Plate. The rupture of the lithosphere was about 500 km long and 200 km wide (Ammon *et al.*, 2011). The earthquake triggered a large tsunami in various locations along the Tōhoku coast which damaged more than 900,000 buildings in Iwate, Miyagi, Fukushima and Ibaraki prefectures (NPA, 2012). In comparison, the earthquake shaking affected about 95,000 buildings (MLIT, 2011). As of 20th February 2012, the Japan National Police Agency confirmed 15,852 deaths, 6,011 injured and 3,287 people missing due to the earthquake and tsunami (NPA, 2012).

With the massive destruction by the tsunami and the widespread ground shaking, the event has now become the world's costliest earthquake, with cost estimates ranging between US$122-235 bn by the World Bank (2011), US$245-613bn by the rating agency Standard and Poor (Reuters, 2011), while the Japanese Government estimating the cost to reach US$297 bn (GoJ, 2011). Uncertainties in these cost estimates are still prevailing a year after the earthquake, attributed to the effect of the Fukushima Daiichi nuclear power plant incident. The staggering cost of the disaster is more than twice the economic loss of the second costliest earthquake, the 1995 Hanshin-Awaji (Kobe) earthquake (also in Japan), based on World Bank's estimates.

The 2011 Tōhoku earthquake at M_w 9.0 was far greater than the forecasted magnitude based on historical seismicity. In view of the repeated underestimation of major subduction earthquake events (including the M_w 9.3 Indian Ocean earthquake and tsunami in 2004), a re-evaluation of subduction earthquakes and tsunami hazard assessment globally is necessary to avoid unforeseen catastrophes in the near future.

3. FIELD SURVEY

The mainshock (M_w 9.0) and aftershocks (particularly the M_w 7.1 event on 7th April 2011) of the Tōhoku earthquake caused severe damage to buildings and infrastructure such as ports, bridges, railways, roads, the Sendai airport, electricity, sewerage and water supply network across many prefectures in the Tōhoku coastal region. Many buildings in the proximity of the coastline were completely swept by the tsunami. Table 1 summarises the damage statistics from both the effects of the earthquake and tsunami. The large incidents of road damage in Chiba prefecture was attributed to the widespread soil liquefaction in Urayasu city (Tokimatsu *et al.*, 2011).

Table 1. Damage statistics of key prefectures, as of 20th February 2012 (NPA, 2012)

Prefecture	Iwate	Miyagi	Fukushima	Ibaraki	Tochigi	Chiba	Total
Property Damage							
Total collapse	20,185	83,932	20,084	3,070	265	798	128,334
Half collapse	4,561	138,715	64,445	23,988	2,070	9,861	243,640
Burn down	15	135	80	31	-	15	276
Inundated	2,084	28,245	1,393	2,430	-	876	35,028
Partially damaged	7,388	216,321	146,291	173,624	69,071	44,162	656,857
Non-dwelling houses	4,752	34,093	1,116	14,451	295	660	55,367
Damaged Roads	30	390	187	307	257	2,343	3,514
Damaged Bridges	4	29	3	41	-	-	77
Landslides	6	51	9	-	40	55	161

3.1. Damage to structures

One of the most advanced building codes under the Building Standard Law have been enforced in Japan since the 1981, incorporating experience from the 1978 Miyagi-Oki earthquake, which introduced the 2-level approach (serviceability and ultimate limit states) and stricter requirements for tall buildings (EEFIT, 1997). The latest amendments to the code were in 2000, where seismic performance requirements and verification based on earthquake response spectra at bedrock with soil amplification factors were spelled out after the inclusion of experiences from more severe earthquakes such as the 1995 Kobe earthquake event (Midorikawa *et al.*, 2004). As a result of the continuous improvement in building regulations, the majority of the buildings in the Tōhoku region suffered minimal damage from the earthquake shaking. There was however some instances of more severely damage buildings which would be briefly discussed in this section.

Residential houses in Japan are predominantly timber-frame structures for single-family houses (accounting for about 60% of EEFIT-visited locations) to steel-frame or reinforced concrete construction for multi-family buildings (remaining 40%). Commercial and industrial buildings are commonly steel-frame or variations of composite steel and reinforced concrete construction. Given the history of the amendments to the building code, older structures are generally less seismically resistant to modern structures.

Diagonal shear cracks and column buckling failures were observed in some buildings during the reconnaissance which were identified as unsafe with red-label notices by the local authorities. Observations of some reinforced concrete (RC) residential apartments such as one shown in Figure 1 indicated the use of smooth reinforcement bars, insufficient hook length and angles. Ground settlement of about 100 to 200mm could also have exacerbated the severity of the damage. Other reinforced concrete buildings such as the Sukagawa city office, constructed in 1970 showed similar failures (see Figure 2). The buckling and shear failure of columns were also largely due to the older version of the code during construction. Emphasis was placed on providing more reinforcements at the joints at that time. As a result, failures occurred towards the middle of the column where provision of reinforcements was lesser.


Figure 1. Failure at column-slab joint


Figure 2. Buckling at mid-span of column


Figure 3. Soft storey collapse of RC building


Figure 4. Collapse of wooden structure

In contrast to the frequent observations of soft storey failures in many reconnaissance missions such as the 2009 Padang earthquake (EEFIT, 2009), soft storey collapse was rarely observed in this Tōhoku earthquake event. An exception was an office building in Sendai constructed in 1969 (Figure 3), where columns failed by shear due to insufficient confining reinforcement stirrups. Damage to wooden structures was also observed in Sendai, Sukagawa and Shirakawa, which indicated the susceptibility of wooden structures against such strong earthquake shaking in these areas (Figure 4).

The sheer impact of the tsunami on structures lying near the coastline was the major contributor to the number of damaged buildings. During the reconnaissance to Tarō, Kamaishi, Ōfunato, Rikuzentakata, Minamisanriku, Ishinomaki, Natori, Wakabayashi, Yamamoto and Watari, these buildings were either swept away by the tsunami or severely damaged by passing waves of the tsunami as typically shown in Figure 5. Reinforced concrete buildings with stiff shear walls did not allow rapid tsunami flow through the buildings. As such, these buildings with small plan layout could suffer from overturning due to extreme tsunami flow as evident in Figure 6.

Figure 5. Damaged steel frame building at Ōfunato

Figure 6. Overturned RC building at Onagawa

3.2. Geotechnical failures and liquefaction

Geotechnical failures such as ground settlement, landslides, liquefaction and coastal subsidence were observed in the Tōhoku region. Several locations in the eastern part of Sendai city suffered ground settlement measuring as much as 70mm. In the affected areas, some reinforced concrete buildings showed lower settlement relative to the surrounding ground (Figure 7), while a handful sank relative to the surrounding ground level (Figure 8). This is likely due to the difference in pile penetration depth and soil condition. Not far from this location, sand boils were observed near the K-NET station in Oroshi district. Ground settlement also affected the use of external staircase and roadways leading to carparks. A high-rise residential building (Takasago apartment), as shown in Figure 9, also suffered differential settlement which rendered its unsuitability for occupancy after the earthquake and had to be demolished.

Locations of slope failure in Sendai and Shirakawa were also visited. These earthquake induced slope failures resulted in damage to low-rise residential wooden houses in Oritate, Sendai. The strong shaking also led to the failure of the gravity stone retaining walls at Komine Castle in Shirakawa due to insufficient horizontal ties within the cobble rocks. Large-scale landslides burying roads and houses at the foot of slopes also resulted in traffic disruption, property losses and 13 casualties in Shirakawa as shown in Figure 10.

It was understood from other reconnaissance reports (GEER, 2011; Takahashi, 2011) that liquefaction induced damage to roads and levees were severe in locations visited by EEFIT. However, most evidence of soil liquefaction had been cleared up as repair work was carried out swiftly following the earthquake. There was however still some evidence of soil liquefaction inferred by the uplift of manholes and lateral spreading in Shirakawa and Sendai. An example is shown in Figure 11.

Overturning of buildings due to impact of the tsunami mainly occurred to buildings with shallow foundation or slender piles. Soil liquefaction can allow piles to be pulled out of the soil more easily. Scouring due to fast-flowing tsunami waves around buildings also reduces ground bearing support which led to tilting of these buildings as shown in Figure 12. Coastal subsidence of more than 0.5m in numerous coastal towns and cities also caused these shorelines to suffer frequent tidal flooding.

Figure 7. Ground settlement around building

Figure 8. Sinking of building relative to surrounding

Figure 9. Tilted building due to differential settlement

Figure 10. Earthquake-induced landslide

Figure 11. Uplift of manhole and lateral spreading

Figure 12. Loss of soil bearing due to scour

3.3. Coastal defences

Two coastline types exist along the coast of Tōhoku, the rias in the north and the plains in the south of Sendai as shown in Figure 13. These different topographies have significant effects on an incoming tsunami. The shape of the river valleys in the rias coastline constraints the incoming waves and amplifies the tsunami's run-up height, but restricts the inland inundation of the waves. In contrast, the coastal plains offer lower resistance to the incoming waves which limit run-up height but allow further inland inundation of the tsunami than the rias.

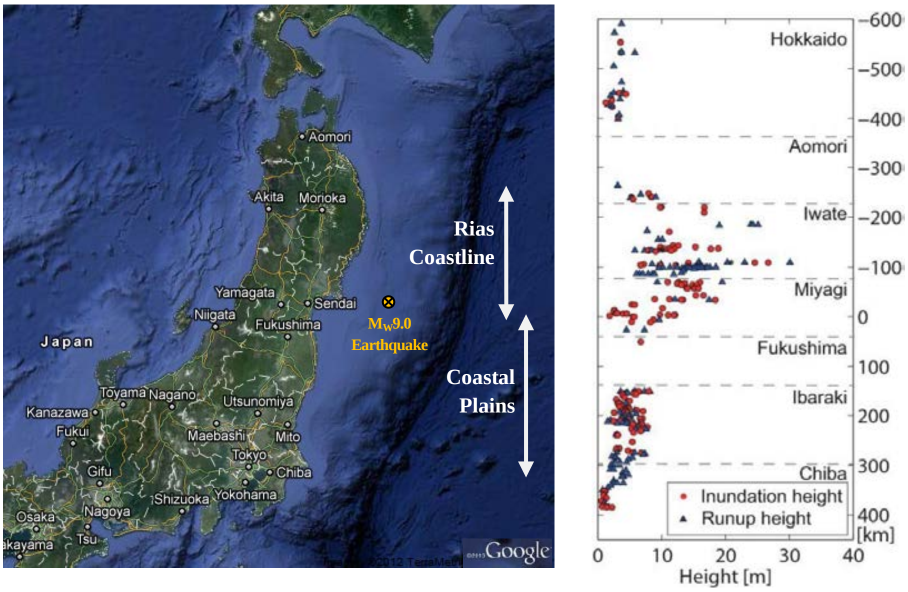

Figure 13. Types of topography with tsunami inundation and run-up heights data from JSCE (2011)

In view of the frequent occurrence of tsunami along the Tōhoku region, coastal defences have been constructed along vulnerable coastlines in Tarō, Kamaishi and Ōfunato. These locations were badly affected by previous events such as the 1896 Meiji Sanriku earthquake tsunami, the 1944 Tonankai earthquake tsunami and the 1960 Chile earthquake tsunami (MLIT, 2006). However, the design height of coastal defences based upon these historical earthquakes was considerably lower than the Tōhoku earthquake tsunami in 2011.

During the 11th March 2011 tsunami, a total of 14 major ports were affected (PIANC, 2011). Breakwaters of estimated length of 8.5km collapsed, including the deepest breakwater in the world at Kamaishi which entered the Guinness Book of Record in 2010. The 'giant' breakwater was designed to protect the port against tsunami waves typical of the 1896 Meiji-Sanriku earthquake tsunami of about 5-6m high. However, its height above the sea level was inadequate to resist the 11th March 2011 tsunami of more than 10m height (PARI, 2011a). The massive hydrostatic pressure onto the seaward side of the breakwater accompanied with scour caused by rapid flow through the 30mm gaps between blocks of the breakwater aggravated the stability of the structure (Kazama, 2011). Similarly, the entire 540m length of breakwater caissons collapsed and were left scattered in Ōfunato.

Concrete seawalls were not spared by the tsunami in various coastal areas such as Minamisanriku, Ryoishi and Tarō, the formerly proclaimed "Town of Tsunami Disaster Prevention" with seawalls resembling the Great Wall of China. In some lengths of the enormous seawall, despite the provision of 10m high seawall, the concrete sections toppled due to insufficient horizontal restraint from interlocking blocks as shown in Figure 14. Similar failures to large concrete seawalls were also observed in Minamisanriku and Ryoishi. Concrete block revetment along the beaches of Yamamoto also performed poorly (Figure 15). Sand in-fill wash-out and breaks in the lattice revetment were observed across the length of the revetment with some sections failing catastrophically due to the overtopping of the tsunami wave. Concrete revetment structures at Arahama also showed a similar failure mechanism of sand infill wash-out. Natural vegetation as a 'soft' method of tsunami protection at Rikuzentakata was also destroyed by the tsunami together with the sandy beach where the pine trees were planted (PARI, 2011b).

In spite of the widespread failures of coastal defences discussed above, large sluice gates appeared to perform much better. One great success was in the town of Fudai, owing to the insistence of the late mayor, Kotaku Wamura to construct costly floodgates spanning about 2km and 15.5m in height at the Fudai River. During the 11th March tsunami, run-up height measuring 20m was observed from water marks on the floodgate towers, which breaches the floodgates slightly (Komo News, 2011). The town suffered little damage as compared to the devastation experienced around similar coves in the Tōhoku region. The tsunami sluice gates in the southern part of Ryoishi Bay, Miyako Bay and in Tarō appeared undamaged from the locations where EEFIT was able to access. However, the sluice gates in Minamisanriku suffered severe damage.

Figure 14. Failed seawall section at Tarō

Figure 15. Sand in-fill wash-out in revetment

3.4. Vertical evacuation facilities

Apart from the coastal defences that were built along key locations of the Tōhoku coastline, the local officials had also prepared for tsunami by developing tsunami warning systems, conducting public education and evacuation drills, and designating new and/or existing buildings as vertical evacuation facilities. These preparedness strategies helped reduce fatalities in the tsunami affected towns and cities. Vertical evacuation facilities are designated by the municipal government offices according to National Government guidelines, which require a building to be reinforced concrete or steel-reinforced concrete construction and constructed after 1981. These buildings must also have a minimum height according to the estimated tsunami depth (Cabinet Office Government of Japan, 2005). Thousands of people took refuge in such facilities, which generally showed little earthquake damage and survived tsunami wave forces, debris strike and scour to fulfill the remit to provide life safety. Some vertical evacuation structures were close to being overtopped and, although all observed facilities escaped fire damage in this event, fire was shown to be an important hazard to consider for such structures.

3.5. Use of Geospatial Tools

The use of remote sensing for disaster mapping has been well-established in Japan as early as 1995 following the Hanshin-Awaji (Kobe) earthquake where remotely sensed data were used in an attempt to map the damage. This includes adopting high-resolution NHK video footage to extract still photos to map the damage using semi-automated methods (Saito, 2008). Building footprints for the entire country have been available commercially such as the NTT data and Zenrin. In this event, remote sensing proved very suitable to assess the huge extent of the inundation along the Tōhoku coastline. Similar to the initiative of using satellite imagery for disaster mapping during the Haiti earthquake in 2010, various satellites were tasked to produce images of the affected areas in Tōhoku. Aerial photographs taken from flying aircrafts were also deployed immediately after the event. The

International Charter was activated upon the request of the Cabinet Office of Japan on 11th March 2011 to allow the country to receive these satellite images free of charge to assist in the relief process. The extent of affected areas can be overlaid on maps that contain statistics data such as the usage of land, population density, number of businesses and employees in grids. Figure 16 shows an example of a tsunami damage mapping system used following the earthquake. Different data sources and assessment methodologies by institutions in Japan however showed significant discrepancies in the estimated inundation extent which led to differing estimates of building stock and population affected by the tsunami.

都道府県	市区町村	町·大字	丁目·字	地番
岩手県	下閉伊郡 山田町	境田町		10番1
岩手県	下閉伊郡 山田町	境田町		10番10
岩手県	下閉伊郡 山田町	境田町		10番11
岩手県	下閉伊郡 山田町	境田町		10番12
岩手県	下閉伊郡 山田町	境田町		10番15
岩手県	下閉伊郡 山田町	境田町		10番2
岩手県	下閉伊郡 山田町	境田町		10番3
岩手県	下閉伊郡 山田町	境田町		10番4
岩手県	下閉伊郡 山田町	境田町		10番5
岩手県	下閉伊郡 山田町	境田町		10番6
岩手県	下閉伊郡 山田町	境田町		10番9
岩手県	下閉伊郡 山田町	境田町		11番1
岩手県	下閉伊郡 山田町	境田町		11番10
岩手県	下閉伊郡 山田町	境田町		11番11
岩手県	下閉伊郡 山田町	境田町		11番13
岩手県	下閉伊郡 山田町	境田町		11番3

Figure 16. Post-tsunami aerial photograph taken by GSI (top left), same aerial photograph overlaid with Zenrin (2011) footprint dataset (middle) and list of addresses of structures recognised by SONPO (2011) to have been washed away by the tsunami (top right).

4. CONCLUSION AND RECOMMENDATIONS

It is clear that Japan had made significant efforts in their preparation against major earthquakes and tsunami. The colossus 11th March 2011 earthquake and tsunami event is one event which was beyond their expectation. Lessons have been learnt from this catastrophic event and efforts by disaster mitigation institutions globally are currently endeavouring to ensure similar events would cause less damage in the near future. EEFIT recommends the following key directions to be undertaken:

- Seismology
  - Re-evaluating subduction earthquakes and tsunami hazard assessment globally after experiences from the M_w 9.3 Indian Ocean earthquake and tsunami in 2004 and this M_w 9.0 Tōhoku earthquake and tsunami.
- Structural
  - Assessing need for retrofitting of buildings built before 1981, when significant revision of building code was implemented.
- Geotechnical
  - Re-evaluating geotechnical design against landslide, soil liquefaction and ground settlement.
- Tsunami
  - Improving prediction of tsunami heights from numerical modelling.
  - Updating hazard maps with better estimates of likely tsunami inundation extent.
  - Re-assessing design and provision of coastal defences, location of evacuation centres, minimum height of vertical evacuation structures and their protection against fire damage.
  - Considering tsunami induced scour and overturning of buildings with shallow pile foundation.

- Geospatial Tools
    - Investigating causes of discrepancies between different remote sensing data sources and methodologies in estimating building damage and inundation extent in post-disaster.

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REFERENCES

Ammon, C.J., Lay, T., Kanaore, H. and Cleveland, M. (2011). A rupture model of the great 2011 Tohoku earthquake. *Earth Planets Space* **63**, 693-696.

Cabinet Office Government of Japan (2005). Guidelines Pertaining to Vertical Evacuation Buildings (In Japanese). [Online] <http://www.bousai.go.jp/oshirase/h17/tsunami_hinan.html> [Accessed on 10 March 2012].

Earthquake Engineering Field Investigation Team, EEFIT (1997). The Hyogo-Ken Nanbu (Kobe) Earthquake of 17 January 1995: Field Report, The Institution of Structural Engineers, U.K. [Online] <http://www.istructe.org/resources-centre/technical-topic-areas/eefit/eefit-reports> [Accessed on 30 June 2011]

Earthquake Engineering Field Investigation Team, EEFIT (2009). The Padang, Sumatra – Indonesia Earthquake of 30 September 2009: Field Report, The Institution of Structural Engineers, U.K. [Online] <http://www.istructe.org/resources-centre/technical-topic-areas/eefit/eefit-reports> [Accessed on 30 June 2011]

Earthquake Engineering Field Investigation Team, EEFIT (2011). The M_w9.0 Tōhoku Earthquake and Tsunami of 11th March 2011: Field Report, The Institution of Structural Engineers, U.K. [Online] <http://www.istructe.org/resources-centre/technical-topic-areas/eefit/eefit-reports> [Accessed on 15 January 2012].

Geotechnical Extreme Events Reconnaissance Association, GEER (2011). Geotechnical Quick Report on the Kanto Plain Region during the March 11, 2011, Off Pacific Coast of Tōhoku Earthquake, Japan. [Online] <http://www.geerassociation.org/GEER_Post%20EQ%20Reports/Tōhoku_Japan_2011/Cover_Tōhoku_2011> [Accessed on 29 Jun 2011].

Fraser, S., Raby, A., Pomonis, A., Goda, K., Chian, S.C., Macabuag, J., Offord, M., Saito, K. and Sammonds, P. (2012). Tsunami damage to coastal defences and buildings in the March 11th 2011 M_w9.0 Great East Japan Earthquake. *Bulletin of Earthquake Engineering*. doi:10.1007/s10518-012-9348-9

Government of Japan, GoJ (2011). 22 July 2011 - Reconstruction of quake-hit areas could cost gov't 23 tn yen. [Online] <http://mdn.mainichi.jp/mdnnews/news/20110722p2g00m0dm023000c> [Accessed on 22 July 2011].

Japanese Society of Civil Engineers, JSCE (2011). Joint ASCE/JSCE Tōhoku Tsunami Survey. [Online] <http://mceer.buffalo.edu/quakesummit2011/program/presentations/19_c-Robertson.pdf> [Accessed 20 Feb 2012].

Kazama, M. (2011). The 2011 off the Pacific Coast of Tōhoku Earthquake – After two months. *Fourteenth Asian Regional Conference on Soil Mechanics and Geotechnical Engineering*.

Komo News (2011). 13 May 2011 – How one Japanese village defied the tsunami. [Online] <http://www.komonews.com/news/national/121775754.html> [Accessed on 27 July 2011].

Midorikawa, M., Iiba, M. and Koshika, N. (2004). Seismic Performance Evaluation of Seismically Isolated Buildings Introduced to the Building Code of Japan. *Journal of Pressure Vessel Technology* **126:1**, 18-24.

Ministry of Land, Infrastructure, Transport, and Tourism, MLIT (2006). Ports and Harbours in Japan. [Online] <http://www.mlit.go.jp/english/2006/k_port_and_harbors_bureau/17_p_and_h/index.html> [Accessed on 27 July 2011].

Ministry of Land, Infrastructure, Transport, and Tourism, MLIT (2011). Great East Japan earthquake (in Japanese). [Online] <http://www.mlit.go.jp/common/000139083.pdf> [Accessed on 30 June 2011].

National Police Agency of Japan, NPA (2012). Damage Situation and Police Countermeasure, 20 February 2012. [Online] <http://www.npa.go.jp/archive/keibi/biki/higaijokyo_e.pdf> [Accessed on 21 February 2012].

Port and Airport Research Institute, PARI (2011a). Executive Summary of Urgent Field Survey of Earthquake and Tsunami Disasters March 25, 2011. [Online] <http://www.pari.go.jp/en/eq2011/20110325.html> [Accessed 27 July 2011].

Port and Airport Research Institute, PARI (2011b). An English Abstract of the Technical Note of Port and Air Port Research Institute, No. 1231, April 28, 2011. Urgent Survey for 2011 Great East Japan Earthquake and Tsunami Disaster in Ports and Coasts – Part I (Tsunami). [Online] <http://www.pari.go.jp/en/files/3653/460607839.pdf> [Accessed on 27 July 2011].

Permanent International Commission for Navigation Congresses, PIANC (2011). Message from Tadahiko Yagyu, Secretary General of PIANC Japan. [Online] <http://www.pianc.org/downloads/sailingahead/Sailing%20Ahead%20April%202011/Japan%20Earthquake.pdf> [Accessed on 27 July 2011].

Reuters (2011). S&P Cuts Japan Credit Outlook on Quake Concerns. [Online] <http://www.huffingtonpost.com/2011/04/27/sp-changes-japan-economic-outlook_n_854255> [Accessed on 22 July 2011].

Saito, K. (2008). Use of High-Resolution Optical Satellite Images for Post-earthquake Damage Assessment. PhD Thesis, Department of Architecture, University of Cambridge, U.K.

General Insurance Association of Japan, SONPO (2011). Addresses certified for “Total Loss Area” (In Japanese). [Online] <http://www.sonpo.or.jp/news/2011quake/area.html> [Accessed on 7 July 2011].

Takahashi, A. (2011). Preliminary Report on the 2011 off the Pacific Coast of Tōhoku Earthquake: Liquefaction Induced Damage on Leeves and Embankment. [Online] <http://eqclearinghouse.cuee.titech.ac.jp/groups/Tōhoku2011/wiki/2dfca/Levees_and_Lifelines.html> [Accessed on 29 Jun 2011].

Tokimatsu, K., Tamura, S., Suzuki, H. and Katsumata, K. (2011). Quick Report on Geotechnical Problems in the 2011 Tōhoku Pacific Ocean Earthquake [In Japanese]. [Online] <http://eqclearinghouse.cuee.titech.ac.jp/groups/Tōhoku2011/wiki/01411/Geohazard.html> [Accessed on 29 Jun 2011].

World Bank (2011). East Asia and Pacific Economic Update 2011, Vol. 1, March 21, 2011: The recent earthquake and tsunami in Japan: Implications for East Asia. [Online] <http://siteresources.worldbank.org/INTEAPHALFYEARLYUPDATE/Resources/550192-1300567391916/EAP_Update_March2011_japan.pdf> [Accessed on 20 December 2011].

Zenrin (2011). Supporting the reconstruction work by comparing the image map data and aerial photo of the house after the earthquake (In Japanese). [Online] <http://www.zenrin.co.jp/news/110415.html> [Accessed on 7 July 2011].