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Improving the Earthquake Resilience of Buildings

The Worst Case Approach

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Preface

Engineers are always interested in the worst-case scenario. The seismic design of buildings should ensure structural safety against the worst possible future earthquakes. The features of this monograph are:

(1) Consideration of elastic–plastic behavior of building structures in the critical excitation method for improved building-earthquake resilience,
(2) Consideration of uncertainties of structural parameters in structural control and base-isolation for improved building-earthquake resilience, and
(3) New insights into structural design of super high-rise buildings under long-period ground motions (case study on tall buildings in mega cities in Japan during the 2011 off the Pacific coast of Tohoku earthquake on March 11).

This book consists of two parts. The first part deals with the characterization and modeling of worst or critical ground motions on inelastic structures. The second part of the book focuses on investigating the worst-case scenario for passively controlled and base-isolated buildings.

Chapter 1 provides an overview of the effects of historic and recent strong earthquake ground motions on building structures and associated life loss.

Chapter 2 provides comprehensive information about the most recent and devastating Tohoku earthquake of moment magnitude 9.0 which hit off the pacific coast of eastern Japan on 11 March 2011. This earthquake and the tsunami following it left severe damage to building structures and caused nearly 20,000 of losses of life.

As is well known, the robust design of buildings for future earthquake loads requires reliable understanding of the ground motion characteristics. Accordingly, Chaps. 3 and 4 report on the characteristics of near-field (near-fault) ground motions with pulse-like acceleration. Furthermore, these two chapters provide simple mathematical models for this class of ground motions and associated structural response. Chapter 3 deals with the simulation of near-field ground motions with pulse-like acceleration while a critical excitation of multiple sequences for inelastic responses is discussed in Chap. 4.

Chapters 5–7 deal with the characterization and modeling of earthquake ground motion of multiple sequences. Recently, this class of ground motions was clearly observed during the 2011 off the Pacific coast of Tohoku earthquake on March 11. This research subject is new and has not received adequate attention from researchers. For instance, most seismic codes specify design ground motions as single events. However, moderate ground motion with repeated acceleration sequences could lead to more severe damage to structures than a single sequence of strong ground motion. The worst-case scenario is studied within the deterministic and probabilistic frameworks. Characteristics of earthquake ground motion of repeated sequences are made clear in Chap. 5 while critical ground motion sequences are discussed in Chap. 6. In Chap. 7, responses of elastic–plastic structures to nonstationary random acceleration sequences are investigated and the reliability of such structures is evaluated.

A practical problem always arises in the design of buildings against earthquake loads. It is always difficult to select a suite of suitable earthquake records from a large set of records as input to the nonlinear time-history analysis of structures. Chapter 8 provides deterministic and probabilistic measures that can be used to identify unfavorable accelerograms. This chapter provides simple concepts which can be utilized to select a suit of appropriate earthquake records for nonlinear time-history analysis of structures.

Chapters 9 and 10 deal with the worst-scenario of earthquake loads on inelastic structures with special emphasis on the type of seismic waves of the ground motion and damage quantification using damage indices.

Chapter 11 deals with the worst-case scenario for bidirectional ground motions. Most of the current seismic-resistant design codes are based on the simulation of building response under uni-directional earthquake input. However, bidirectional input is inevitable for the reliable design of columns.

Chapters 12 and 13 tackle the worst-case scenario for passively controlled buildings. The structural member stiffness and strength of buildings are uncertain due to various factors resulting from randomness, material deterioration, temperature dependence, etc. The passive damper systems are also uncertain depending on various sources. The concept of sustainable building design under such uncertain structural-parameter environment may be one of the most challenging issues to be tackled recently. By predicting the response variability accurately, the elongation of service life of buildings may be possible.

Chapter 14 focuses on the worst-case scenario for base-isolated buildings. The stiffness and damping of the base-isolation system and the stiffness of the superstructure are selected as uncertain parameters. An efficient methodology is explained to evaluate the robustness (variability of response) of an uncertain base-isolated building.

The book closes with Chap. 15 on current challenges and future directions on design of building structures with greater earthquake resilience.

The importance of the worst-scenario approach for improved earthquake resilience of buildings and nuclear reactor facilities has been recognized and demonstrated by the recent great earthquake (March 11, 2011) in Japan. Such understanding is of extreme significance especially for large or important structures.

The word ‘unexpected incident’ is often used in Japan after the 2011 great earthquake. It may be true that the return period of this class of earthquakes at the same place could be 500–1,000 years and the use of this word may be acceptable to some extent from the viewpoint of the balance between the construction cost and the safety level. However, the critical excitation method is expected or has a potential for enhancing the safety level of building structures against undesirable incidents drawn from this irrational concept in the future. One of the most important and challenging missions of structural engineers may be to narrow the range of such unexpected incidents in building structural design. Redundancy, robustness, and resilience are expected to play important roles in such circumstances.

Izuru Takewaki
Abbas Moustafa
Kohei Fujita

Contents

Chapter 1
Introduction

1.1 Background and Review

The 1994 Northridge earthquake and the 1995 Kobe earthquake have remained as two of the most destructive earthquakes in the world and have changed thinking of earthquake and structural engineers for many years. Modern seismic codes have been revised taking into account lessons learned from these earthquakes. Notwithstanding this, the two recent devastating earthquakes in Japan (11 March 2011) and in Haiti (12 January 2010) have raised significant concerns within the earthquake engineering community [1, 2]. Perhaps these two quakes are the strongest earthquakes during the last 100 years. These earthquakes have brought to our attention the challenges still facing the developing as well as the developed countries. The 2011 Tohoku earthquake has caused massive structural damage and enormous economic loss off the Pacific coast of Tohoku in Japan. On the other hand, the 2010 Haiti earthquake has killed about 250,000 people and left a long-term suffer for the residents of the country. The signature of these two earthquakes will remain for a long time in the minds of earthquake and structural engineers. These earthquakes bring to our attention the worst-case scenario or what is also known as the critical excitation.

As is well known, engineers are always interested in the worst-case scenario. This is because engineering structures must resist static and dynamic loads during their service life without loss of safety and functionality. In the field of earthquake-resistant design, seismic design of buildings should ensure structural safety against the possible worst future earthquakes. The features of this monograph are:

(1) Consideration of elastic–plastic behavior of building structures in the critical excitation method for improved building earthquake resilience.
(2) Consideration of uncertainties of structural parameters in structural control and base isolation for improved building earthquake resilience.

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(3) New insights into structural design of super high-rise buildings under long period ground motions (case study on tall buildings in megacities in Japan during the 2011 off the Pacific coast of Tohoku earthquake on March 11).

It is well recognized and widely accepted that earthquake ground motions are uncertain even with the up-to-date cutting-edge knowledge and it does not appear easy to predict forthcoming earthquake events precisely at a specific site both in time and frequency contents [3–5]. It is therefore strongly desirable to develop a *robust* structural design method taking into account these uncertainties, enabling the design of safer structures to a broader class of design earthquakes. This also enables structural engineers to narrow the range of 'out of Scenario' and to enhance the structural safety. The concept of "critical excitation" or "worst-case input" is promising and seems to enable the realization of a rational design concept. As the limit states of structures play an important role in setting allowable structural capacity and alternative performance levels of structures during disturbances, the clarification of critical excitations for a given structure or a group of structures appears to provide the structural designers with useful information in determining excitation parameters in a reasonable and reliable way.

The method of the critical excitation was proposed in earthquake engineering by Drenick in 1970 [3] for linear elastic single-degree-of-freedom (SDOF) systems in order to take into account inherent uncertainties in the ground motions. The critical excitation that produces the maximum response from a class of allowable inputs defines the critical excitation for the given structure.

By using the Cauchy–Schwarz inequality, Drenick [3] showed that the critical excitation for a linear elastic SDOF system is its impulse response function reversed in time. This implies that the critical envelope function for linear elastic SDOF systems in deterministic problems can be represented by an increasing exponential function and the critical excitation must be defined from the time at minus infinity. This result may be unrealistic and of only theoretical significance. However, Drenick's paper in 1970 is pioneering in the field of critical excitation since it paved way for developing a new concept. It was often suggested that the critical response by Drenick's model (1970) is conservative. To remedy this point, Shinozuka [4] discussed the same problem in the frequency domain and proved that, if an envelope function of Fourier amplitude spectra can be specified, a narrower upper bound of the maximum response can be derived.

After the works of Drenick and Shinozuka, many useful theories and methods have been proposed on critical excitation including the work of Iyengar [6] and Iyengar and Manohar [7]. The interested readers can refer some of the recent review articles e.g., [5, 8]. The works of Takewaki [5, 8] and Abbas and Manohar [9] tackle the probabilistic modeling of critical excitations in the frequency domain. Abbas and Manohar [9] and Abbas [10], Moustafa [11, 12] tackled the deterministic modeling of critical excitations.

1.2 Input Ground Motion and Worst-Case Scenario

The structural response under random or uncertain loads, such as wind or strong ground motion, depends primarily on how accurate the mathematical models adopted in describing the structural behavior and in predicting possible future earthquake events at the site. In general, the earthquake load can be specified as input to the structure using the response spectrum method, the recorded ground accelerations, or using the theory of random vibration. Each of these methods accounts for uncertainty involved in the earthquake load in a different way. As is well known, the uncertainty involved in the dynamic load, resulting from the fault properties, travel path, and local soil condition, represents the main source of uncertainty arising in the structural response compared to the uncertainty resulting from the variability in the structure's parameters (e.g., cross-section dimensions and capacity). For instance, it is difficult to predict the future ground motion that can cause maximum damage to the structure during its lifetime. This difficulty includes the time, location, and ground motion characteristics (e.g., total duration, energy, frequency content, peak acceleration, etc.). On the other hand, the structural behavior can be accurately described using mathematical models with relatively lower uncertainty.

Structural engineers are required to design safe structures against possible future earthquake events on one hand, and to achieve optimum use of the construction material on the other hand. This implicitly implies that one has to model the worst future ground motion capable of causing the largest damage in the structure. The preface of the recent book by Elishakoff and Ohsaki [13] provides a historic review on the development of the worst-case scenario or what is also known as the critical excitation. The senior author communicated with Drenick (Drenick, 2002, "Private communication") and was informed that the work by Prof. Drenick was motivated by his communication with Japanese researchers in the late 1960s.

In short, the worst-case scenario is an asymptotic scenario in which the maximum response of the structure under possible worst future earthquakes is estimated. Theoretically, the predicted future seismic load represents the worst earthquake load that can happen at the site and the associated response, i.e., the worst response. In this case, the worst ground motion is mathematically obtained using constrained optimization techniques. The constraints associated with the optimization problem involve the main characteristics of the earthquake loads estimated from the seismic data available at the site or from other sites with similar geological soil conditions.

1.3 Organization of the Book

This book consists of two parts. The first part deals with the characterization and modeling of worst or critical ground motions on inelastic structures. The second part of the book focuses on investigating the worst-case scenario for passively controlled and base-isolated buildings.

This chapter provides an overview on the effects of historic and recent strong earthquake ground motions on building structures and associated life loss.

Chapter 2 provides a comprehensive information on the most recent and devastating Tohoku earthquake of moment magnitude 9.0 which hit off the pacific coast of eastern Japan on 11 March 2011. This earthquake and the tsunami following it left severe damage to building structures and caused nearly 20,000 life loss [1].

As is well known the robust design of buildings for future earthquake loads requires reliable understanding of the ground motion characteristics. Accordingly, Chaps. 3 and 4 report on the characteristics of near-fault ground motions with pulse-like acceleration. Furthermore, these two chapters provide simple mathematical models for this class of ground motions and associated structural response [14, 15].

Chapters 5–7 deal with the characterization and modeling of earthquake ground motion of multiple sequences [16–18]. This research subject is new and has not received adequate attention from researchers. For instance, most seismic codes specify design ground motions as single events. However, moderate ground motion with repeated acceleration sequences could lead to severe damage to structures than strong ground motion of a single sequence. The worst-case scenario is studied within the deterministic and the probabilistic frameworks.

A practical problem always arises in the design of buildings against earthquake loads. It is always difficult to select a suite of suitable earthquake records from a large set of records as input to the nonlinear time-history analysis of structures. Chapter 8 provides deterministic and probabilistic measures that can be used to identify unfavorable accelerograms [19]. This chapter provides simple concepts which can be utilized to select a suite of appropriate earthquake records for nonlinear time-history analysis of structures.

Chapters 9 and 10 deal with the modeling worst scenario of earthquake loads on inelastic structures with special emphasis on the type of seismic waves of the ground motion and structural damage quantification using damage indices [12, 20, 21].

Chapter 11 deals with the mathematical modeling of the worst-case scenario for bidirectional ground motions [22]. In this context, it may be recalled that, most of current seismic-resistant design codes are based on the simulation of building response under unidirectional earthquake input. However, bidirectional input is inevitable for the reliable design of columns.

Chapters 12 and 13 tackle the modeling of the worst-case scenario for passively controlled buildings. The structural properties such as the member stiffness and strength of buildings are modeled as uncertain due to various factors resulting from randomness, material deterioration, temperature dependence, etc. [23, 24]. The passive damper systems could also contain uncertain parameters depending on various sources. The concept of sustainable building design under such uncertain structural-parameter environment may be one of the most challenging issues to be tackled recently. By predicting the response variability accurately, extending the service life of buildings may be possible.

Chapter 14 focuses on the worst-case scenario for base-isolated buildings [25]. The stiffness and damping parameters of the base-isolation system and the stiffness of the super structure are modeled as random variables. An efficient methodology is explained to evaluate the robustness (variability of response) of an uncertain base-isolated building.

This book closes with Chap. 15 on current challenges and future directions on design of building structures with greater earthquake resilience.

The importance of the worst scenario approach for improved earthquake resilience of buildings and nuclear reactor facilities has been recognized and demonstrated by the recent great earthquake in Japan. Such understanding is of extreme significance especially for important structures and critical facilities.

The word ‘unexpected scenario’ is often used in Japan after the 2011 great earthquake. In fact, this quake reminds us of the 1923 Great Kanto earthquake that killed more than 140,000 people in Tokyo and surrounding area and left massive damage to structures. It may be true that the return period of this class of earthquakes at the same place could be 500–1,000 years and the use of this word may be acceptable to some extent from the viewpoint of the balance between the construction cost and the safety. However, the critical excitation method is expected or has a potential for narrowing the range of ‘unexpected scenario’ and enhancing the safety of building structures against undesirable incidents drawn from this irrational concept in the future.

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Chapter 2
Earthquake Resilience of High-Rise Buildings: Case Study of the 2011 Tohoku (Japan) Earthquake

2.1 Introduction

Accumulated data and experiences are very important in the reliable seismic design of structures. However, it is also true that theoretical expectations and predictions are also of significance for the design of extremely important structures and facilities which are influential for the society and wide district. This was demonstrated in the past earthquakes which are very rare from the viewpoint of return period in the same area.

The most devastating earthquake in Japan after the 1923 Great Kanto earthquake hit eastern Japan in the afternoon of March 11, 2011 (see [1], Takewaki [2, 3], Takewaki et al. [4]). The moment magnitude 9.0 earthquake is one of the five most powerful earthquakes in the world since modern record-keeping began in 1900. It was made clear afterward that the recording system for low-frequency and large-amplitude ground motions was not sufficient in Japan and the first preliminary Japan Meteorological Agency (JMA) magnitude was smaller than 8 (7.9 exactly). The JMA magnitude was updated immediately as 8.4. Records of earthquake ground motions outside Japan were then used to determine the exact moment magnitude of 9.0 (intermediate announcement was 8.8). The earthquake resulted from the thrust faulting near the subduction zone plate boundary between the Pacific and North America Plates (AIJ [1], NIED [5], USGS [6]).

Nearly 20,000 people were killed or are still missing by this great earthquake and the ensuing monster tsunami as of November 1, 2011. The principal cause of this devastating result is due to the great tsunami following the large earthquake. Table 2.1 and Fig. 2.1 show the human and economic loss in recent major natural disasters (data from Asahi newspaper [7]). It can be observed that the economic loss in the 2011 off the Pacific coast of Tohoku earthquake is extremely large.

The maximum height (run-up height) of the tsunami was reported to have attained almost 40 m (Miyako City, Iwate Prefecture) and this was observed in the

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Table 2.1 Human and economic loss in recent major natural disasters (data from Asahi newspaper [7])

	Number of victims	Economic loss (Billion dollars)
East Japan great earthquake disaster (2011)	20,631	309
Hurricane Katrina (2005)	1,833	135
Hyogoken–Nanbu earthquake (Kobe EQ 1995)	6,437	100
China (2008)	87,476	85
Chile earthquake (2010)	562	30
New Zealand earthquake (2011)	181	13
Haiti earthquake (2010)	222,570	7.8
North Pakistan earthquake (2005)	73,338	5.2
Sumatra earthquake (2004)	165,708	4.5
Cyclone Nargis (Myanmar 2008)	138,366	4.0

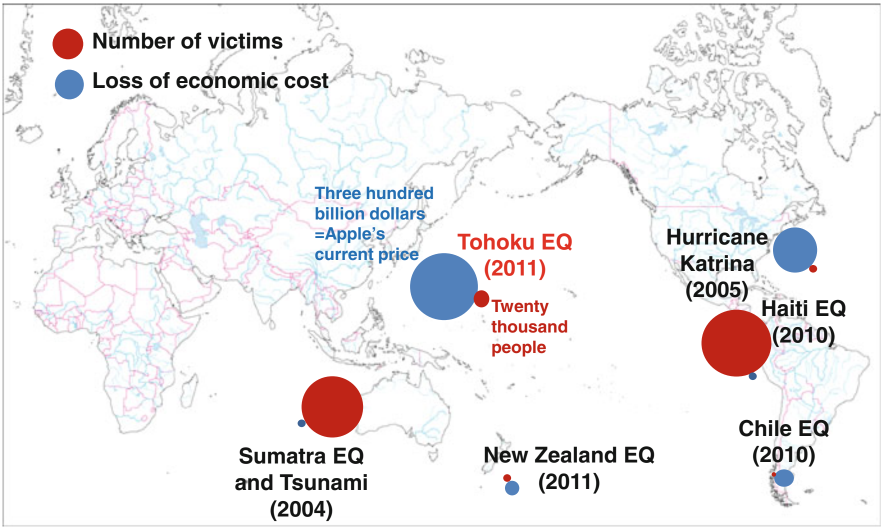


Fig. 2.1 Human and economic loss in recent major natural disasters (data from Asahi newspaper [7])

bay area with complex coast line shapes. It was also reported that the tsunami arrived at the third or fourth story in some buildings and invaded over 5 km from the coastline (Natori City, Miyagi Prefecture). It should be remarked that the number of collapsed (or damaged) buildings and houses remains not clear because most of the damages resulted from the tsunami and a clear record was not left. More detailed data on this earthquake can be obtained from the National Research Institute for Earth Science and Disaster Prevention (NIED) of Japan.

Because super high-rise buildings in mega cities in Japan have 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 now one of the most controversial issues in the field of earthquake-resistant design in Japan [8]. The issue of long-period ground motion and its effect on building structural design was initially brought up in Mexico, the USA, and Japan during 1980–1990s (for example [9–10]). Some clear observations have actually been reported recently (most famous one is the severe sloshing in oil tanks during the Tokachioki earthquake, Japan in 2003 [11]) and the earthquake ground motions in Tokyo, Yokohama, and Osaka during the March 11, 2011 earthquake are regarded to be extremely influential for super high-rise buildings. In December 2010, just before this earthquake, a set of simulated long-period ground motions was constructed and provided by the Japanese Government [8] for the retrofit of existing high-rise buildings and as a design guideline for new high-rise buildings.

In this chapter, we describe first the characteristics of this 2011 earthquake and discuss the properties of long-period ground motions from the viewpoint of critical excitation, i.e., the phenomenon of resonance characterized by the coincidence of the predominant period of ground motions with the fundamental natural period of high-rise buildings. It is shown that the criticality of the long-period ground motions can be investigated based on the theory of critical excitation [12–14]. This theory is intended to overcome the difficulty resulting from the uncertainty of earthquake ground motions (for example Geller et al. [15]). The credible bounds of input energy responses are obtained using the critical excitation method with the constraints on acceleration and velocity powers. It is demonstrated that the long-period ground motions can be 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 fairly large long-period wave components.

Furthermore, tentatively designed 40- and 60-story steel buildings are subjected to such long-period ground motion as recorded in Shinjuku, Tokyo during the 2011 off the Pacific coast of Tohoku earthquake. It is shown that high-hardness rubber dampers, a kind of viscoelastic dampers with low temperature and frequency dependency, are able to damp the building vibration during long-period ground motions in an extremely shorter duration than in case of the building without those dampers. It is reported recently that this high-hardness rubber damper has a damping performance comparable with oil dampers. Two assumed 40-story steel buildings are also subjected to a set of simulated long-period ground motions taken from a December 2010 document of the Japanese Government [8] for the detailed investigation of response characteristics of super high-rise buildings under many simulated long-period ground motions in various areas.

2.2 General Characteristics of the 2011 Off the Pacific Coast of Tohoku Earthquake

The general characteristics of the 2011 off the Pacific coast of Tohoku earthquake are explained first. The source inversion and slip distribution using near-source strong ground motions are shown in Fig. 2.2a [16]. Since it is necessary to understand the size of the 2011 earthquake, the comparison of slipped fault size is shown in Fig. 2.2b among the 2004 Sumatra earthquake ($M = 9.1$), the 1923 Great Kanto earthquake ($M = 7.9$), the 1995 Hyogoken-Nanbu (Kobe) earthquake ($M = 7.3$), and the 2011 off the Pacific coast of Tohoku earthquake ($M = 9.0$) [17]. Due to the large magnitude and the distance from the source to the Honshu island of Japan, fairly wide areas in the eastern Japan were influenced and shaken by this earthquake.

The representative near-source ground motions along the Pacific coast in the eastern Japan are illustrated from north to south in Fig. 2.3a [18]. It can be found that two or more series (or groups) of waves exist in some areas and most ground motions continue for over 2 min. This implies the repeated occurrence of the fault slips in wide areas. This phenomenon has been pointed out by many researchers (for example Elnashai et al. [19], Hatzigeorgiou and Beskos [20], Moustafa and Takewaki [21]). It was reported afterwards that three main fault slips were observed in this series of events, i.e., the first at the eastern side of Sendai City (off Miyagi Prefecture), the second at the southern (off Miyagi and Fukushima Prefectures) and northern (off Iwate Prefecture) parts of the first one, and the third at the further southern side of the second slip (off Ibaragi Prefecture).

Figure 2.3b presents a more detailed description of those recorded ground motions (Yellow star indicates the epicenter). The following is the interpretation by NIED of Japan [22]. In Tohoku area (from Iwate Prefecture through Fukushima Prefecture), two wave groups (pink and yellow colors) can be observed from the vicinity of the epicenter (star mark). This means that main fault ruptures occurred twice in the vicinity of the epicenter one after another. In Fukushima Prefecture, a wave group (blue color) can be observed around 200 s toward the north. There are intensive waves between the yellow and the blue arrows. In Ibaragi Prefecture, a wave group (blue color arrow downward) can be seen. These results imply that a fault rupture occurred around the epicenter and this rupture induced many subsequent ruptures.

It is believed that the data of ground motions in Fig. 2.3 are very useful for the investigation of the accuracy of methods for constructing the ground motions from several sources. The distributions of the maximum ground accelerations and the maximum ground velocities determined from K-NET and KiK-net (NIED) data are shown in Fig. 2.4 [23].

Table 2.2 shows the top ten largest observed peak ground accelerations during this earthquake [18]. It is found that the maximum ground acceleration over 2.9 g was recorded at the K-NET station of Tsukidate in Kurihara City of Miyagi Prefecture. However, it is reported that the predominant period of this ground

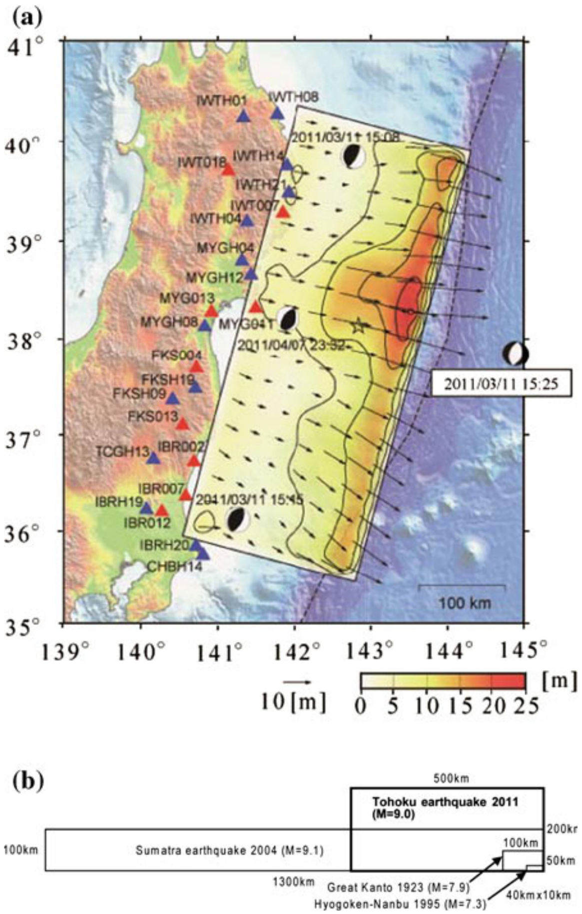
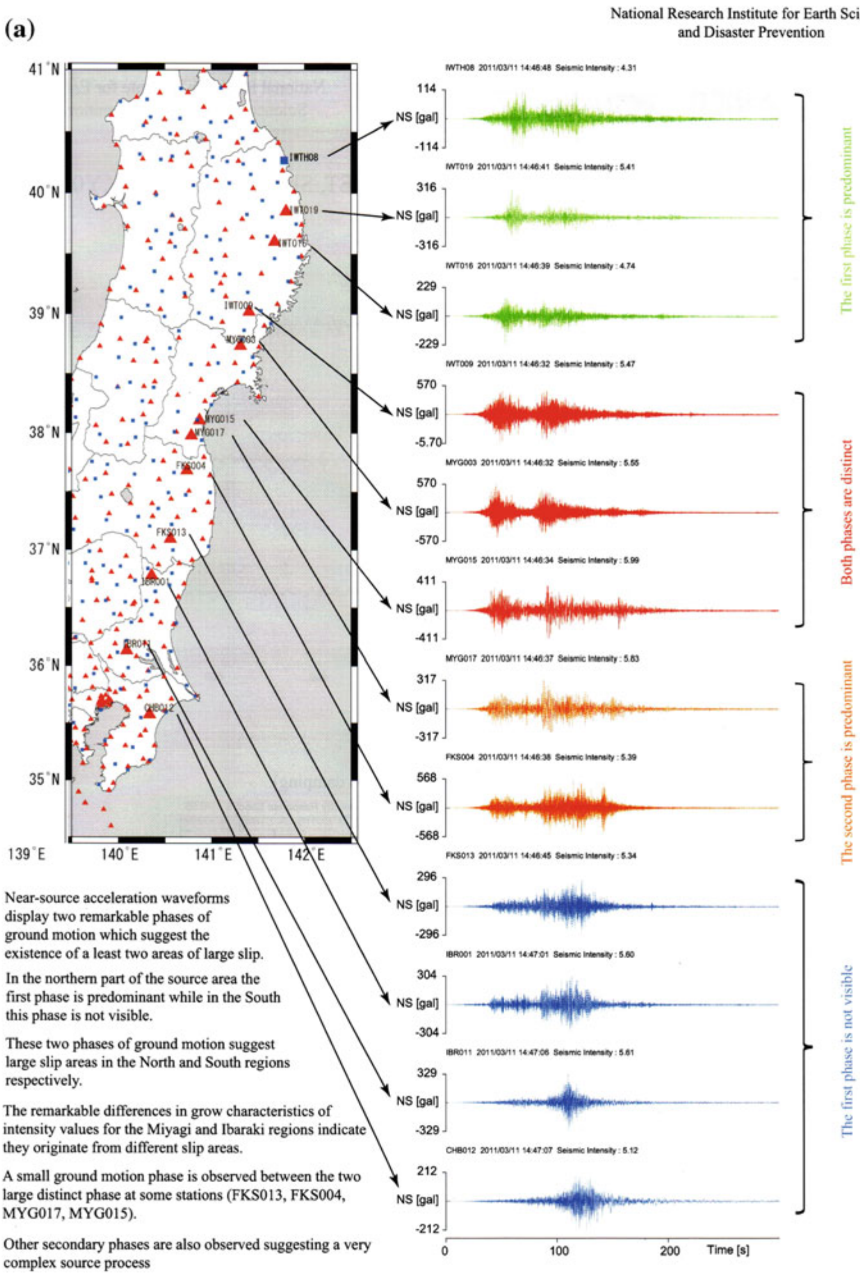


Fig. 2.2 **a** Source inversion and slip distribution using near-source strong ground motions [16], **b** Fault size of 2004 Sumatra earthquake ($M = 9.1$), 1923 Great Kanto earthquake ($M = 7.9$), 1995 Hyogoken-Nanbu (Kobe) earthquake ($M = 7.3$), and 2011 off the Pacific coast of Tohoku earthquake ($M = 9.0$) (data from Asahi newspaper [17]) (Reproduced from Takewaki et al. [4] with kind permission from © Elsevier)

motion is shorter than 0.3 s and this ground motion did not affect most buildings so much. These ground motion characteristics are common in almost all the areas along the Pacific coast in eastern Japan and the damage to buildings is not so large in spite of the tremendous magnitude of 9.0. The damages of most buildings are thought to result from the monster tsunami.

Other peculiar points observed in this 2011 earthquake may be a wide spread of liquefaction and settlement of land along the Pacific coast in Miyagi and Iwate Prefectures. It was reported that remarkable liquefaction occurred in many places on soft grounds including sands (over 42 km^2 even in Tokyo bay area) and the settlement over 1 m of land in Miyagi and Iwate Prefectures may result from the movement of plates near the epicenter. It is understood that the unexpected wide spread of liquefaction in spite of not so high level of maximum ground acceleration results from the long duration of shaking (over 2 min and four times longer than the Hyogoken-Nanbu earthquake). It is thought that this long duration of



Near-source acceleration waveforms display two remarkable phases of ground motion which suggest the existence of a least two areas of large slip.

In the northern part of the source area the first phase is predominant while in the South this phase is not visible.

These two phases of ground motion suggest large slip areas in the North and South regions respectively.

The remarkable differences in grow characteristics of intensity values for the Miyagi and Ibaraki regions indicate they originate from different slip areas.

A small ground motion phase is observed between the two large distinct phase at some stations (FKS013, FKS004, MYG017, MYG015).

Other secondary phases are also observed suggesting a very complex source process

Fig. 2.3 **a** Characteristics of near-source ground motions along Pacific coast in East Japan [18], **b** Relation among fault rupture, wave propagation, and ground motion sequences (*Yellow star* indicates the epicenter) [22]

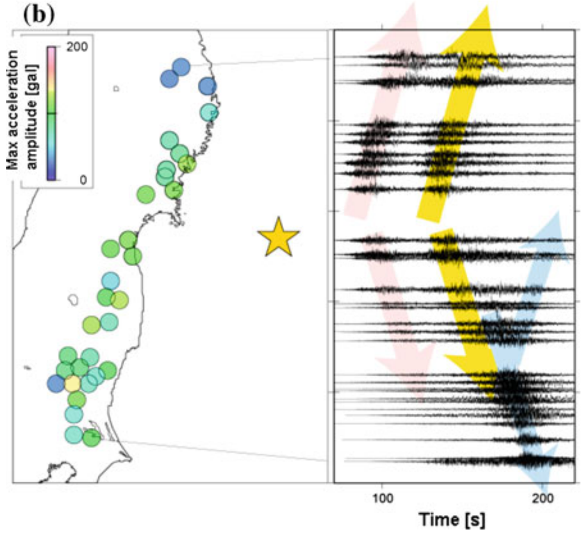


Fig. 2.3 (Continued)

shaking caused a rapid increase of excess pore water pressure. The liquefaction was also observed in Tokyo bay area and it was reported that 14.5 km^2 experienced liquefaction in Urayasu City in Chiba prefecture (one of Tokyo bay area cities).

As stated above, one of the most important issues in mega cities like Tokyo, Osaka, and Nagoya during this 2011 earthquake is the occurrence of long-period ground motions which could affect severely most super high-rise buildings through the resonant phenomenon. It is often reported that many super high-rise buildings in Tokyo and Osaka were severely shaken by those long-period ground motions. This issue will be discussed in the following sections in detail.

2.3 Seismic Response Simulation of Super High-Rise Buildings in Tokyo

2.3.1 Properties of Ground Motions in Tokyo

Figure 2.5a shows the acceleration waveforms of the long-period ground motion recorded at K-NET, Shinjuku station (TKY007) [18] and Fig. 2.5b presents the corresponding velocity wave forms [18]. 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 velocity response spectra for 1 and 5 % damping are shown in Fig. 2.6 [18]. The corresponding ones of Japanese seismic design code for 5 %

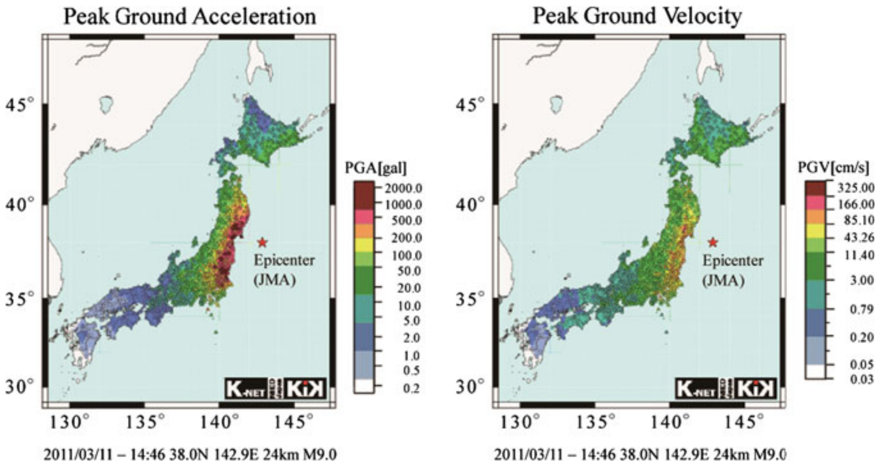


Fig. 2.4 Maximum ground accelerations and maximum ground velocities determined from K-NET and KiK-net data [23]

Table 2.2 List of 10 largest observed peak ground accelerations [18]

	Station name	PGA (gal)	JMA instrumental intensity[a]
1	MYG004	2,933	6.6
2	MYG012	2,019	6.0
3	IBR003	1,845	6.4
4	MYG013	1,808	6.3
5	IBR013	1,762	6.4
6	FKSH10	1,335	6.0
7	TCGH16	1,305	6.5
8	TCG014	1,291	6.3
9	IBRH11	1,224	6.2
10	MYGH10	1,137	6.0

[a] *JMA* Japan Meteorological Agency

MYG Miyagi prefecture, *IBR* Ibaragi prefecture, *FKS* Fukushima prefecture, *TCG* Tochigi prefecture. This list is based on information obtained by March 13, 2011 from 276 K-NET and 112 KiK-net sites

damping are also plotted in Fig. 2.6. It is understood that these ground motions include long-period components up to 10 s. The duration of records at K-NET stations is 300 s and it was found that this duration is not sufficient for the investigation of long-period ground motions.

For investigating further the long-period characteristics of that record, the Fourier amplitude spectra of both acceleration and velocity records have been obtained. Figure 2.7 shows the Fourier amplitude spectra of accelerations of Fig. 2.5a and Fig. 2.8 illustrates those of velocities of Fig. 2.5b [2].

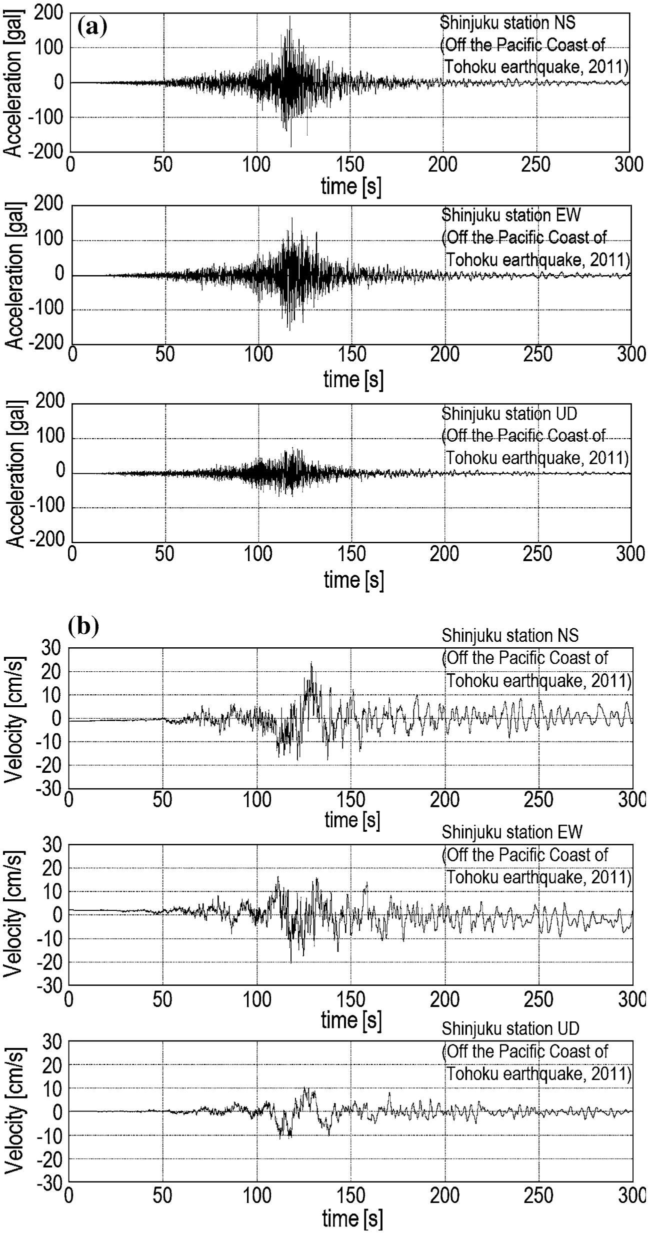


Fig. 2.5 **a** Long-period acceleration ground motion recorded at K-NET, Shinjuku station (TKY007) (Reproduced from Takewaki et al. [4] with kind permission from © Elsevier), **b** Long-period velocity ground motion recorded at K-NET, Shinjuku station (TKY007) (Reproduced from Takewaki et al. [4] with kind permission from © Elsevier)

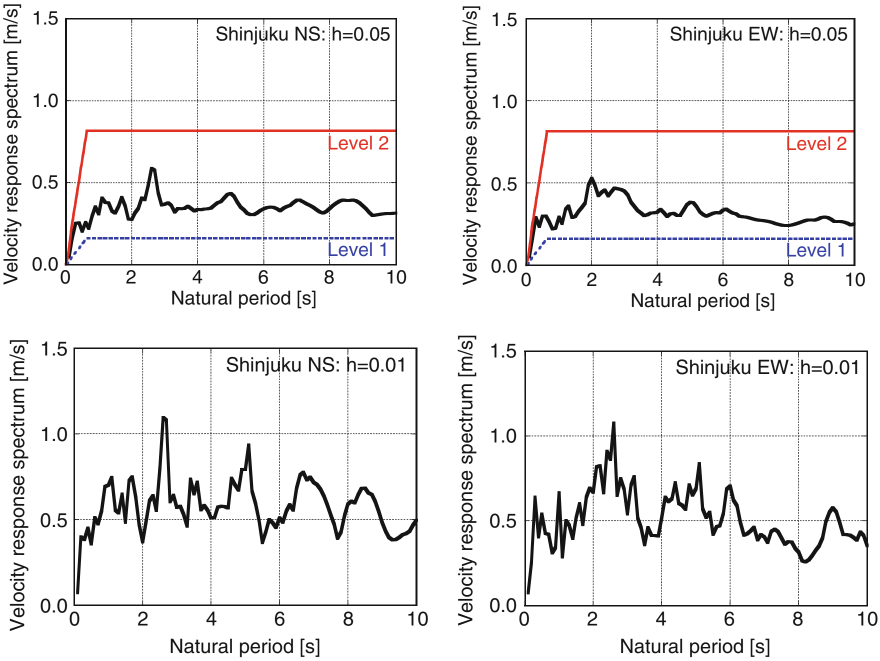


Fig. 2.6 Velocity response spectra (5 and 1 % damping) of ground motions at Shinjuku station (TKY007) and the corresponding ones of Japanese seismic design code for 5 % damping (Reproduced from Takewaki et al. [4] with kind permission from © Elsevier)

Fig. 2.7 Fourier amplitude spectra of acceleration ground motion at K-NET, Shinjuku station (TKY007) (Reproduced from Takewaki et al. [4] with kind permission from © Elsevier)