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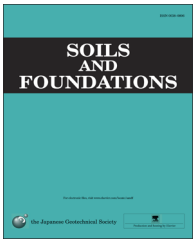

Damage to coastal structures

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Abstract

On March 11, 2011, the largest earthquake ever recorded in Japan struck off the coast of the Tohoku region of the country, and was subsequently named the 2011 off the Pacific coast of Tohoku Earthquake by the Japan Metrological Agency. The M_w 9.0 earthquake generated strong motions that affected the island of Honshu from Tokyo Bay to the northern extent of the island, and induced a series of tsunamis that devastated coastal communities throughout the region. Significant aftershocks ($M_w > 7$) were experienced that further contributed to damage in the coastal Tohoku region during emergency response and recovery efforts. This paper summarizes the findings of the Port and Airport Research Institute (PARI) research team as it investigated coastal structures along approximately 600 km of coastline as well as the team's follow-up experiments and analyses. Two characteristics of the ground motion observed were the long duration and the high-frequency component. For this reason, the degree of damage caused to coastal facilities by the ground motion was relatively small. The wide-ranging investigation by the PARI team facilitated the interpretation of damage patterns across the entire region affected by the earthquake, with a primary goal of distinguishing damage to coastal structures resulting from strong ground shaking and secondary effects (such as liquefaction, ground failures, and settlement) from that caused by the subsequent and significant tsunami inundation.

Keywords: The 2011 off the Pacific coast of Tohoku Earthquake; Tsunami; Port facilities; Coastal structures

1. Introduction

On March 11, 2011, the largest earthquake ever recorded in Japan struck off the coast of the Tohoku region of the country, and was subsequently named the 2011 off the Pacific coast of Tohoku Earthquake by the Japan Metrological Agency. The M_w 9.0 earthquake generated strong motions that affected the island of Honshu from Tokyo Bay to the northern extent of the island, and induced a series of tsunamis that devastated coastal communities throughout the region. Significant aftershocks ($M_w > 7$) were experienced that further contributed to damage in the coastal Tohoku region during emergency response and recovery efforts. This paper summarizes the findings of the Port and Airport Research Institute (PARI) research team as it investigated coastal structures along approximately 600 km of coastline. The wide-ranging investigation by the PARI team facilitated the interpretation of damage patterns across the entire region affected by the earthquake, with a primary goal of distinguishing damage to coastal structures resulting from strong ground shaking and secondary effects (such as liquefaction, ground failures, and settlement) from that caused by subsequent and significant tsunami inundation.

In many cases, the condition of structures examined at the time of our investigation showed a combination of effects

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resulting from both the earthquake and the subsequent tsunami, and a determination of the sequence of damage and relative influence of seismic and tsunami loading was not possible in the field. These suppositions are based on the collective engineering evaluation of the team members, tempered by first-hand experience at coastal structures following earthquakes worldwide, and a considerable amount of effort involved in making analyses of case studies (forensic investigations) of many such events. Many of the interpretations of failure modes provided in this paper are opinions that will be refined with time as more data become available at key sites. The findings and recommendations provided in this initial report are intended to initiate discussions within the port engineering community, foster applied research efforts, and ultimately lead to enhanced knowledge and best practices.

2. Observations of strong ground motions and tsunami caused by the 2011 off the Pacific coast of Tohoku Earthquake

2.1. Strong ground motions observed in coastal areas and their implications

Strong ground motions caused by the 2011 off the Pacific coast of Tohoku Earthquake were observed by nationwide strong-motion networks such as K-NET (Kinoshita, 1998) and KiK-net (Aoi et al., 2000), as well as by Strong-Motion Earthquake Observation in Japanese Ports (e.g., Nozu and Wakai, 2011a). Fig. 1 shows the acceleration time histories observed at four representative strong-motion stations along the coast of Tohoku and Kanto district during the 2011 off the Pacific coast of Tohoku Earthquake. In the figure, Kamaishi-G, Sendai-G, and Onahama-ji-G are stations in the Strong-Motion Earthquake Observation in Japanese Ports located at Kamaishi, Sendai, and Onahama ports, respectively. IBR007 is a station for K-NET. All the records were obtained at the ground surface. As already pointed out by many researchers (e.g., Kurahashi and Irikura, 2011; Goto and Morikawa, 2012), the acceleration time histories in Iwate and Miyagi Prefectures (represented by Kamaishi-G and Sendai-G) were characterized by "two wave packets" indicating contributions from at least two subevents. Peak ground acceleration at Onahama-ji-G exceeded 14 m/s^2, which is the highest peak ground acceleration ever recorded at Japanese ports.

To understand the effect of ground motions on structures, it is important to pay attention to the frequency characteristics. Fig. 2 shows Fourier spectra observed at the surface by three strong-motion stations along the coast during the 2011 off the Pacific coast of Tohoku Earthquake (thick lines), compared with the Fourier spectrum observed at the surface for Port Island, Kobe city, during the 1995 Hyogo-ken Nambu earthquake (dotted lines). All the spectra are compositions of two horizontal components and processed through a Parzen window with a band width of 0.05 Hz. The vertical dashed lines indicate the frequency range from 0.3 to 1 Hz, which is closely related to the large-scale deformation of quay walls (e.g., Nozu et al., 2000). At Kamaishi-G and Sendai-G, the observed ground motions during the 2011 event were much smaller than the ground motion at Port Island during the 1995 event in terms of frequency components around 0.3–1 Hz. Although the observed ground motions at Onahama-ji-G were larger than those at Kamaishi-G and Sendai-G at around 0.3–1 Hz, they were still smaller than the Port Island record.

It is important to investigate the reason that the strong ground motions observed at these ports did not exceed those at Port Island for the 1995 event at around 0.3–1 Hz. One

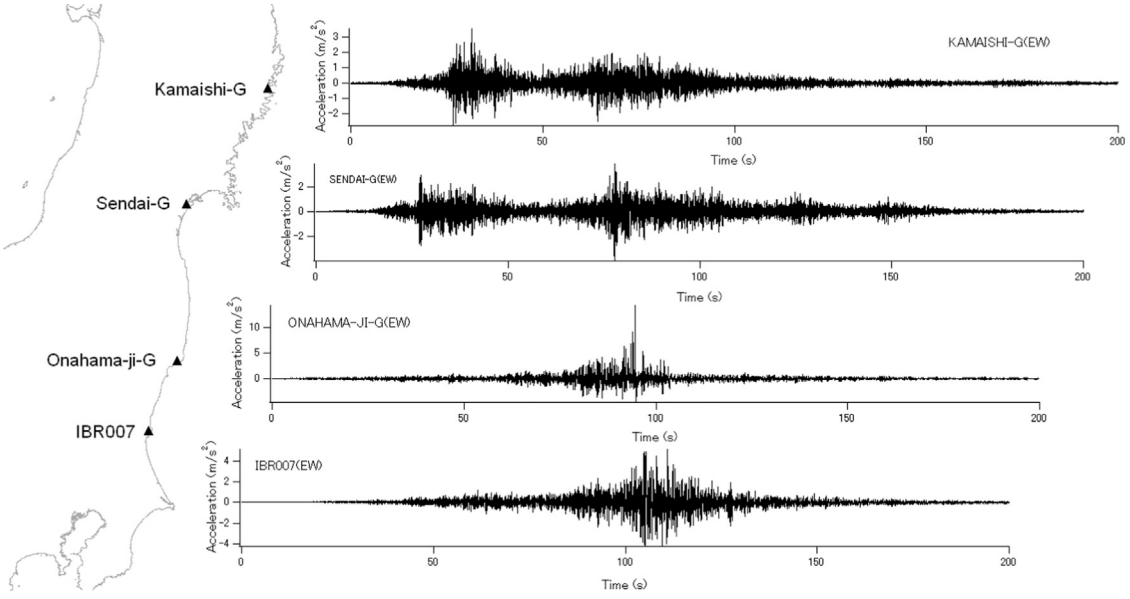

Fig. 1. Acceleration time histories observed at the surface by four strong motion stations along the coast during the 2011 off the Pacific coast of Tohoku Earthquake. EW components are shown.