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UNCERTAINTIES OF LONG-PERIOD GROUND MOTION AND ITS IMPACT ON BUILDING STRUCTURAL DESIGN

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ABSTRACT: On March 11, 2011, Japan was shaken by the 2011 off the Pacific coast of Tohoku earthquake (the Great East Japan Earthquake). This paper reports some aspects of this earthquake and its impact on building structural design. It was reported that long-period ground motions were induced in Tokyo, Nagoya and Osaka. The response of high-rise buildings to the recorded ground motions during this earthquake and the simulated ground motions provided by the Japanese Government is discussed from the viewpoint of resonance and critical excitation.

Key Words: Great East Japan earthquake, long-period ground motion, resonance, critical excitation, earthquake input energy, passively controlled structure

INTRODUCTION

The most devastating earthquake in Japan after the 1923 Great Kanto earthquake occurred on March 11, 2011 (AIJ 2011a, b, USGS 2011). The moment magnitude was 9.0 and this is the largest so far in Japan. The earthquake resulted from the thrust faulting near the subduction zone plate boundary between the Pacific and North America Plates (AIJ 2011a, b, USGS 2011). Nearly 20,000 people were killed or are still missing by that earthquake and the subsequent monster tsunami as of November 1, 2011.

Because super high-rise buildings in mega cities in Japan had never been shaken by the so-called long-period ground motions with high intensities, the response of high-rise buildings to such long-period ground motions is one of the most controversial subjects in the field of earthquake-resistant design in Japan (MLIT 2010). The issue of long-period ground motion and its effect on building structural design was initially brought up in Mexico, USA and Japan during 1980-1990s (for example Earthquake Spectra 1988, Heaton et al. 1995, Kamae et al. 2004, Ariga et al.

2006).

This paper discusses the response of assumed super high-rise buildings (40 and 60-story) in Tokyo during this earthquake through the comparison with the reported fact. The issue of long-period ground motion and its impact on building structural design are also discussed by using the simulated long-period ground motions provided in December, 2010 by the Japanese Government (the Ministry of Land, Infrastructure, Transport and Tourism (MLIT)) (MLIT 2010). Two 40-story steel buildings are subjected to these simulated long-period ground motions. It is further demonstrated that the high-hardness rubber dampers with high damping capacity (Tani et al. 2009) are extremely effective for the reduction of response level and response duration.

Furthermore the criticality and uncertainty of the long-period ground motions are investigated based on the theory of critical excitation (Drenick 1970, Takewaki 2004, 2006, 2008a). The credible bounds of input energy responses are obtained by using the robust critical excitation method with the constraints on acceleration and velocity powers. It is shown that the long-period ground motions with a large power in a long-period range are controlled primarily by the velocity power and the ground motion recorded in Tokyo during the 2011 off the Pacific coast of Tohoku earthquake actually included long-period wave components.

RESPONSE SIMULATION OF SUPER HIGH-RISE BUILDINGS

Fig.1 shows the velocity waveforms of the long-period ground motion recorded at K-NET, Shinjuku station (TKY007). It can be observed that the maximum ground velocity attains about 0.25(m/s) and the ground shaking continues for more than several minutes. The corresponding velocity response spectra are shown in Fig.2. The corresponding ones of the Japanese seismic design code for 5% damping are also plotted in Fig.2. It is understood that these ground motions include long-period components up to 10 seconds.

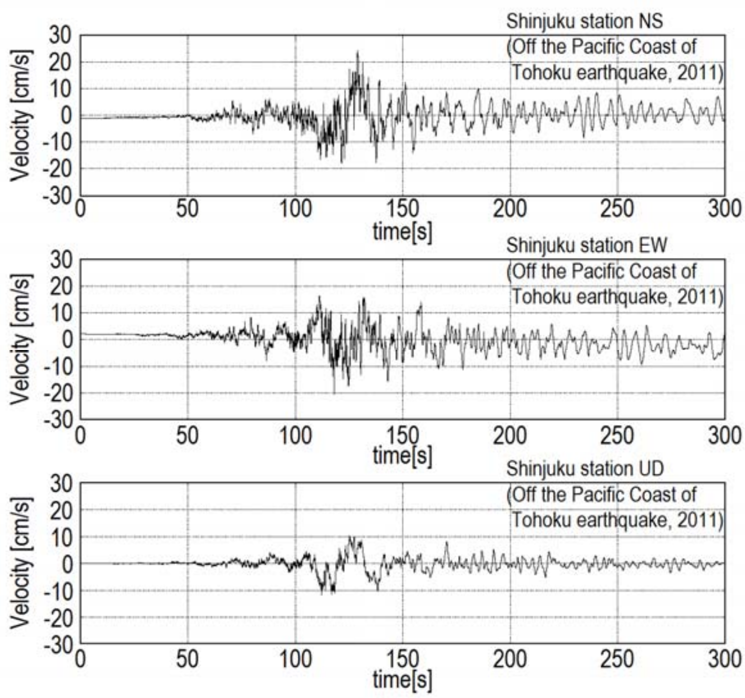


Fig.1 Long-period ground motion at K-NET, Shinjuku station (TKY007) (NIED 2011b)

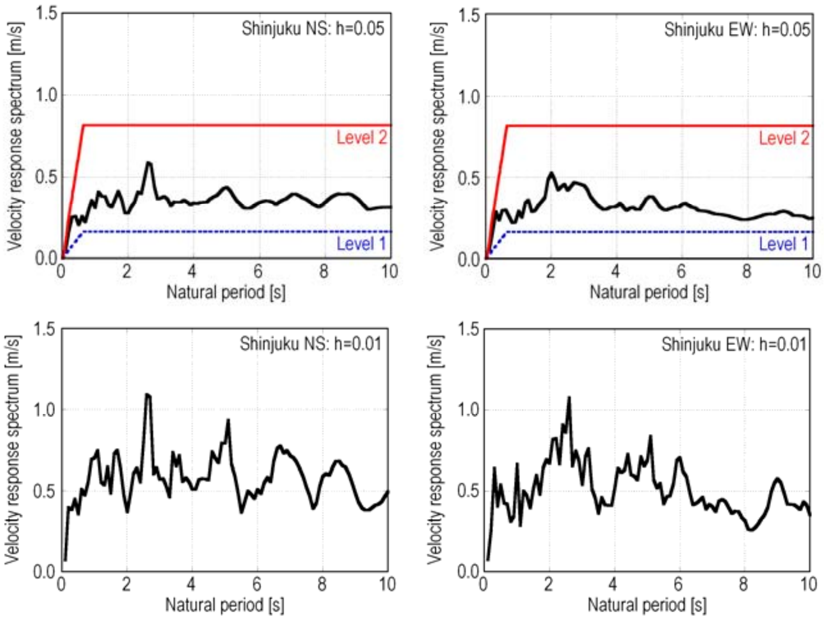


Fig.2 Velocity response spectra of ground motions at TKY007 (NIED 2011b) (Takewaki et al. 2011)

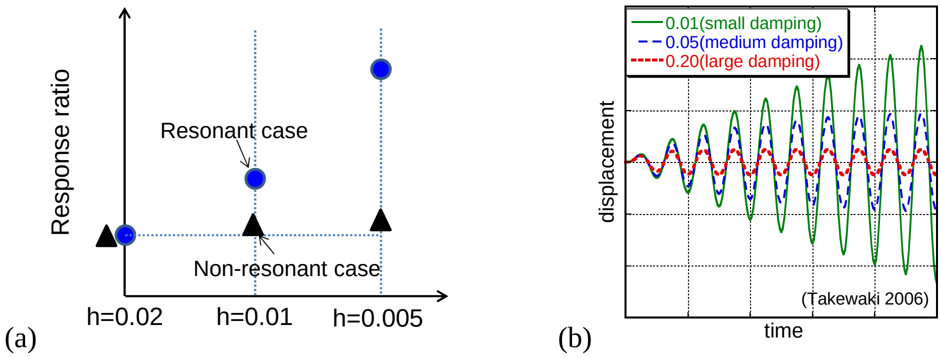


Fig.3 (a) Response amplification in resonant and random cases, (b) damping effect in resonance

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 buildings have a plan of 40 m× 40 m (equally spaced 36 columns; span length.8 m) and one planar frame is taken as the object frame. The uniform story height is 4 m. The floor mass per unit area is assumed to be 800 kg/m^2. The damping ratio is taken as 0.01 in accordance with the well-accepted database. The detail of member size and its material property are shown in the reference (Takewaki et al. 2011). The 40-story building has the fundamental natural period of 4.14s and the 60-story building has that of 5.92s. 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 dampers with high damping capacity (Tani et al. 2009)), the buildings of 40 and 60 stories without and with these high-hardness rubber dampers have been subjected to the long-period ground motion recorded at K-NET, Shinjuku station (TKY007).

It may be useful to note that the amplification by damping can be expressed by

$1/h$ for resonant long-period ground motion (1a)

$1.5/(1+10h)$ for non-resonant conventional ground motion (ratio to h=0.05) (1b)

This implies that the high sensitivity of the response to damping in resonant long-period ground motions (Fig.3).

Fig.4 shows the maximum story displacements and interstory drifts of two 40-story buildings of T_1=4.14s without and with high-hardness rubber dampers to the ground motion at Shinjuku station (TKY007) (frame response: elastic or plastic). On the other hand, Figs.5(a) and (b) illustrate the maximum story displacements and interstory drifts of a 60-story building of T_1=5.92s to the ground motion at Shinjuku station (TKY007) (frame response: plastic, without or with high-hardness rubber dampers). Fig.5(c) presents the time history of the story displacement at top.

It has been reported recently (Asahi newspaper 2011) that a 54-story steel building (height=223m: fundamental natural period=6.2s (short-span direction), 5.2s (long-span direction)) retrofitted with new-type passive oil dampers including the supporting bracing system in Shinjuku, Tokyo experienced the top displacement of 0.50(m) during the 2011 off the Pacific coast of Tohoku earthquake. The vibration duration was reported to be over 13 minutes. It was also explained that that building would have attained the top displacement of 0.7(m) if the passive dampers would not have been installed. This fact corresponds well to the result explained above.

There is another report that a 55-story super high-rise building in Osaka (height=256m: T_1=5.8s (long-span direction), 5.3s (short-span direction)) was shaken severely regardless of the fact that Osaka is located far from the epicenter (about 800km) and the JMA instrumental intensity was 3 in Osaka. Afterwards the natural periods were found to be longer ones reflecting the flexibility of pile-ground systems. It should be pointed out that the level of velocity response spectra of ground motions observed here (first floor) is almost the same as that at the Shinjuku station (K-NET) in Tokyo and the top-story displacement are about 1.4m (short-span direction) and 0.9m (long-span direction). Fig.6 shows the ground acceleration, ground velocity and top-story displacement. It can be observed that a clear resonant phenomenon occurs during about eight cycles. This implies the need of consideration of long-period ground motions in the seismic resistant design of super high-rise buildings in mega cities even though the site is far from the epicenter. The seismic retrofit using hysteretic steel dampers and oil dampers is being planned.

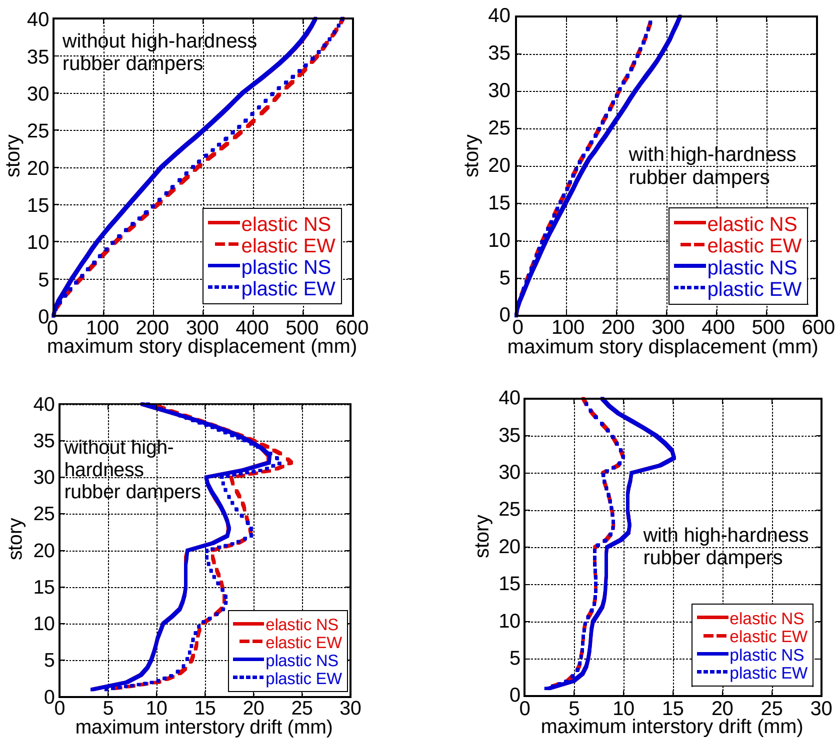
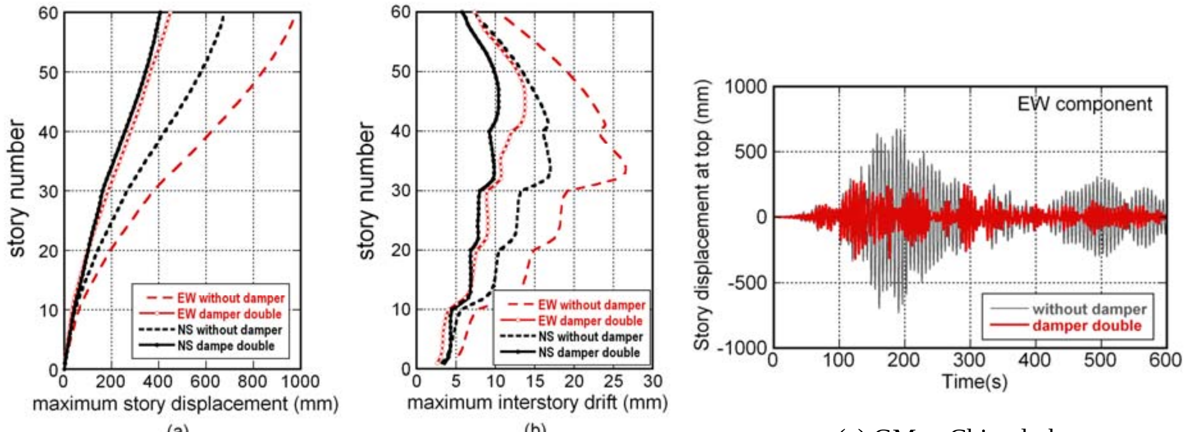


Fig.4 Maximum story displacement and interstory drift of an assumed 40-story building of T_1=4.14s to ground motion at Shinjuku station (TKY007) (frame response: elastic or plastic)



(c) GM at Chiyoda-ku

Fig.5 Maximum displacement and interstory drift of an assumed 60-story building of T_1=5.92s to GM at K-NET, Shinjuku station (TKY007) (frame response: plastic, without or with high-hardness rubber dampers) (Takewaki et al. 2011)

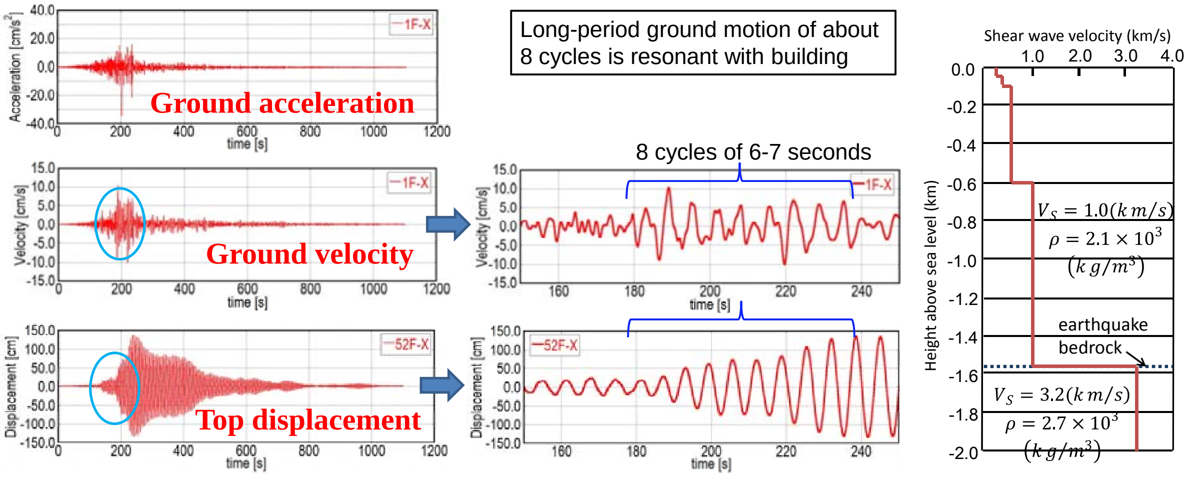


Fig.6 Ground acceleration, velocity and top-story displacement of a 55-story building in Osaka

RESPONSE OF HIGH-RISE BUILDINGS TO PREDICTED LONG-PERIOD GROUND MOTIONS

Simulated long-period ground motions

On December 21, 2010, the Japanese Government made a press release to upgrade the regulation for high-rise buildings under long-period ground motions. The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) selected and specified 9 areas in Osaka, Nagoya and Tokyo (see Fig.7). Areas 1-4 exist in Tokyo, areas 5-7 in Nagoya and areas 8, 9 in Osaka. MLIT provided simulated long-period ground motions in each area based on the advanced theory of ground motion generation. It was found that large velocity waves appear in later times and the velocity spectra in 2-8 seconds have relatively large magnitudes. It should be remarked that this project was conducted before the present Tohoku earthquake and a revision of the simulation is under preparation together with the inclusion of the simultaneous occurrence of three great earthquakes predicted in West Japan.

Osaka (Area 8, 9) Nagoya (Area 5-7) Tokyo (Area 1-4)

Fig.7 Zoning areas in Osaka, Nagoya and Tokyo (MLIT 2010)

Response simulation of high-rise buildings without and with high-hardness rubber dampers

In order to investigate the influence of the simulated ground motions in areas 1-9 on the response of high-rise buildings, two assumed buildings of 40 stories have been used. The parameters of the buildings are the same as those stated above. The stiffness of beams has been evaluated as double the original stiffness for the building frame of T_1=3.6s and as 1.5 times the original stiffness for the building frame of T_1=4.14s. The model of T_1=3.6s is a slightly stiff building model and the model of T_1=4.14s is a slightly flexible model. Only the latter one has been treated above. For the purpose of clarifying the merit of visco-elastic dampers (high-hardness rubber dampers (Tani et al. 2009) as in the previous case), the buildings of 40 stories without and with these high-hardness rubber dampers have been subjected to the simulated long-period ground motions. One damper unit consists of rubber thickness=15mm and rubber area=0.96m^2. 'Damper single' includes 2 damper units at every story and 'damper double' includes 4 damper units at every story. The 'damper double' has been treated above.

Fig.8 illustrates the comparison of the time histories of the top displacement of the 40-story buildings of T_1=3.6s without and with high-hardness rubber dampers (damper double, frame response; elastic) under a simulated long-period ground motion in area 5 (Nagoya area). It can be observed that the high-hardness rubber dampers are able to damp the building vibration in an extremely shorter duration compared to the building without those dampers.

The comparison of the top displacements of the 40-story buildings of T_1=3.6(s) (elastic or elastic-plastic, without or with dampers) has been made under the simulated long-period ground motion in area 5. It has been observed that the elastic-plastic response of the building frame decreases the response level to some extent. It has also been seen that the high-hardness rubber dampers can damp the vibration so quickly. It has been confirmed that this quick vibration reduction rate can be achieved also by viscous dampers like oil dampers so long as an appropriate amount of dampers is provided. The P-delta effect of columns has also been investigated. It has been made clear that the P-delta effect of columns has a small influence on the response in this case.

Fig.9 shows the ground acceleration, ground velocity and top-story displacement. It can be observed that a clear resonant phenomenon occurs during about three cycles and intensive vibration of the building corresponds well to the velocity wave of the ground motion, not the acceleration wave of that. This is a special character of the response of high-rise buildings under long-period ground motions.

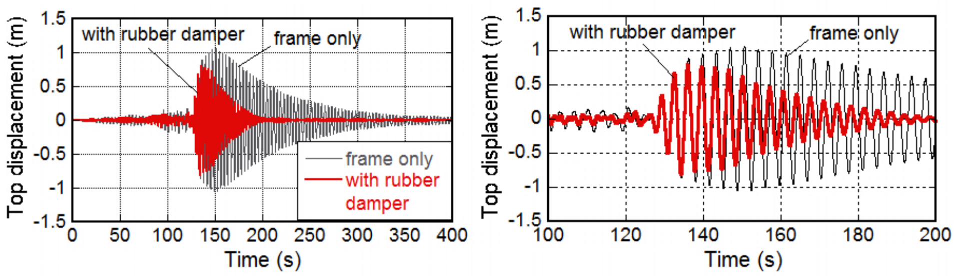


Fig.8 Time histories of top-story displacement of an assumed 40-story building

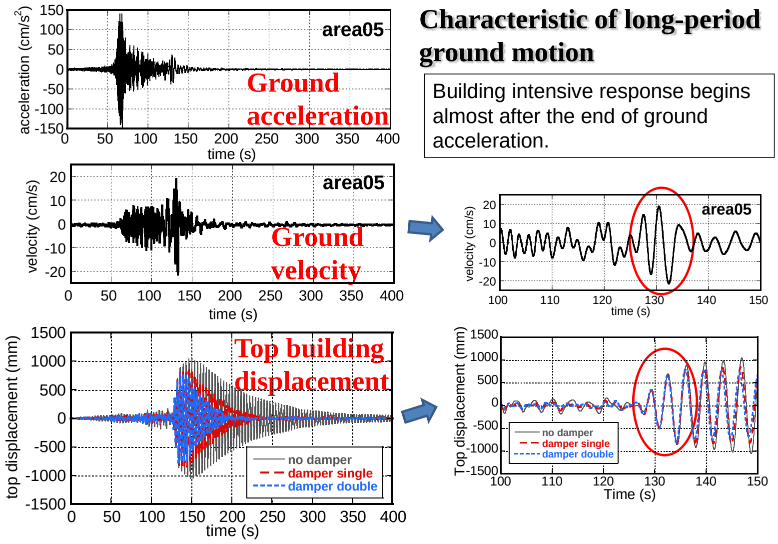


Fig.9 Ground acceleration, velocity and top displacement of an assumed 40-story building in Nagoya

NEW PARADIGM OF EARTHEQUAKE RESISTANT DESIGN FOR GROUND MOTIONS INCLUDING LONG-PERIOD GROUND MOTION

In order to respond to the issue of long-period ground motions, a new paradigm is desired. There are various buildings in a city. Each building has its own natural period and its original structural properties. When an earthquake occurs, a variety of ground motions are induced in the city. The combination of the building natural period with the predominant period of the induced ground motion may lead to disastrous phenomena in the city (see Fig.10). Many past earthquake observations demonstrated such phenomena repeatedly. Once a devastating earthquake occurs, some building codes are revised and upgraded. However, it is true that this repetition never resolves all the issues and new serious problems occur. In order to overcome this problem, a new paradigm has to be posed. The concept of "critical excitation" (Drenick 1970, Takewaki 2004, 2006, 2008a) and the structural design based upon this concept can become one of such new paradigms (Takewaki 2006).

Earthquake inputs are uncertain both in epistemic and aleatory sense even with the present knowledge and it does not appear easy to predict forthcoming events precisely (Geller et al. 1997, Stein 2003, Aster 2012). Near-field ground motions (Northridge 1994, Kobe 1995, Turkey 1999 and Chi-Chi, Taiwan 1999) and the Mexico Michoacan motion in 1985 have some peculiar, unpredictable characteristics. It is also true that the civil, mechanical and aerospace engineering structures are often required to be designed for disturbances including inherent uncertainties due mainly to their "low rate of occurrence". It is said in fact that the return period of the earthquake of March 11 is about 1,000 years. Worst-case analysis combined with proper information based on reliable physical data is expected to play an important role in avoiding difficulties induced by such uncertainties. Approaches based on the concept of "critical excitation" seem to be promising.

The most critical issue in the seismic resistant design is the resonance. One of the promising approaches to this phenomenon is to shift the natural period of the building through seismic control (Takewaki 2009) and to add damping in the building. However it is also true that the seismic control is under development and more sufficient time is necessary to respond to uncertain ground motions.

It is believed that earthquake has a bound on its magnitude and the earthquake energy radiated from the fault has a bound (Trifunac 2008). The problem is to find the most unfavorable ground motion for a building or a group of buildings (see Fig.10). The Fourier spectrum of a ground motion acceleration has been proposed at the rock surface depending on the seismic moment M_0, distance R from the fault, etc. (for example Boore 1983).

$$\left|A(\omega)\right| = CM_0 S(\omega,\omega_C) P(\omega,\omega_{\max}) \exp(-\omega R/(2\beta Q_\beta)/R \tag{2}$$

Such spectrum may have uncertainties. One possibility or approach is to specify the acceleration or velocity power as a global measure and allow the variability of the spectrum.

The problem of ground motion variability is very important and tough. Code-specified design ground motions are usually constructed by taking into account the knowledge from the past observation and the probabilistic insights. However, uncertainties in the occurrence of earthquakes (or ground motions), the fault rupture mechanisms, the wave propagation mechanisms, the ground properties, etc. cause much difficulty in defining reasonable design ground motions especially for important buildings in which severe damage or collapse has to be avoided absolutely (Takewaki 2006, Geller et al. 1997, Stein 2003, Aster 2012).

A significance of critical excitation is supported by its broad perspective. In general there are two classes of buildings in a city. One is the important building which plays an important role during and after disastrous earthquakes. The other is ordinary building. The former one should not get damaged during an earthquake and the latter one may be damaged partially especially for critical excitation larger than code-specified design earthquakes. Just as the investigation on limit states of structures plays an important role in the specification of response limits and performance levels of structures during disturbances, the clarification of critical excitations for a given structure or a group of structures appears to provide structural designers with useful information in determining excitation parameters in a risk-based reasonable way. It is expected that the concept of critical excitation enables structural designers to make ordinary buildings more seismic-resistant and seismic-resilient.

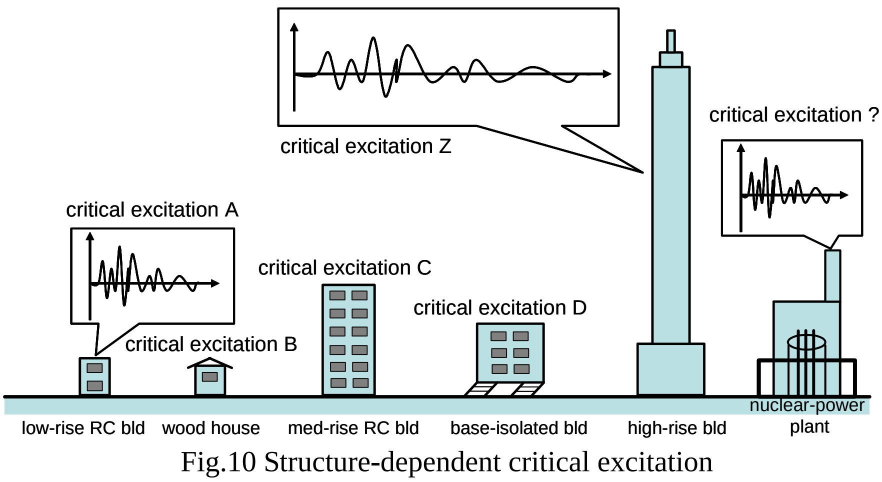


Fig.10 Structure-dependent critical excitation

The total input energy is an appropriate quantity for evaluating the demand of earthquake ground motions (Housner 1959, Akiyama 1985, Takewaki 2004). Fig.11 presents the credible bounds of input energy for JMA Kobe NS during Hyogoken-Nanbu earthquake 1995, Petrolia NS during Cape Mendocino earthquake 1992, Ofunato NS during Miyagiken-oki earthquake 1978 and Vina del Mar NS during Chile earthquake 1985. It is seen that the property of the uniform risk still holds. On the other hand, Fig.12 shows those for ground motions recorded at K-NET, Shinjuku station (TKY007) and Fig.13 illustrates those for ground motions recorded in Osaka bay area. It can be found that the ratio of actual input energy to the bound is large. This implies that the ground motion of March 11 includes wave components in a broad period range.

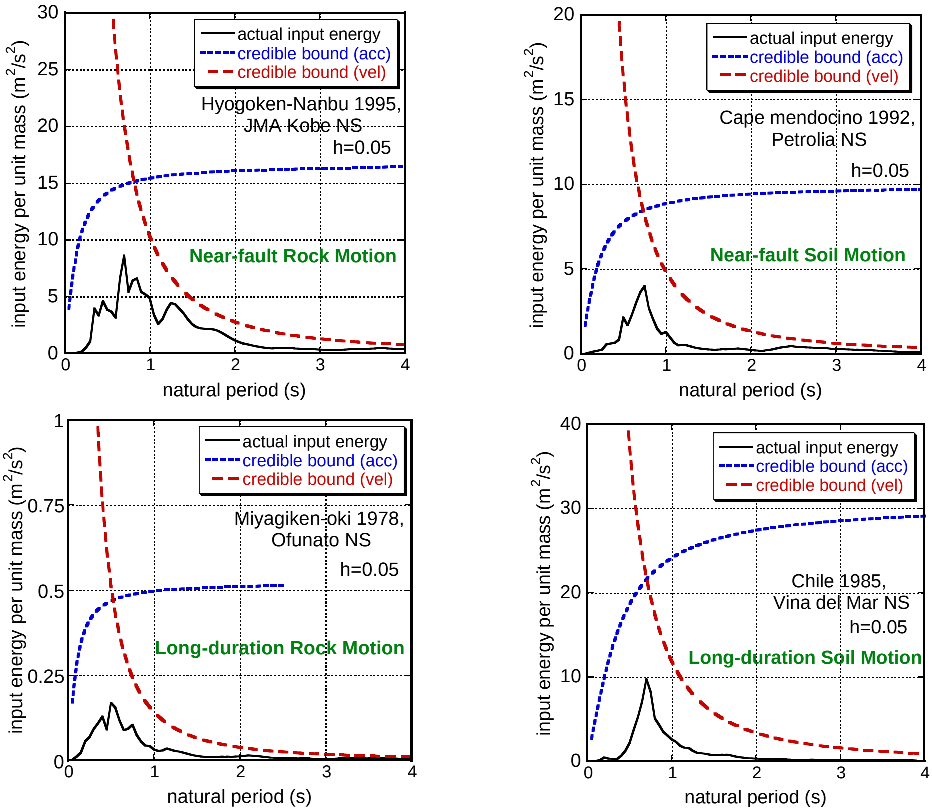


Fig.11 Credible bound of input energy for various types of ground motions (near-fault rock motion, near-fault soil motion, long-duration rock motion, long-duration soil motion) (Takewaki 2004)

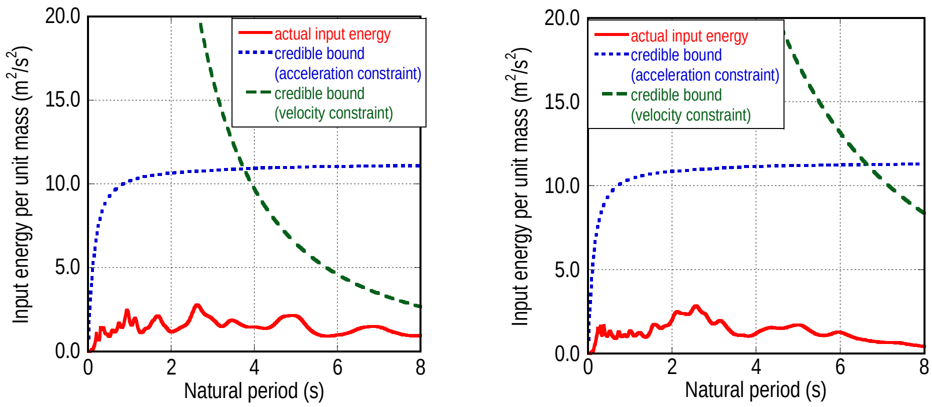


Fig.12 Credible bound of input energy for ground motion recorded at K-NET, Shinjuku station (TKY007)

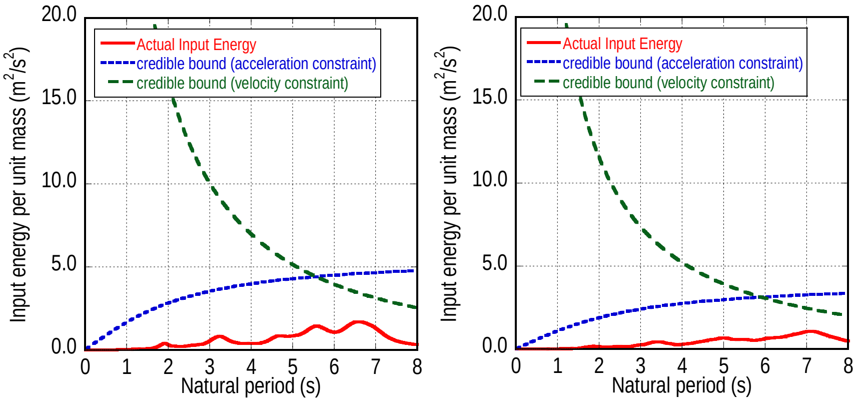


Fig.13 Credible bound of input energy for ground motion recorded in Osaka bay area

CONCLUSIONS

The following conclusions have been obtained.

(1) The 2011 off the Pacific coast of Tohoku earthquake is the most devastating earthquake in Japan after the 1923 Great Kanto earthquake in terms of the damaged area and loss cost. This earthquake may be the largest inter-plate earthquake which affected mega cities after the construction of super high-rise buildings. However this earthquake may not be the most influential one. This fact has been confirmed from the comparison with the result using the simulated ground motions provided by the Japanese Government.

(2) The 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 (2-6 seconds). This can be observed from not only the velocity response spectra (and Fourier spectra) but also the earthquake input energy spectra taking into account of the concept of critical excitation.

(3) The region of short natural period in the input energy spectrum can be controlled by the credible bound for the acceleration constraint and the region of long period by the credible bound for the velocity constraint (Takewaki 2004, 2006). The introduction of both credible bounds enables the construction of a reliable bound with uniform risk in all the natural period range. Especially the credible bound (Takewaki 2004, 2006) for the velocity constraint can control the bound of input energy from the long-period ground motion and this bound plays a role for overcoming the difficulties caused by uncertainties on period and duration of long-period ground motions.

(4) Visco-elastic dampers (high-hardness rubber dampers with high damping capacity) and viscous dampers (oil dampers) are able to damp the building vibration during long-period ground motions in an extremely shorter duration compared to the building without those dampers. It has been made clear that the safety is not the only target and the functionality together with the consideration of psychological aspects of residents has to be protected appropriately.

(5) The word ‘unexpected issue’ is often used in Japan after this great earthquake. It may be true that the return period of this class of earthquakes at the same place could be 500-1000 years and the use of this word may be acceptable to some extent from the viewpoint of the balance (or trade-off) between the construction cost and the safety. However, the critical excitation method is expected to enhance rationally the safety level of building structures under uncertain circumstances by expecting the unexpected (Aster 2012).

(6) The concepts of redundancy, robustness (Takewaki 2008b, AIJ 2011c) and resilience (Committee on Nat. Earthq. Resilience Res., Implementation, and Outreach (2011)) and their relationship may be a key factor for designing building structures with greater earthquake resilience.

ACKNOWLEDGMENTS

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