Tohoku, Japan, Earthquake and Tsunami of 2011

Survey of Port and Harbor Facilities, Northern Region

PREPARED BY
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Preface

On March 11, 2011 the largest earthquake ever recorded in Japan struck off the coast of the Tohoku region of the country. 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. Following these events the Coasts, Oceans, Ports, and Rivers Institute (COPRI) of the American Society of Civil Engineers (ASCE) committed to send multiple reconnaissance teams to Japan to investigate the performance of port and coastal structures to the effects of strong ground motions and tsunami inundation. This report summarizes the findings of the Port and Harbor team as they investigated over 20 major port facilities along approximately 600 km of coastline. This broad coverage facilitated the interpretation of damage patterns across the entire region affected by the earthquake, with a primary goal of distinguishing port damage due to strong ground shaking and secondary effects (i.e., liquefaction, ground failures, and settlement) from that caused by subsequent and significant tsunami inundation.

Given the widespread, regional extent of the damage to port facilities COPRI formed two reconnaissance teams to investigate bayfront and coastal regions extending from Tokyo to Hachinohe in northern Honshu. In partnership with personnel from the Port and Airport Research Institute (PARI), Yokosuka, Japan, the COPRI Ports and Harbors team visited key sites in Japan from May 12 to 27, 2011. During this time the COPRI-PARI investigation teams visited key sites, documented observable damage, met with facility personnel, eyewitnesses, researchers, and government officials, and initiated efforts to develop an extensive collection of geotechnical, structural, coastal, and seismological data for valuable case studies. This report includes findings of the field observations as well as preliminary recommendations for port engineers and risk management personnel intended to highlight the most prevalent port vulnerabilities observed during the post-earthquake investigation and contribute to improvements in the seismic performance of port facilities.

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1 Introduction

On March 11, 2011 the largest earthquake ever recorded in Japan struck off the coast of the Tohoku region of the country. This M_w 9.0 subduction zone earthquake resulted in damage extending from the metropolitan Tokyo region to the northern extent of Honshu, and produced a series of tsunamis that impacted over 2000 km of Japanese coastline [Mori et. al. 2011]. The earthquake and tsunamis led to the death or disappearance of over 20,000 people in Japan [Mori & Takahashi 2011], and resulted in a death on the US west coast. Following these devastating events, the American Society of Civil Engineers (ASCE) and the Coasts, Oceans, Ports, and Rivers Institute (COPRI) committed to send multiple teams to Japan to investigate the performance of port and coastal structures. ASCE / COPRI worked closely with the Japanese Society of Civil Engineers (JSCE) and the Ports and Airports Research Institute (PARI). This extensive field reconnaissance was conducted by roughly 20 engineers representing COPRI, PARI, and related organizations in Japan. This partnership contributed to a wealth of field observations, varied and valuable interpretations of field damage patterns, and the sharing of diverse solutions to earthquake hazard mitigation at port facilities.

The primary purpose of this reconnaissance investigation was to examine the tsunami and earthquake effects specific to port waterfront structures and ancillary components such as cargo crains, conveyance systems, and intermodal links. While the earthquake and subsequent tsunami were devastating to many coastal communities as observed immediately after these events, the effects on ports and port-specific structures were not initially as clearly defined. The loss of equipment and cargo at the ports was visible from satellite imagery, as were localized failures of waterfront structures at many ports and harbors. In a broad and general sense; however, most of the major port facilties in the affected region appeared to have performed quite well in light of the long- duration and, in some locations, strong ground motions experienced (> 0.5g), as well as subsequent tsunami inundation. In most areas the waterfront port structures did not appear to have suffered the level of damage observed in surrounding communities. This investigation focused on the design and construction of these structures, with an emphasis on the lessons learned from both failures and successes. The material presented in this report incorporates information from on-site observations and interviews with facility operators, eyewitnesses, researchers, and government officials. This investigation was solely of observable, above-water performance; no underwater assessment was performed, therefore some findings may be speculative in nature, with opinion based on the combined experience and knowledge of the COPRI investigation team.

Specific topics of interest in this report include evaluation of the relative impacts of the strong ground motions and secondary seismic effects, and the tsunami inundation on the ports. It is anticipated that this will facilitate subsequent evaluations of the performance of existing earthquake shaking and tsunami warning systems on the operations of port facilities in Japan, the outcome of which will yield direct benefits to the maritime transportation system in seismically active regions of the United States. Additionally, damage assessment of cranes, tanks, and piping systems will also be directly applicable to US facilities. The correlation of damage levels to port structures and ancillary equipment to operational down-

time will improve our understanding of port vulnerabilities and seismic risk in the U.S. As demonstrated following recent earthquakes such as the M_w 8.8 2010 Chile earthquake, the loss of lifelines such as commercial power, telecommunications, and surface transportation links can have a significant impact on port operations and the recovery efforts at ports.

The extensive strong motion arrays in Japan (e.g., K-NET, KIK-NET arrays managed by the National Research Institute for Earth Science and Disaster Prevention) have provided an unprecedented collection of ground motion data for a mega-thrust earthquake. Strong ground motions from the M_w 9.0 mainshock and numerous significant aftershocks ($M_w > 7$) have been have been recorded at dozens of coastal sites providing data for a wide variety of geologic conditions. Of primary interest for this investigation is the regional strong motion array established at port facilities by the Port and Airport Research Institute. This data, combined with geotechnical site characterization, seismic code considerations, structural design information and as-built plans, and ground treatment applications adjacent to quay walls provide by far the most complete data base for case studies of port performance during large magnitude, long-duration ground shaking. Where it is possible to obtain this requisite data at key sites it will be feasible to develop case studies that allow for validation of existing seismic design procedures for port waterfront structures, and the development of enhanced methods of analysis and design. The field observations made by this and other reconnaissance teams in the affected region, supplemented with supporting documentation at key sites will lead to the improvement of seismic design criteria for port structures worldwide.

As previously outlined the primary objective of this investigation was the documentation of field observations and perishable evidence of phenomena associated with strong ground motions and tsunami inundation. As is common during early reconnaissance efforts following major earthquakes, the timing of the investigation generally precludes the collection of pertinent engineering, construction, and maintenance reports on the facilities being investigated. The COPRI team is indebted to our investigation partners at PARI for their tremendous efforts in collecting and sharing numerous cross sections, background on waterfront development and construction, and strong motion records obtained at several ports. Despite this valuable information it was often difficult to ascertain the exact sequence and modes of failure for waterfront structures. It is important to consider that in addition to the strong ground motions, secondary seismic effects, and tsunamis experienced on March 11, 2011 most of the ports in this investigation were subjected to strong ground motions during multiple aftershocks that occurred prior to the arrival of the COPRI Teams, and in some cases these ground motions exceeded those generated during the main shock. In addition, at the time of the field investigation the COPRI Teams generally did not have access to port maintenance reports or documentation of condition assessments for waterfront structures and nearshore bathymetry existant immediately prior to the earthquake.

On the basis of the observed construction materials and general condition of exposed structures, it appeared that active inspection and maintenance programs are executed at the major Japanese ports visited during this investigation. Anecdotally, several port representatives and longshoremen interviewed by the teams stated that structures at their terminals had been inspected shortly before the earthquake. The high level of seismic design, quality of construction materials, modes of construction, contemporary nature of

many of the port facilities (post-1990 construction), and maintenance programs, coupled with the excellent strong motion instrumentation program in coastal Japan (and specifcally at the ports themselves) this earthquake provides a unique opportunity to advance the body of knowledge and standard of practice for seismic risk reduction at ports worldwide.

Several additional, ancillary benefits of this investigation for subsequent investigations have been identified by the COPRI Ports investigation team. Two primary topics include; (1) direct comparison of the performance of waterfront structures at ports located between Soma and Hachinohe subjected to strong ground motions and tsunamis from multiple earthquakes that have occurred since 1968, and (2) insights relevant to the potential impact of global sea level rise on port facilities. With respect to the former topic significant earthquakes have occurred in the region resulting in varying levels of damage at several of the ports visited by the COPRI team (M_{JMA} 7.8 1968 Tokachi-Oki earthquake, M_{JMA} 7.4 1978 Miyagi-ken-oki earthquake, M_w 7.0 2003 Sanriku-minami earthquake, M_w 7.2 2005 Miygai-Oki earthquake). The relative performance of port and coastal structures during these earthquakes provides important data on the influence of ground motion characteristics and tsunami heights on damage patterns. On the second topic the tectonic plate movement from this earthquake resulted in land subsidence and relative water elevation changes similar to those expected due to global sea level rise over the next century; thus, the impact of tectonic movement on facility operations provides a preview of effects expected in the U.S. during this time frame.

The COPRI ports and harbors investigation was closely coordinated by team members prior to, and during, the reconnaissance efforts in Japan, with significant interaction with partners at PARI. The investigation was conducted by two COPRI teams in order to cover as much of the affected region as possible; with one team visiting ports and harbors from the Hachinohe to Soma areas in the northerly prefectures of Aomori, Iwate, Miyagi, and Fukushima (Tohoku region), and the second team focusing on ports from Tokyo to Onagawa in the prefectures of Tokyo, Chiba, Ibaraki, Fukushima, and Miyagi (Kanto and Tohuku regions). The significance of the observations made at locations such as the ports of Soma and Sendai, as well as the town of Onagawa necessitated some overlap in the investigation. This allowed the second team to benefit from the observations and findings made by the first team at these locations. The “Northern” Team executed their field investigation and data collection from May 12th to May 18th and the “Southern” Team followed with field work extending from May 18th to May 26th. The Northern Team held a project de-briefing for the Southern Team in Tokyo on May 18th.

The primary port sites visited by the COPRI Ports teams are shown in Figure 1.1-1 and Figure 1.1-2. Itineraries for the northern and central teams are given in Table 1-1 and Table 1-2 respectively. The teams typically spent 5 to 8 hours a day in the field, not including driving time to and from lodging, and were limited to accessing the site during daylight hours. In addition to office meetings for briefings and data collection (PARI, Yokosuka; Port of Tokyo, Tokyo; JX Nippon Oil & Energy Corporation, Tokyo; Sendai Airport, Sendai) numerous additional field sites were visited by both teams, thus this report is not all-inclusive, but provides a concentrated examination of damages to port and harbor structures that were of typical construction and configuration at the major ports in the region.

Additional sites included;

- Sendai Airport
- Several Tokyo Bay front sites in the Tokyo and Chiba areas
- Low lying coastal plain at Natori south of Sendai
- Small commercial fishing harbors and public marinas throughout the region
- Riverfront damage to earth retentions sytems, levees, and bridge approach embankments due to ground failures along several moderate to large rivers

The observations made at these locations greatly contributed to the regional characterization of damage patterns, considerations of seismic performance for a broad array of structures, insights on the implementation and benefits of instrumentation at major civil works, and differences in the seisic design requirements for a variety of civil applications.

Additional discussion specific to the performance of coastal structures can be found in the report *Tohoku, Japan, Earthquake and Tsunami of 2011: Survey of Coastal Structures* performed by the ASCE-COPRI-PARI Coastal Structures Field Survey Team.