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Preliminary report of the 2011 off the Pacific coast of Tohoku Earthquake*

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Abstract: On March 11, 2011, eastern Japan was shaken by the 2011 off the Pacific coast of Tohoku Earthquake (the Great East Japan Earthquake). Almost 30 000 people have been killed or are missing as a result of that earthquake and the subsequent monster tsunami, as of April 11, 2011. This paper reports several aspects of this devastating earthquake. It has been reported that long-period ground motions, which had been predicted by many researchers, occurred in Tokyo, Nagoya and Osaka. The response characteristics of high-rise buildings to the recorded long-period ground motions are discussed from the viewpoint of resonance and critical excitation. It is shown that high-hardness rubber dampers are very effective in the reduction of vibration duration in addition to the reduction in vibration amplitude.

Key words: Tohoku Earthquake, Disaster, Long-period ground motion, High-rise building, Critical excitation, Tsunami
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1 Introduction

The most devastating, killer earthquake in Japan after the 1923 Great Kanto Earthquake occurred on March 11, 2011 (Architectural Institute of Japan, 2011). The moment magnitude is 9.0, which is the largest so far in Japan. It is said that the recording system for the low-frequency component of ground motions was not sufficient in Japan and records outside Japan were used to determine the magnitude. Almost 30 000 people were killed or are missing as a result of this earthquake and the subsequent monster tsunami, as of April 11, 2011. The maximum height of the tsunami is reported to have been almost 40 m. It is remarkable in this earthquake that the number of collapsed or damaged buildings and houses remains unclear because most of the damage resulted from the tsunami.

This paper explains the characteristics of this earthquake and discusses the response characteristics of super high-rise buildings (40 to 60 stories) in Shinjuku, Tokyo, during this earthquake from the viewpoint of long-period ground motion. The issue of long-period ground motion and its impact on the structural design of buildings was raised in Mexico, the USA and Japan during the 1980s and 1990s (Heaton *et al.*, 1995; Kamae *et al.*, 2004; Ariga *et al.*, 2006). A set of simulated long-period ground motions was provided in December, 2010 by the Japanese Government (MLIT (the Ministry of Land, Infrastructure, Transport and Tourism), 2010) for the retrofit of existing high-rise buildings and as a design guideline for new high-rise buildings. In this paper the assumed 40- and 60-story steel buildings were subjected to the long-period ground motion recorded in Shinjuku, Tokyo, during the 2011 off the Pacific coast of Tohoku Earthquake.

The criticality of the long-period ground motions can be investigated based on the theory of critical

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excitation (Drenick, 1970; Takewaki, 2004; 2006; 2008). This theory is intended to overcome the difficulty resulting from the uncertainty of earthquake ground motions (Geller *et al.*, 1997; Stein, 2003). The credible bounds of input energy responses are obtained by using the critical excitation method with constraints on the power of acceleration and velocity. It is shown that long-period ground motions can be controlled primarily by the velocity power and that the ground motion recorded in Tokyo during the 2011 off the Pacific coast of Tohoku Earthquake actually included fairly large long-period wave components.

2 Characteristics of the 2011 off the Pacific coast of Tohoku Earthquake

First the characteristics of the 2011 off the Pacific coast of Tohoku Earthquake are described. The fault slip area and the slip magnitude are shown in Fig. 1. The comparison of the slip fault size is shown in Fig. 2 comparing the Sumatra Earthquake 2004, the Great Kanto Earthquake 1923, the Hyogoken-Nanbu Earthquake 1995, and the 2011 off the Pacific coast of Tohoku Earthquake. Because the fault slip area was huge in this earthquake, extremely wide areas of eastern Japan were affected by this earthquake. The representative ground motions along the Pacific coast of eastern Japan are illustrated in Fig. 3. It can be observed that two or more waveforms exist in some areas and the duration of most ground motion is over 2 min. This means that the fault slips occurred repeatedly in wide areas. Actually, it is reported that three main fault slips occurred in this series of events. Fig. 4 indicates the epicenter map of earthquakes during the 30 days after March 10. The maximum ground accelerations and velocities from K-NET and KiK-net (National Research Institute for Earth Science and Disaster Prevention (NIED), Japan) are shown in Fig. 5. It is reported that ground acceleration over 2.5g was recorded in Tsukidate, Kurihara City, Miyagi Prefecture (Fig. 6). However, it is also made clear that the predominant period of this ground motion is smaller than 0.3 s and this ground motion did not affect most buildings so much (Fig. 7).

3 Response simulation of super high-rise buildings in Tokyo

3.1 Ground motions in Tokyo

Fig. 8 shows the velocity waveforms of the long-period ground motion recorded at K-NET,

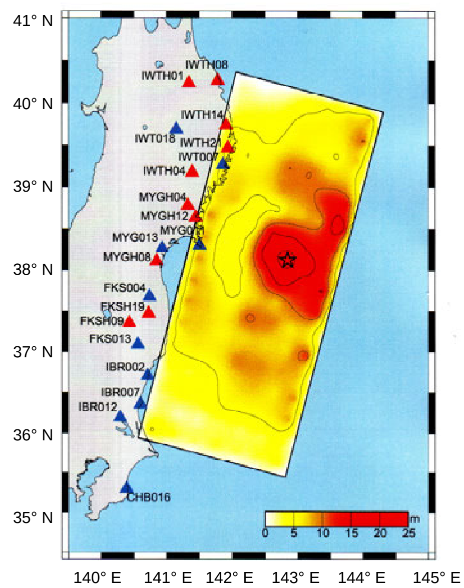


Fig. 1 Stations used for inversion and slip distribution taken from NIED (2011a)
Red: K-NET stations, blue: KiK-net borehole stations. A red arrow displays the epicenter.
Fault model: strike: 195°, dip: 13°; size: 510 km×210 km.
Results: M_0=3.28×10^{23} N·m (M_w=8.9), largest slip: 23 m.
This is a preliminary result and it will be updated

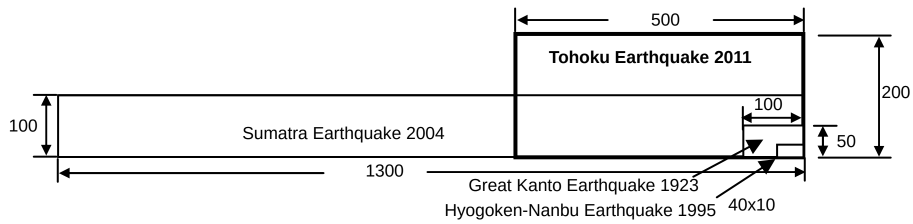


Fig. 2 Comparison of slip fault size comparing the Sumatra Earthquake 2004, Great Kanto Earthquake 1923, Hyogoken-Nanbu Earthquake 1995 (Kobe) and 2011 off the Pacific coast of Tohoku Earthquake (data from Asahi Newspaper (2011a)) (unit: km)

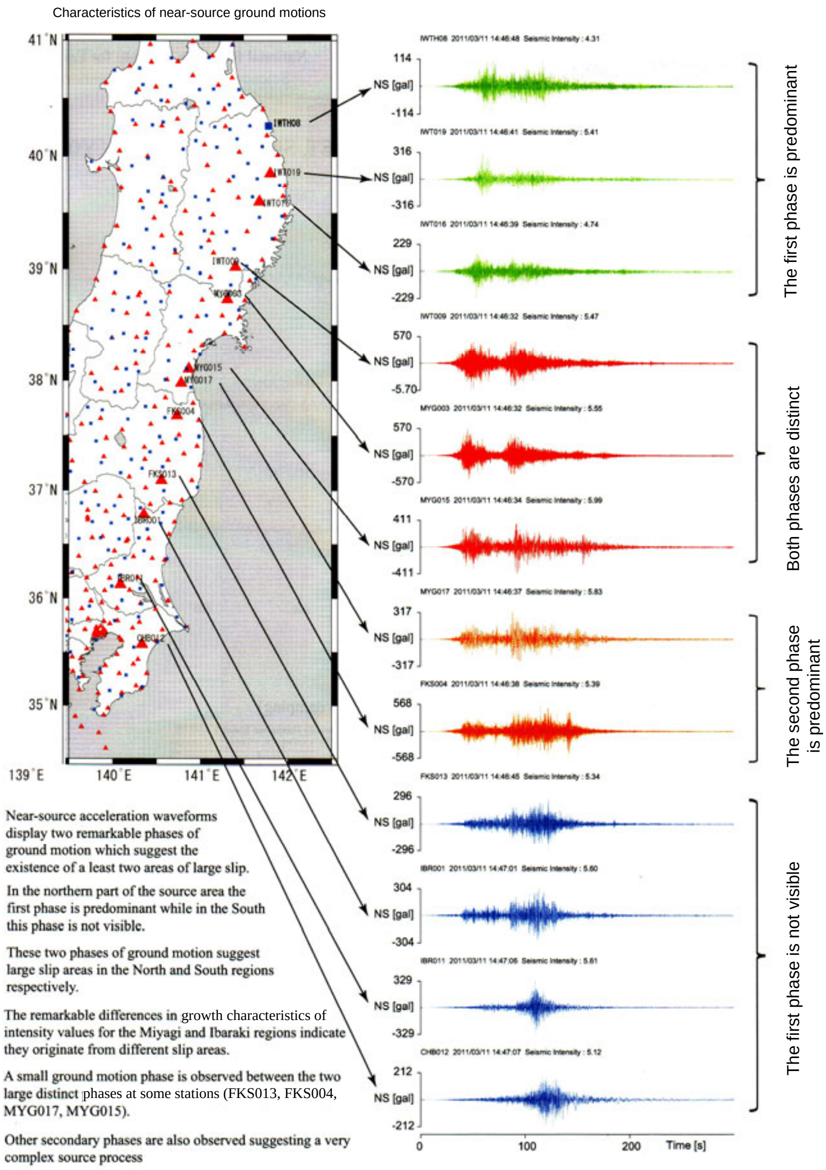


Fig. 3 Characteristics of ground motions taken from NIED (2011a)

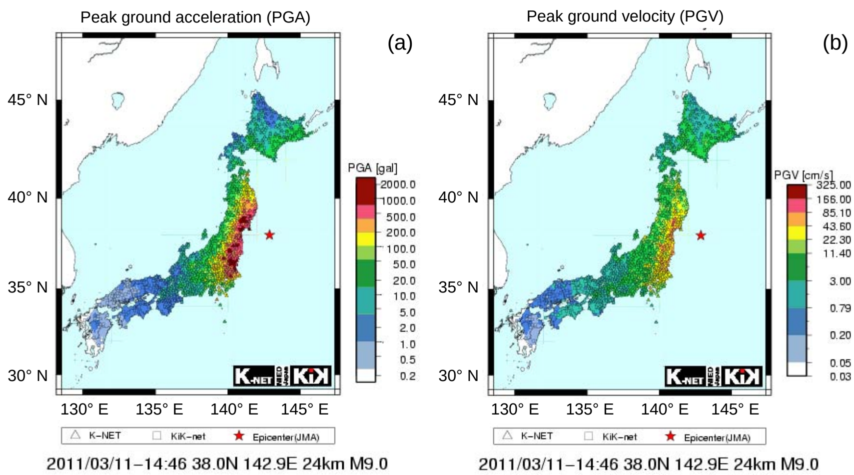


Fig. 5 Maximum ground acceleration (a) and velocity (b) from K-NET and KiK-net taken from NIED (2011c)

(Fig. 4 is on the next page)

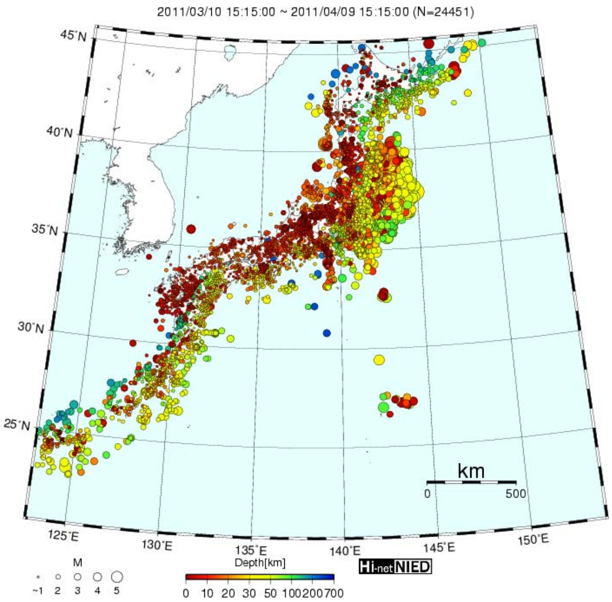


Fig. 4 Epicenter map during the 30 days after March 11 taken from NIED (2011b)

(Fig. 5 is on the previous page)

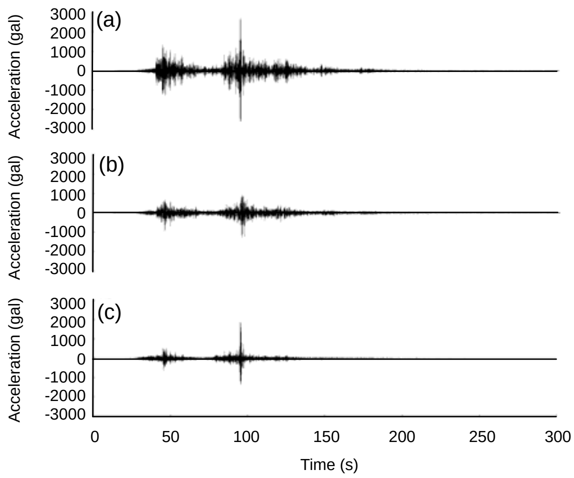


Fig. 6 Acceleration record at Tsukidate (MYG004) in Kurihara City, Miyagi Prefecture exhibiting the maximum ground acceleration (2933 gal: synthesized from three components) among those in K-NET and KiK-net stations taken from NIED (2011c)
(a) NS component; (b) EW component; (c) UD component

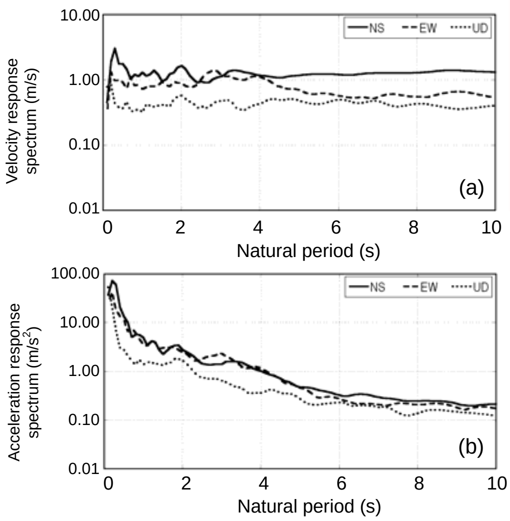


Fig. 7 Velocity (a) and acceleration (b) response spectra for 5% damping of the ground motions recorded at Tsukidate (MYG004) taken from NIED (2011c)

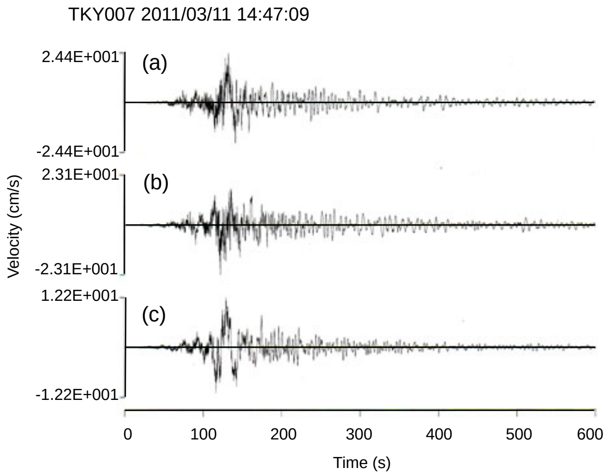


Fig. 8 Long-period ground motion recorded at K-NET, Shinjuku Station (TKY007) taken from NIED (2011a)
(a) NS component; (b) EW component; (c) UD component

Shinjuku Station (TKY007). It can be observed that the maximum ground velocity attains about 0.25 m/s and the ground shaking continues for over several minutes. The corresponding velocity response spectra are shown in Fig. 9. It is understood that shaking of a period of 5–6 s is predominant in addition to 2 s.

In order to investigate further the characteristics of that record, the Fourier amplitude spectra of acceleration and velocity records have been computed. Figs. 10 and 11 show the Fourier amplitude spectra of accelerations and velocities, respectively. It can be observed that the velocity is predominant in longer

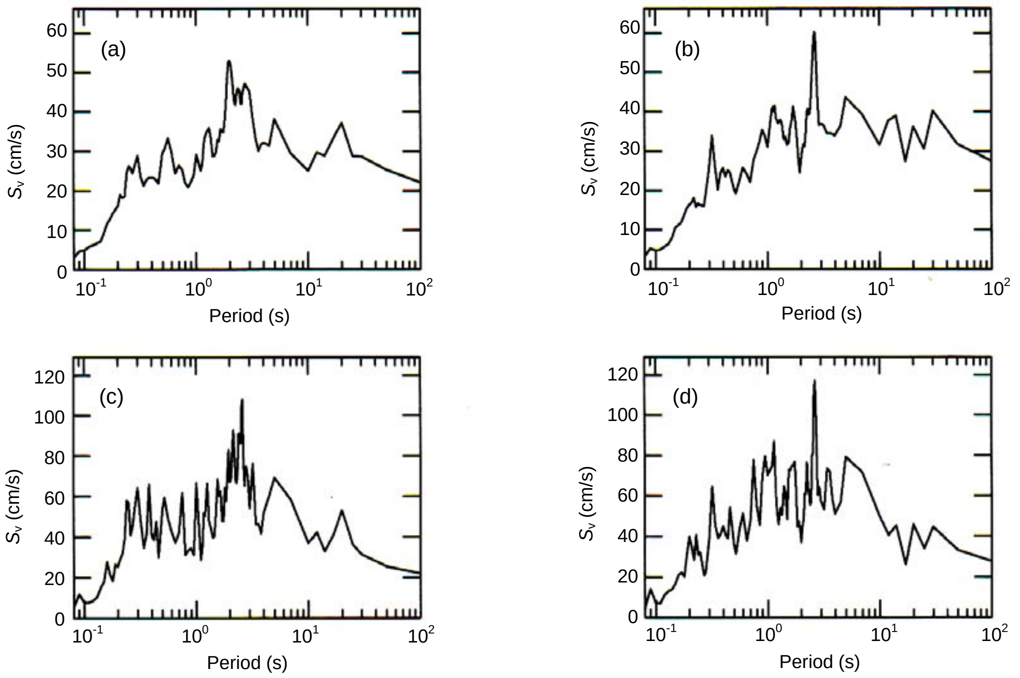


Fig. 9 Velocity response spectra of ground motions at Shinjuku Station (TKY007) taken from NIED (2011a)
(a) EW component, 5% damping; (b) NS component, 5% damping; (c) EW component, 1% damping; (d) NS component, 1% damping

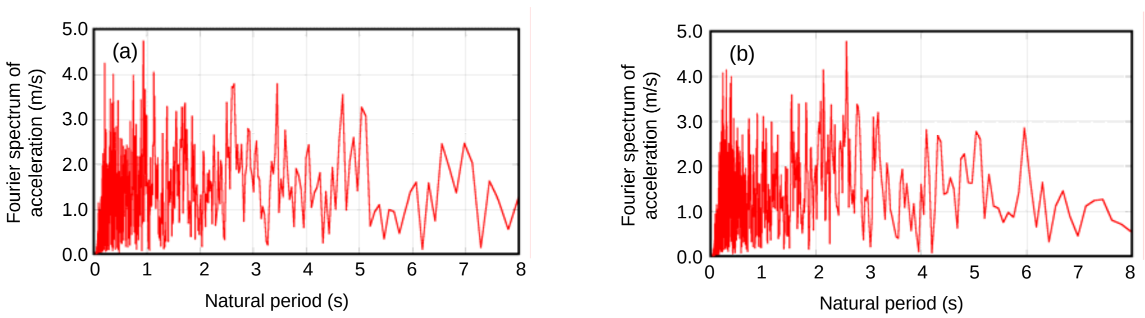


Fig. 10 Fourier amplitude spectra of acceleration ground motion at K-NET, Shinjuku Station (TKY007)
(a) NS component; (b) EW component

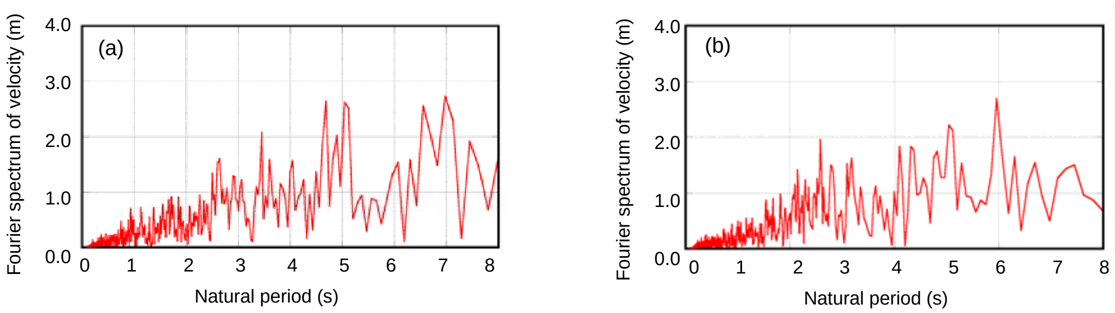
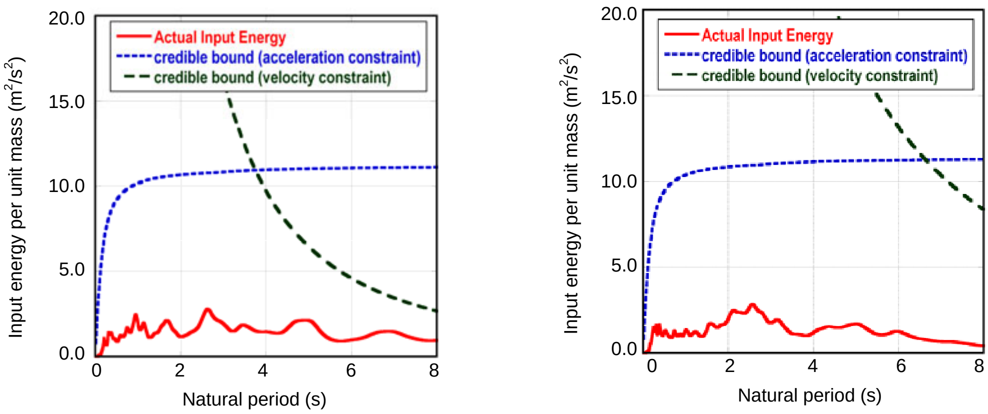


Fig. 11 Fourier amplitude spectra of velocity ground motion at K-NET, Shinjuku Station (TKY007)
(a) NS component; (b) EW component

period ranges. Fig. 12 presents the comparison of the actual input energies (5% damping), the credible bounds (Takewaki, 2004; 2006) for acceleration constraints (acceleration power (Housner and Jennings, 1975)) and the credible bounds for velocity constraints (velocity power (Housner and Jennings, 1975)) for NS component and EW component. The intersection point indicates the predominant period. 4 s and 6 s are such predominant periods and this supports the idea that the ground motion recorded at K-NET, Shinjuku Station (TKY007) actually included fairly large long-period wave components. For comparison, Fig. 13 shows the corresponding figures for El Centro NS 1940 and JMA Kobe NS 1995 (Hyogoken-Nanbu Earthquake). The intersection point exists in rather shorter period ranges.

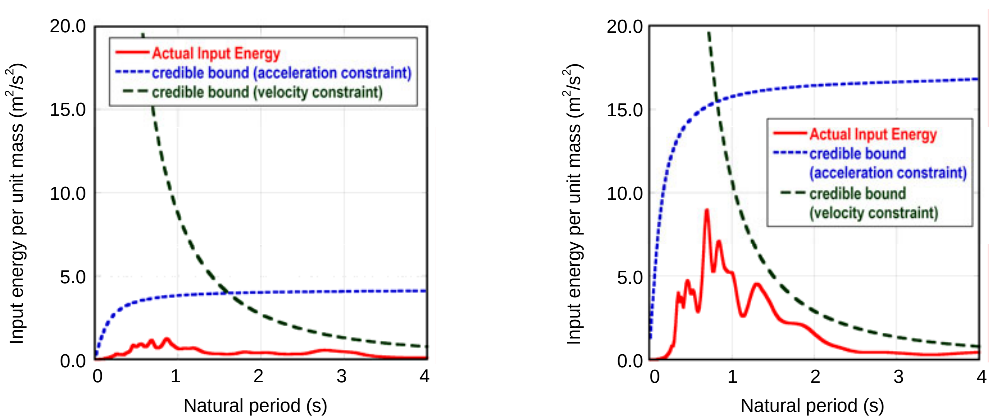
3.2 Response simulation of super high-rise buildings in Tokyo

In order to investigate the influence of this ground motion on high-rise buildings, two assumed buildings of 40 and 60 stories have been treated. The 40-story building has the fundamental natural period of T_1=4.14 s and the 60-story building has that of T_1=5.92 s. The damping ratio is 0.01. Furthermore, it is well accepted that the passive dampers are very effective in the reduction of earthquake response in high-rise buildings. The 2011 off the Pacific coast of Tohoku Earthquake may be the first plate-type earthquake to have affected super high-rise buildings in mega cities. For the purpose of clarifying the merit of visco-elastic dampers (high-hardness rubber



(a) (b)

Fig. 12 Actual input energies (5% damping), the credible bounds for acceleration constraints and the credible bounds for velocity constraints for the ground motion at K-NET, Shinjuku Station (TKY007) (Takewaki, 2004; 2006)
(a) NS component; (b) EW component



(a) (b)

Fig. 13 Actual input energies (5% damping), the credible bounds for acceleration constraints and the credible bounds for velocity constraints for El Centro NS 1940 (a) and JMA Kobe NS 1995 (b)

dampers (Tani *et al.*, 2009)), the buildings of 40 and 60 stories with and without these high-hardness rubber dampers have been subjected to the long-period ground motion recorded at K-NET, Shinjuku Station (TKY007).

Fig. 14 shows the maximum story displacements and interstory drifts of an assumed 40-story building of T_1=4.14 s to ground motion at Shinjuku Station (TKY007) (frame response: elastic or elastic-plastic). On the other hand, Fig. 15 illustrates the maximum story displacements and interstory drifts of an assumed 60-story building of T_1=5.92 s to ground motion at Shinjuku Station (EW component of TKY007) (frame response: elastic-plastic, with or without high-hardness rubber dampers (Tani *et al.*, 2009)). It can be observed that the high-hardness rubber dampers are very effective in the reduction of vibration amplitude. Fig. 16 presents the comparison of time histories of top-story displacements of an assumed 60-story building of T_1=5.92 s to ground motion at Shinjuku Station (EW component of TKY007) during the 2011 off the Pacific coast of Tohoku Earthquake (frame response: elastic-plastic, with or without high-hardness rubber dampers). It can be understood that the high-hardness rubber dampers can damp the building vibration in an extremely short duration.

It is reported recently (Asahi Newspaper, 2011b) that a 54-story building (height=223 m; fundamental natural period=6.2 s (short-span direction), 5.2 s (long-span direction)) with passive oil dampers in Shinjuku experienced a top displacement of 1.08 m during the 2011 off the Pacific coast of Tohoku Earthquake. The vibration duration was over 13 min. It is also stated that that building would have undergone a top displacement of 1.4 m if the passive dampers had not been installed. This fact corresponds well with the result explained above.

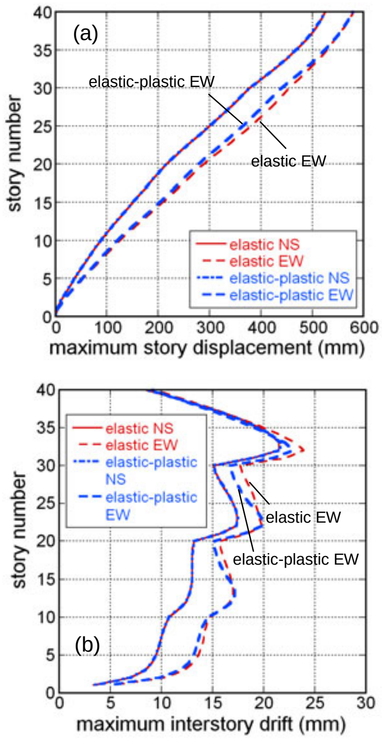


Fig. 14 Maximum story displacement (a) and interstory drift (b) of an assumed 40-story building of T_1=4.14 s to ground motion at Shinjuku Station (TKY007) during the 2011 off the Pacific coast of Tohoku Earthquake (frame response: elastic or elastic-plastic)

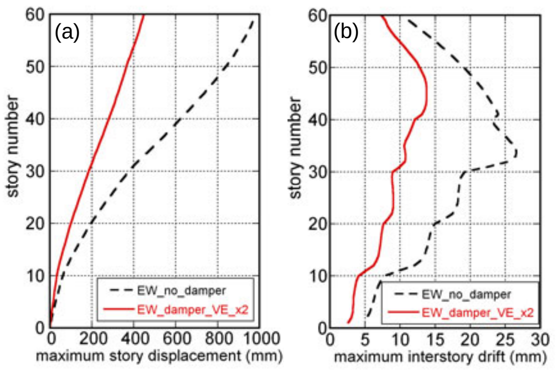


Fig. 15 Maximum story displacement (a) and interstory drift (b) of an assumed 60-story building of T_1=5.92 s to ground motion at Shinjuku Station (EW component of TKY007) during the 2011 off the Pacific coast of Tohoku Earthquake (frame response: elastic-plastic, with or without high-hardness rubber dampers)

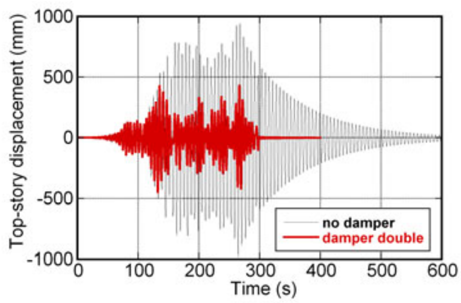


Fig. 16 Comparison of time histories of top-story displacement of an assumed 60-story building of T_1=5.92 s to ground motion at Shinjuku Station (EW component of TKY007) during the 2011 off the Pacific coast of Tohoku Earthquake (frame response: elastic-plastic, with or without high-hardness rubber dampers)

4 Conclusions

The following conclusions have been obtained.

1. The 2011 off the Pacific coast of Tohoku Earthquake was the most devastating earthquake in Japan after the 1923 Great Kanto Earthquake. This earthquake is the first one which attacked mega cities after the construction of super high-rise buildings. However, this earthquake is not the most influential one because the influence depends on the plate (including epicenter) on which mega cities lie.

2. The long-period ground motion recorded at K-NET, Shinjuku Station (TKY007), Tokyo contains fairly large long-period wave components and has a frequency content of broad band signals. This can be observed from not only the velocity response spectra (and Fourier spectra) but also from the earthquake input energy spectra taking into account the concept of the critical excitation method.

3. The high-hardness rubber dampers can damp the building vibration during long-period ground motions in an extremely shorter duration compared to a building without those dampers.

4. The word 'unpredictable' is often used in Japan following this great earthquake. It may be true that the return period of this class of earthquake is 500–1000 years and the use of this word may be accepted to some extent. However, the critical excitation method is expected to overcome this irrational concept in the future.

Acknowledgements

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