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MASSIVE DESTRUCTION CAUSED BY THE MARCH 11TH, 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE AND ITS IMPACT ON EARTHQUAKE ENGINEERING PRACTICE

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ABSTRACT

The March 11th, 2011 Off the Pacific Coast of Tohoku Earthquake was the fifth-largest in the world since 1900, and the biggest instrumentally recorded earthquake Japan has ever been shaken by. The extent of the damage caused by the tsunami that followed the quake was more extraordinary paling the shaking damage. Looking back over the last year, not a small number of cause-and-effect links remain to be defined yet. Moreover making unfair or misleading selections from or arrangement of facts can occur all the more because the damage and losses were extensive and complicated. This summary report overviews physical aspect of the massive destruction that the earthquake and tsunami brought based upon as many original and official survey/ investigation reports as possible, and discusses the role of earthquake engineering experts.

Key words: Great East Japan Earthquake, Tsunami, Wrong Messaging, Role of Engineers.

Introduction

On March 11th, 2011, an inter-plate earthquake of moment magnitude Mw 9.0 occurred off the Pacific coast of Tohoku, Honshu Island, Japan, at 14:46 local time (05:46 UTC.). The Japan Meteorological Agency (JMA) named this earthquake "The 2011 off the Pacific coast of Tohoku Earthquake [1]," which is more generally known

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by the name of “The Great East Japan Earthquake.” The earthquake has stimulated seismic activities over the entire eastern Japan. Japan has experienced over 600 aftershocks over M5.0 since the March 11th earthquake until today (March 19th, 2012) with about 98 being over 6.0 M and at least six over 7.0 M [2]. Shaking damages due to these ground motions were significant, but they were paled by the overwhelming damage caused by a massive tsunami and the disaster at the Fukushima Daiichi Nuclear Power Plant of the Tokyo Electric Power Company (TEPCO), which disaster was a series of equipment failures, nuclear meltdowns, and releases of radioactive materials that followed the quake and tsunami [3]. With prominent coverage given by news media exclusively to the tsunami, the nuclear accident and sometimes liquefactions in the Tokyo Bay Area, Landslide Disaster Division of the National Institute of Earth Science and Disaster Prevention (NIED) put up on its website an open-to-public request for information of landslides because the information of earthquake-induced landslides had been so scanty that the division were making little progress in mapping landslides [4].

Accumulation of errors resulting from a person to person whispering spreading through lines of people, i.e. as in the broken telephone game, can occur even in the line of experts. Looking back on the past year, this summary report overviews physical aspect of the massive destruction that the earthquake and tsunami brought based upon as many original and official survey/ investigation reports as possible, and then discusses the role of earthquake engineering experts.

Overview of the Quake and Tsunami

The quake was the fifth-largest in the world since 1900, and the biggest instrumentally recorded earthquake Japan has ever been shaken by, with its epicenter located approximately 100 km off the coast of Miyagi at a depth of 22 km. According to the Japan Meteorological Agency (JMA [1]), frequent aftershocks have been observed over a 200 km wide and 500 km long zone on the plate boundary where the Pacific Ocean Plate is subducting beneath the North American Plate at a rate of 10 cm/year. Kairei, a vessel for deep-sea floor surveys of the Japan Agency for Marin-Earth Science (JAMSTEC), has conducted a multi-channel reflection survey across the Japan Trench, an oceanic trench of about 7500 to 7600 m deep around the surveyed area.

By comparing the observed sea bottom image with the one before the earthquake, JAMSTEC showed its official view that the deepest sea bottom on the North American Plate side moved 50 m sideways in ESE direction, and 7 m upward [5]. The large tectonic displacements were also observed inland at all stations of GEONET (GPS Earth Observation Network) in the northeastern Honshu. GEONET is a Japanese nationwide network of a total of 1,200 GPS permanent stations operated by the Geographical Survey Institute.

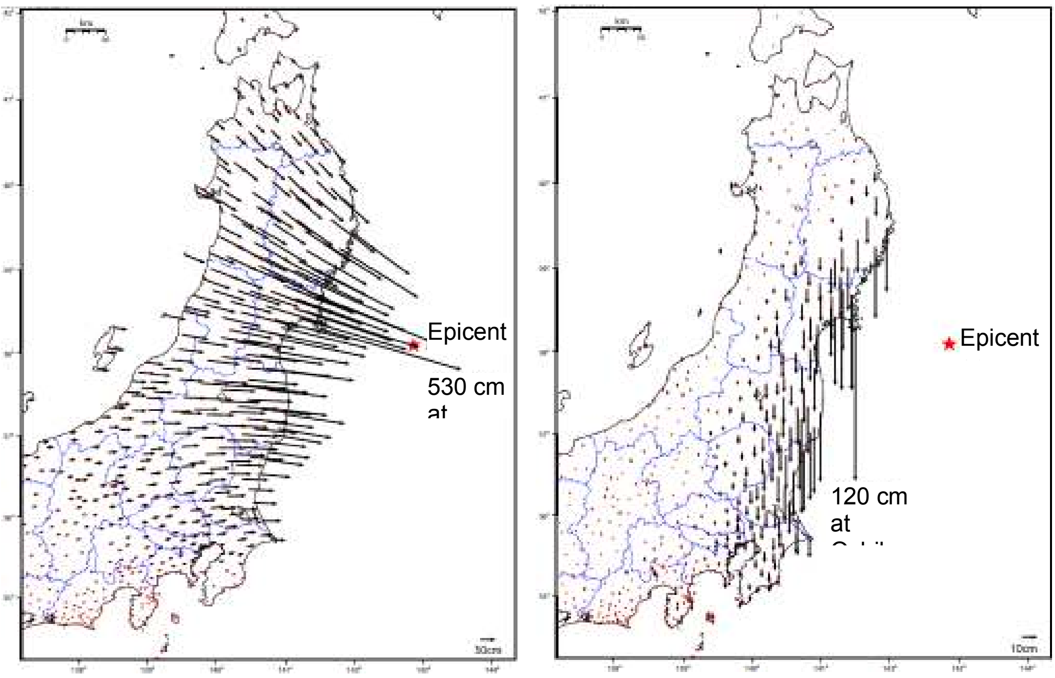

Figure 1 : Displacement vectors at the GEONET stations obtained by comparing data for 2011/03/01 21:00 - 2011/03/09 21:00 and for 2011/03/11 18:00 - 2011/03/11 21:00 [6].

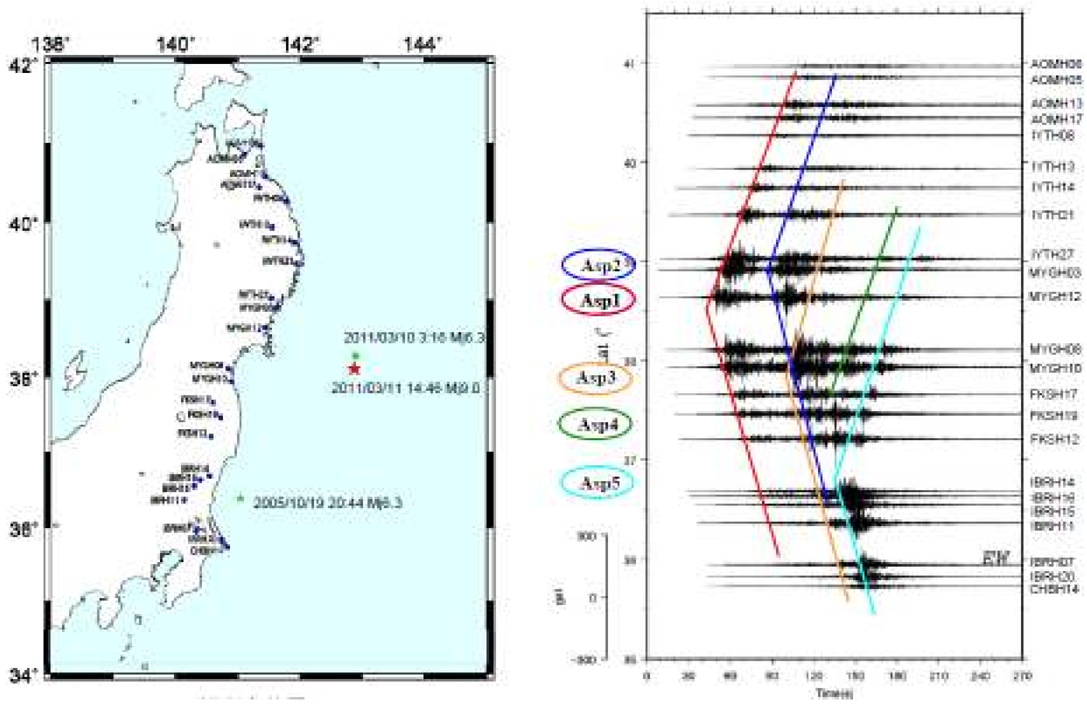

Figure 2 : 0.1 to 10 Hz band-pass filtered accelerograms from a north-south trending row of 23 stations of KIK-net strong motion network along the Pacific coast of east Japan [7].

Fig. 1 showing the displacement vectors at the GEONET stations indicates that the northeastern Honshu, which had been slowly and continuously moving west, has rebounded all at once [6]. Fig. 2 shows 0.1 to 10 Hz band-pass filtered accelerograms from a north-south trending row of 23 stations of KIK-net strong motion network along the Pacific coast of east Japan [7]. The figure shows that the rupture front traveled away from the epicenter, triggering sub-events at several barriers and asperities, and the entire rupturing process took longer than 1 minute. As a consequence, observed seismic motions exhibited long duration times reaching several minutes. The long-continuing shakes are considered to have been responsible for buildups of soil deformations. Among many geotechnical problems, soil liquefactions along the Tokyo Bay area, a home to millions of people as well as the port/factory zone to support urban lives, emerged as one of the most serious economic and social impacts [8].

The overwhelming devastations were due to tsunami waves. According to the reports by the Coastal Engineering Committee of JSCE, (Fig.3, [9]), the Japan Weather Association (JWA) [10], and the analysis of aerial photographs by the Geospatial Information Authority of Japan (GIA) [11], indented coast line was responsible for amplifying tsunami waves such that the maximum run-up height of 40.4 m was reached near Miyako. At Rikuzen-Takada and along the Kitakami River, tsunami waves, 9 to 10 m and 5 m in average above the sea level, surged 7 km and 13 km inland, respectively. Tsunami also flooded up to 5 km inland over remarkably flat terrains of Sendai plain with the maximum inundation height of 19.5 m. Due to the tectonic subsidence observed all along the Pacific coastline, a total area of 561 km2 in 64 municipalities has remained underwater.

The Japan Meteorological Agency (JMA), the sole authority to issue domestic tsunami warnings/advisories to the public in Japan, has organized an exploratory Committee for discussing the problems of its early warning system and seeking new systems to better assess giant tsunamis [12]. JMA initially estimated the magnitude of the earthquake to be 7.9 based on hypocentral parameters such as locations, depths and magnitudes, and the tsunami-simulation database covering more than one hundred thousand examples. The system actually worked out successfully as far as reducing the time for a quick warning is concerned, and the first warning was issued at 14:49 JST, namely three minutes after the earthquake. However the inaccurate early assessment of its magnitude led to huge underestimates of tsunami heights such as 3 m, 6 m and 3 m in Iwate, Miyagi and Fukushima Prefectures, respectively. For a more precise estimate of the magnitude, JMA needed to analyze signals from broadband seismographs. However most of the broadband seismographs went off the scale. JMA raised, at the later time of 15:14 JST, their estimates to 6 m, 10 m and 6 m in Iwate, Miyagi and Fukushima Prefectures, respectively, getting a signal showing a sudden sea-level increase at a GPS buoy off the coast of Kamaishi. With further detailed data from buoys and tide gauges, JMA raised again tsunami-warning grades and widened warning areas at 15:30 JST, which warning was unfortunately not in time for the coastal areas of Sanriku. Moreover the warning did not arrive at areas where the electric power went out.

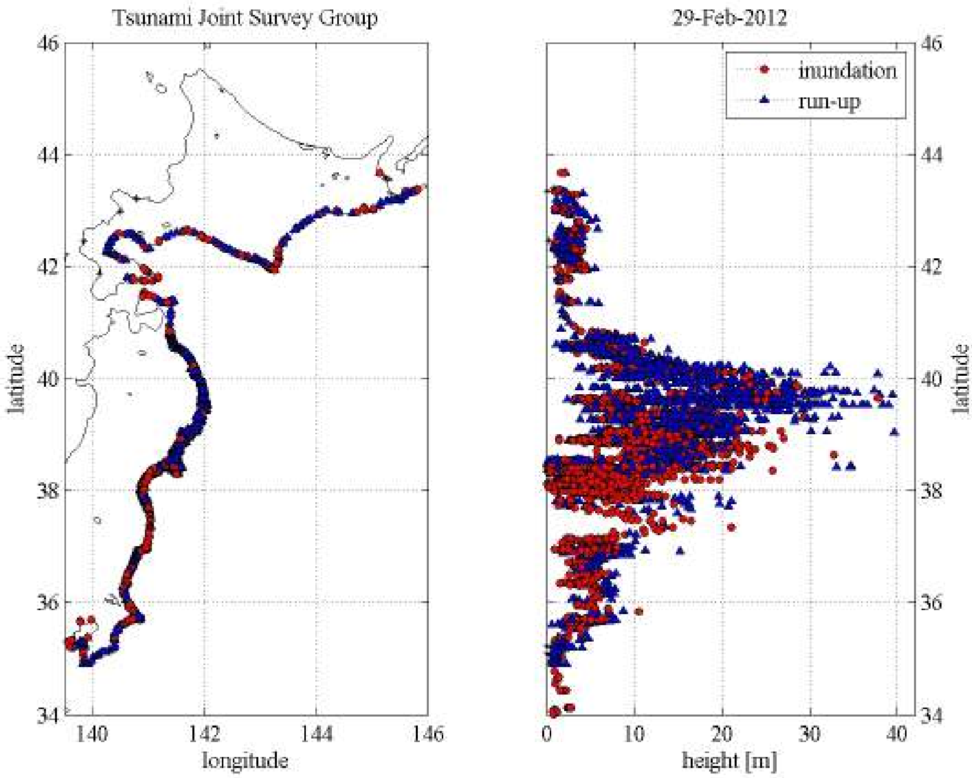

Figure 3 : Run-up and inundation heights of tsunami caused by the March 11th, 2011 Off the Coast of Tohoku Earthquake [9]

Fig. 3, showing both tsunami run-up and inundation heights, has an about 60 km stretch of the coastline completely lacking data because the government set up a restricted area within a 30-kilometer radius of the disabled Fukushima Daiichi Nuclear Power Station (Fukushima I Station hereafter). Although all off-site power was lost when the earthquake occurred, the automatic systems at Fukushima I successfully inserted all the control rods into its three operational reactors upon detection of the shakes reaching 0.52 to 0.56 g, and all available emergency diesel generator power systems were in operation, as designed [13]. However Tower No. 27 of the Yonomori transmission line, one of the transmission lines through which the nuclear power plant receives power from Shin Fukushima Substation, has been taken out by a coherent soil mass detached from an embankment of the Fukushima I station, and drawing transmission cables, the tower fell down to the ground. Since the station received no power through this line about two minutes after the quake hit the station, TEPCO reported to the Ministry of Economy, Trade and Industry its official view that the landslide took place about two minutes after the quake [14]. The other lines also malfunctioned due to short-circuit of transmission cables etc. The tsunami then followed the shake about 50 minutes later and overtopped tsunami walls at the

Fukushima I station, which walls were only designed to withstand waves of a maximum of 5.7 m high. The inundation heights of OP+11.5 to 15.5 m and OP+13.5 to 14.5 m were reached in the yards for the reactors No. 1 through 4 and No. 5 to 6, respectively. As a consequence, the tsunami stopped Fukushima I station's backup diesel generators, causing a station blackout. The subsequent lack of cooling led to explosions and partial meltdowns at the Fukushima I facility [15], [16]. As has been mentioned, the Japanese Government advised everyone within a 20 km radius of Fukushima I station and a 10 km radius of Fukushima II to evacuate, and those within a 20 to 30 km radius of Fukushima I station to stay indoors. Later on March 25th, those within 20 to 30 km were asked to evacuate. The populations within 20 km and 20 to 30 km radii of Fukushima I are estimated to be about 77,000 and 59,000, respectively [17].

The National Police Agency data put up on the web on March 12th, 2012 shows the following [18]:

(1) Human suffering
    Confirmed deaths: 15,854
    Missing: 3,155
    Injured: 26,992

(2) Damage to buildings and houses
    Complete collapse: 129,107
    Half collapse: 254,139
    Burnt down, and partially burnt down: 281
    Inundated above floor level: 20,427
    Inundated below floor level: 15,503
    Others (garages, warehouses, chicken coops, etc): 57,268

(3) Damage to infrastructures
    Roads: 3,918
    Bridges: 78
    Slope failures: 205

The figures above include those from aftershocks and induced earthquakes such as the April 7th, 2011 Off the Coast of Miyagi Earthquake (M7.4), the April 11th, 2011 Fukushima Prefecture Hamadori Earthquake (M7.0). Meanwhile, it is noted that thorough investigations have not been done yet in the restricted area of the radiation exposure risk around the Fukushima I station. An autopsy report on April 11th, 2011 states that 12,143 dead bodies, namely 92.4% of 13,135 examined dead bodies, were found drowned, 4.4% crushed, 1.1% burnt and that 1.1% perished for unknown reasons [19]. Victims aged 60 or older accounted for 65.2% of the deaths, with 46% of the total victims being in their 70s or older, indicating that tsunami waves engulfed areas with problems of aging.

The cabinet office announced on June 24th, 2011 its estimate of the earthquake and tsunami damage to be 1,690 billion JPY in total [20]. Out of the total, 10,400 billion JPY were for buildings and houses, 1,300 billion JPY for lifelines, 2,200 billion JPY for civil infrastructures, 1,900 billion JPY for forestry and fisheries-related damages, and 1,100 billion JPY for others. These figures do not include the damages resulting from the accident at the Fukushima I station, and the accident will surely have massive impacts on Japan beyond the direct damage. It will take several decades to clean up the accident at the Fukushima I station. The Japan Center for Economic Research estimated that if existing nuclear power plants shut down, the impact which would last decades or more, would reach 5.7 to 20 trillion JPY [21].

Actions taken by JSCE, MLIT and Municipalities

Three academic societies of engineering, the Japan Society of Civil Engineers (JSCE), the Japanese Geotechnical Society (JGS) and the City Planning Institute of Japan (CPIJ), issued in the names of their presidents, an emergency statement on March 23rd, 12 days after the East Japan Earthquake and Tsunami of March 11th, 2011 [22]. To quote some lines of it: "The first thing to do is to collect and accumulate exact information of the destructions caused by this quake and tsunami for reevaluating the progress which we had made for mitigating potential impact of natural disasters. Second actions shall be to propose effective measures for urgent and long-lasting problems of rehabilitations and national land conservations, and risk management issues, given a growing threat of scenario earthquakes such as Tonankai and Nankai". The statement also had a line saying "We shall not use the phrase "beyond the scope of assumption" as an excuse." This line implicitly highlights the importance to discuss what-if scenarios beyond our areas of specialty. Based on this statement, JSCE organized an ad-hoc liaison and a coordination committee and set up several task forces for examining proposals toward rational rehabilitation and strategies for disaster preparedness. Their recommendations were released at JSCE 2011 Great East Japan Earthquake Commemorative Symposium, on March 4th and 5th, 2012 [23].

Tohoku Regional Bureau of the Ministry of Land, Infrastructure and Transport (MLIT) has immediately started up a task force headed by the director general of the bureau [24]. Given a freehand by the Minister of MLIT for coping with any problems beyond its authority, the taskforce first collected information to get the whole picture of the devastation. It was 37 min after the quake and about 10 min before the tsunami reached the Sendai Airport that a helicopter of the Tohoku Regional Bureau took off from the airport. Later on, three more helicopters from other regional bureaus of MLIT joined the operation. Experts and officers were quickly dispatched by land via every available transportation means to the devastated coastal areas. They were carrying portable satellite phones, and these phones, as a result, allowed mayors and top officials at isolated city halls to communicate with prefectural governments. Secondly, the taskforce conducted a quick road clearing operation, in which pre-selected contractors and reduced "red tape" allowed for a rapid response for debris removal and reconstruction of damaged roads. Tohoku region has a long stretch of coastal area and inland basins. Major traffic arteries run along these two belts connecting major cities. Since the artery along the Pacific Coast was seriously devastated, restoration of road network was made such that the inland longitudinal artery (Tohoku expressway and National Route No. 4) would shoot 16 transverse lines leading to coastal cities. The recovered road network has gotten its name "Comb" from its resemblance in shape with a back (artery) and teeth (transverse roads). Road clearing operation in areas which were still on tsunami alert has been done taking care of occasionally found dead bodies and assuming some RC buildings along the roads to be temporary tsunami shelters for clearing workmen. 15 out of the planned clearings for 16 transverse routes, excluding the one leading to the restricted radioactively-contaminated area, were completed by March 15th. The operation was then followed by clearings of coast Route No. 45, and 97% of the planned clearing operation was completed by March 18th.

The taskforce started removing debris from three major hub ports, Miyako, Kamaishi and Sendai-Shiogama, after all tsunami alerts were called off on March 14th. These ports became operational from March 15th to 17th. The taskforce also collected all available pump trucks for draining runways at the Sendai International Airport, which has tectonically subsided by 15 cm in average, stopping water of tsunami. Something that should not be forgotten regarding the clearing operation of the Sendai Airport is that the United States Armed Forces mobilized to aid Japan's disaster relief efforts and launched 'Operation Tomodachi', which literally means 'Operation Friend'. American Troops, after parachuting down near the airport on March 16th, cleared debris with Japanese troops of the Self Defense Forces such that a 1500 m stretch of a runway was opened in three hours for a US megacarrier, C130. As for permanent measures, the Ministry of Land, Infrastructure and Transport (MLIT) and affected local autonomous bodies came to an essential agreement for reconstructing the tsunami walls. The agreement states that a new tsunami wall shall be designed to withstand tsunamis with the recurring time period of several tens to a hundred and several tens of years (Fig. 4, [25]).

Both Iwate and Miyagi Prefectures Governments have drawn up their rehabilitation plan documents in June and September, 2011, respectively. The document of Iwate Prefecture offers the following three workable plans (Fig. 5) for tsunami-engulfed coastal municipalities [26]:

(1) Relocating an entire town to terraces for perfect protection of lives and properties,

(2) Allowing tsunami waves to surge across planned tsunami control reservoirs for perfect protection of lives and partial protection of properties, and

(3) Constructing multiple barriers such as road and railway embankments in addition to the sea-frontal tsunami wall, and relocating dwellings, governmental, industrial

and commercial facilities etc. in order of priority for perfect protection of lives and partial protection of properties.

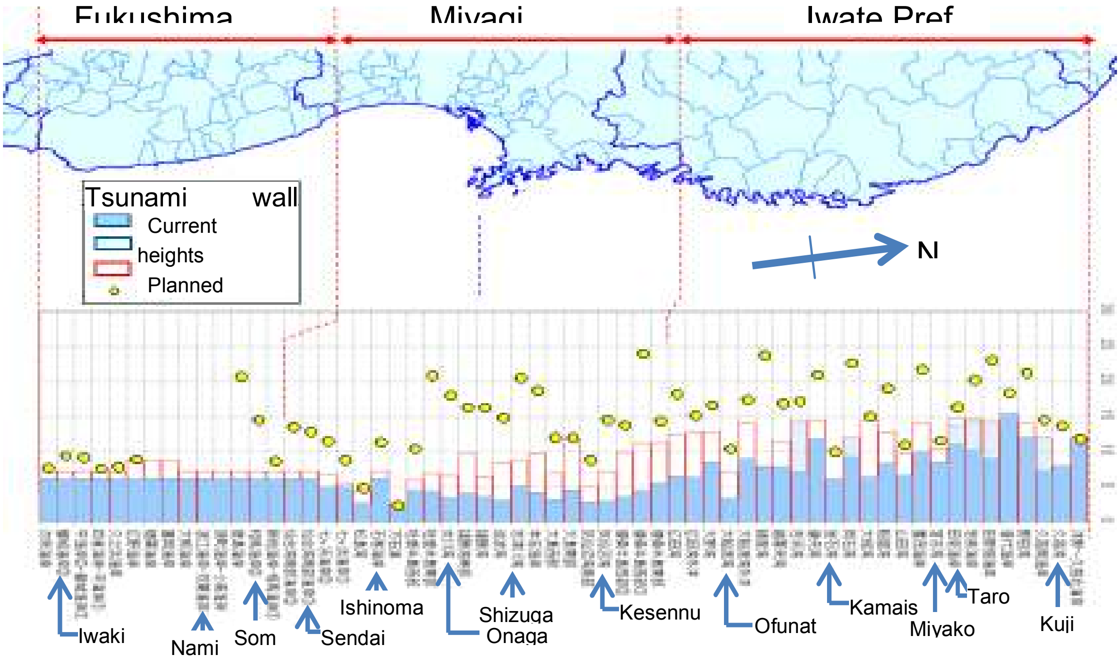

Figure 4 : Current, planned and newly agreed tsunami wall heights along the Pacific coast [25]

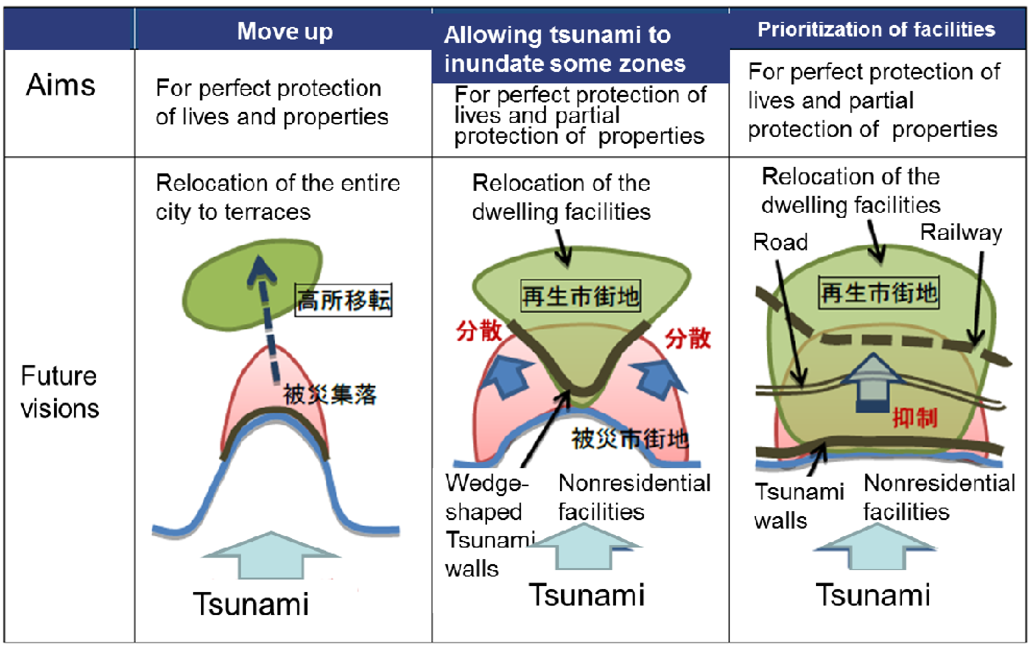

Figure 5 : Three types of proposals appeared in the Master Plan for rehabilitation of tsunami-engulfed coastal municipalities, Iwate Prefecture [26]

Future Problems and Summary

The above-mentioned plans for rehabilitations retain reminders of the past rehabilitation plans for the same coastal areas devastated by the tsunami waves caused by the March 2nd 1933 Sanriku Earthquake. The city planning division of the Minister's secretariat at the Ministry of Internal Affairs mapped out strategies for rehabilitating devastated coastal cities, by tracing tsunami run-up lines and possible relocation plans on surfaces of tracing papers which are overlaid on all aerial photographs covering 29 and 9 municipalities along the Sanriku ria coast and the Sendai Bay area, respectively (Fig. 6, [27]).

The drawings of its rehabilitation plans include the same three ideas that appeared in the Iwate Prefecture's rehabilitation plan document of 2011. There is the following short mention on the sheet of tracing paper for Otsuchi Town:

"The tsunami of 1933, which was 3m high in average above the sea level at Otsuchi Town, was destructive with 222 dwellings washed away and 135 inundated, and yet the relocation of the entire town will be very difficult because the town had been one of the local cores of economy.

Therefore the area of the city in between Otsuchi River and Kozuchi River should be planned to be a tsunami control reservoir".

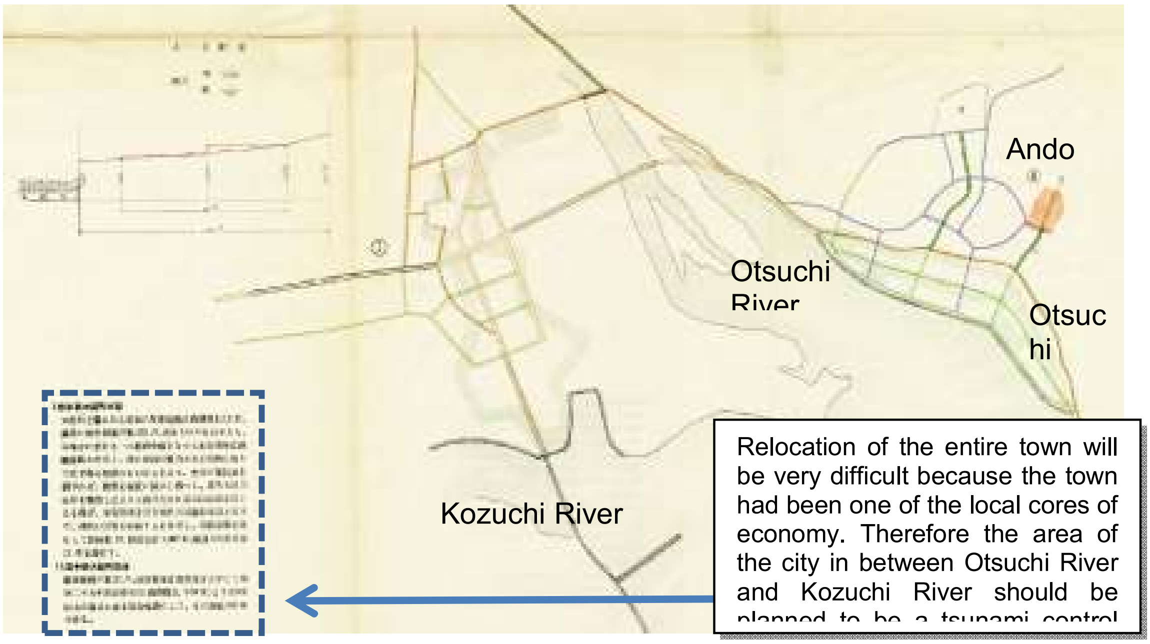

Figure 6 : Otsuchi engulfed by the tsunami caused by the 1933 Sanriku Earthquake, and its recovery plan developed by Minister's secretariat at the Ministry of Internal Affairs [27]

The comment goes on to the following lines: "20 dwellings on a terrace of Ando, north of Otsuchi Town, were relocated immediately after the tsunami caused by the June 15th 1896 Meiji Sanriku Earthquake. The terrace is about 3100 m2 large in area and 8m high above the high tide level, and thus survived the tsunami this time". An aerial photograph of Otsuchi taken in 1946 by the US Army [28] shows that the area between the two rivers had been open as it was planned. However there was a rapid urbanization in this area during the high economic growth period, and the area was completely destroyed in the tsunami of 2011.

Fig. 7 shows the latest plan for reconstructing Otsuchi prepared by the Council for rehabilitating Otsuchi Town [29]. With the green space allocated between the two rivers, the plan seems to "recycle" the very essence of the plan developed in 1934 by the city planning division of the Minister's secretariat at the Ministry of Internal Affairs.

The above example shows that good ideas can be dismissed in the long haul reflecting the necessity of the time, and thus it is really difficult to convey what we experienced to the future generations. Accumulation of errors, resulting from a person to person whispering spreading through a line of people, i.e. as in the broken telephone game, can occur even in the line of experts.

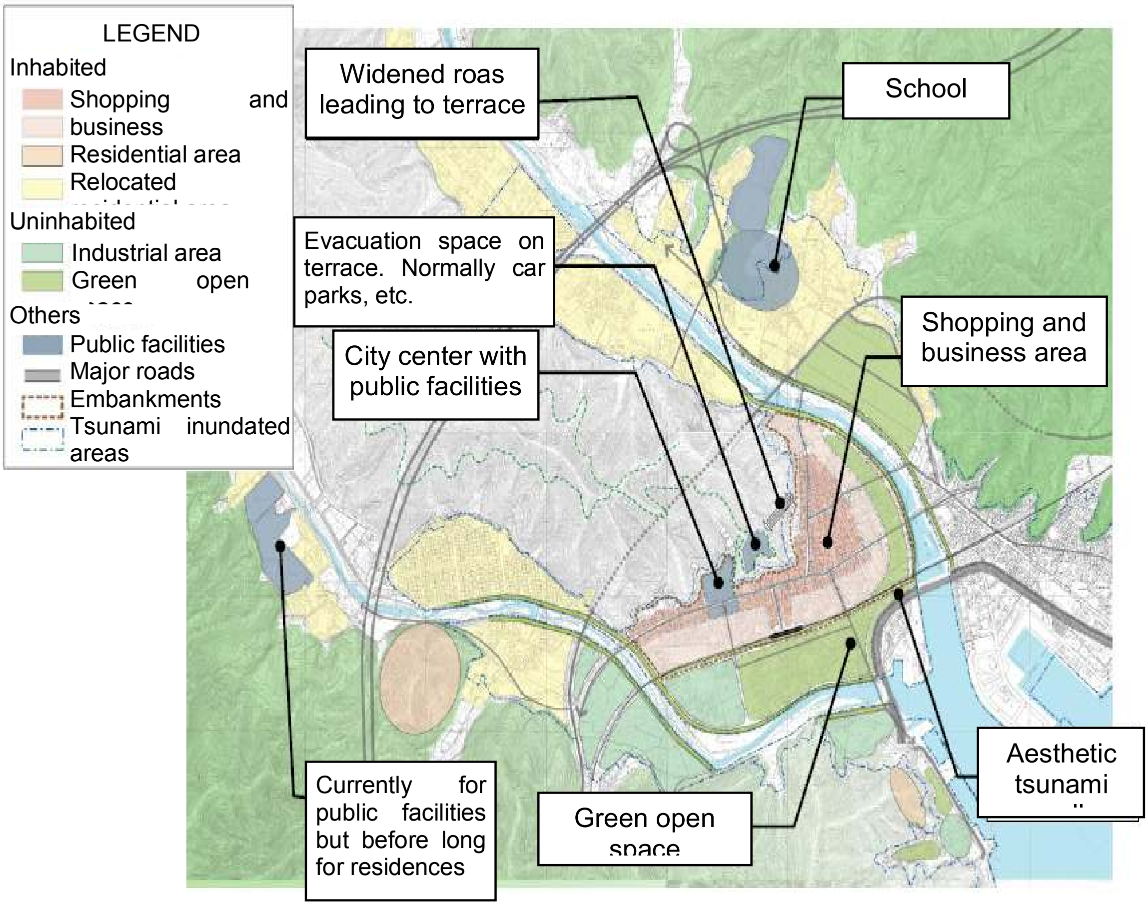

Figure 7 : Reconstruction plan of Otsuchi prepared by the Council for rehabilitating Otsuchi [29]

It had been long believed that the death toll in the 1923 Kanto Earthquake was about 142,000 until Muroi and Takemura [30] found that there was an overlap in counting deaths in two major sets of statistical data, and the number of confirmed deaths fell down to 105,385. One of the most important missions at this moment for experts in academic fields will be to make our best efforts to gather credible information of the real devastations caused by the March 11th Earthquake and Tsunami, and then leave precise reports based on credible information. We have a long way to go.

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