17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

CAN GROUND MOTION STUDIES CONTRIBUTE TO ANTI-CATASTROPHE DESIGN?

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Abstract

After the serious tsunami disaster during the 2011 Tohoku earthquake and the subsequent severe accident at the Fukushima-Daiichi Nuclear Power Plant, civil engineers in Japan have been discussing the preparedness of infrastructures to unexpected events. They proposed a new design concept called the “anti-catastrophe design concept”, where a structure is said to be “anti-catastrophe” when the structure or the structure-environment system does not exhibit catastrophic situation even in an unexpected event. The author joined the working group as an engineering seismologist. Therefore, the question that the author had to face was “Can ground motion studies contribute to this new design concept?” In this article, the author tried to answer the question by reviewing the current situations faced by ground motion studies in Japan and by discussing what ground motion studies can really tell about future ground motions.

After the 1995 Hyogo-ken Nanbu (Kobe) earthquake, there were high expectations for ground motion studies among civil engineers in Japan. The proposals issued by the Japan Society of Civil Engineers were in favor of incorporating the results of ground motion studies to the design of infrastructures. The author’s observation is that such expectations for ground motion studies have decreased and that the tendency was influenced by engineers’ suspicion about the maturity of ground motion studies. Based on the above observations, the question is “Can ground motion studies really contribute to the safety of the society?” To answer this question, the author’s view was summarized in terms of what ground motion studies can and cannot tell about future ground motions. Ground motion studies can reliably tell about the relative amplitude of ground motions between different sites and the site-specific predominant frequencies. On the other hand, it is necessary to admit that the absolute amplitude of ground motions accompanies significant amount of uncertainty as suggested by insightful engineers, mainly because the location and size of a future earthquake involve significant uncertainty. Given the limitations above, the author still believes that ground motion studies can contribute to the safety of the society by preparing site-specific design ground motions that are consistent with the amplification characteristics and the site-specific predominant frequencies at each site. On the other hand, because of our experience of past damaging earthquakes in Japan, the Japanese engineers are reluctant about using the results of PSHA to evaluate the safety of structures.

To understand the performance of structures under extreme events, every kind of available tools should be used. Ground motion studies can contribute to anti-catastrophe design by providing a group of realistic site-specific ground motions that can be used in shake table tests or earthquake response analyses.

Keywords: Anti-catastrophe design, Ground motion studies, Site-specific ground motions, uncertainty

1. Introduction

As already discussed in our papers presented in the previous WCEE [1, 2], civil engineers in Japan have been discussing the preparedness of infrastructures such as railway structures, highway structures and port structures to unexpected events, motivated by the serious tsunami disaster during the 2011 Tohoku earthquake and the subsequent severe accident at the Fukushima-Daiichi Nuclear Power Plant. The author joined a working group to discuss this issue within the framework of the Earthquake Engineering Committee, the Japan Society of Civil Engineers.

In the conventional seismic design of these structures, two kinds of design ground motions, namely, the level 1 and 2 design ground motions have been considered and the structures have been designed so that they satisfy respective performance requirements. In particular, the level 2 design ground motion have been determined by taking into account severe ground motions from shallow crustal and subduction earthquakes. In the conventional design, however, less attention has been paid to the performance of structures subject to a strong ground motion exceeding the level 2 design ground motion.

In light of the lessons learnt from the 2011 Tohoku earthquake, the working group recognized the necessity to consider the performance of structures under unexpected events and its consequences. The working group proposed a new design concept called the “anti-catastrophe design concept” [1], where a structure is said to be “anti-catastrophe” when the structure or the structure-environment system does not exhibit catastrophic situation even in an unexpected event.

The author joined the working group as an engineering seismologist. Therefore, the question that the author had to face was “Can ground motion studies contribute to this new design concept?” In this article, the author tries to answer the question by reviewing the current situations faced by ground motion studies in Japan and by discussing what ground motion studies can really tell about future ground motions.

2. Decreasing expectations for ground motion studies

The author decided to devote himself to ground motion studies after the great damage to infrastructures caused by the 1995 Hyogo-ken Nanbu (Kobe) earthquake (M_J7.3). This decision was made mainly because the author was so impressed by the research results on this earthquake by the group of Professor Irikura, who was in Kyoto University at that time. The great damage during this event was caused by pulse-like ground motions having a period of 1-2 s. Professor Irikura’s group revealed that the pulse-like ground motions were generated by the rupture of asperities. Their fault model with multiple asperities accurately reproduced pulse-like ground motions [3]. Fig. 1 shows the improved version of their source model [4]. Fig. 2 shows how the pulse-like ground motions can be reproduced with the source model. Although their analyses were postdictions instead of predictions, their success of explaining actual phenomena seemed to suggest the promising future of ground motion studies. The author believed that ground motion simulations will soon be an indispensable tool to improve the safety of infrastructures.

The author was not the only engineer who was impressed by the achievements of ground motion studies at that time. After the Kobe earthquake, the Japan Society of Civil Engineers issued proposals on seismic design standards for infrastructures [6, 7]. The proposals were in favor of incorporating the results of ground motion studies to the design of infrastructures. The third proposal stated “the level 2 design ground motion should be determined taking into account historical earthquakes, the distribution of potential earthquake faults, subsurface structures, ground conditions and the results of earthquake observations”. Such expressions indicate great expectations by the civil engineers for the future of ground motion studies at that time.

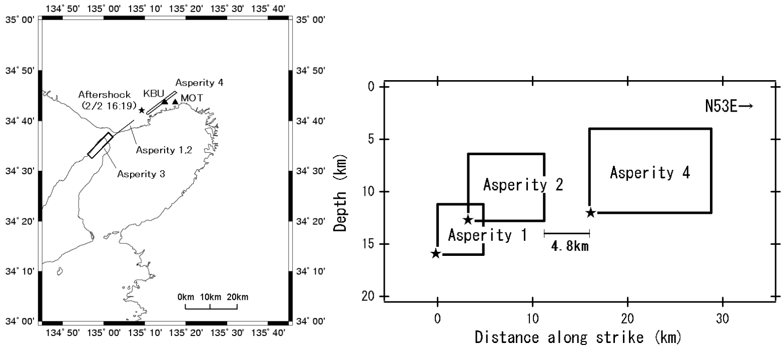

Fig. 1 – The source model with asperities by Yamada *et al.* [4] for the 1995 Hyogo-ken Nanbu (Kobe) earthquake (M_J7.3), which is an improved version over the model by Kamae and Irikura [3].

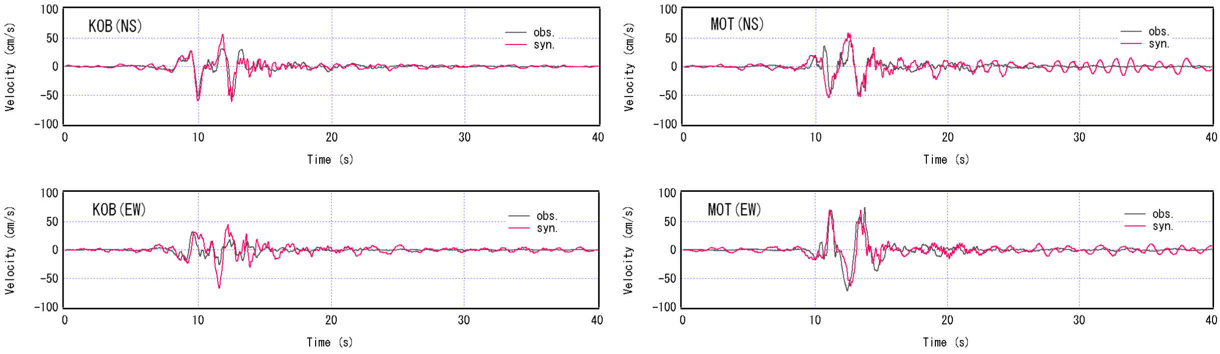

Fig. 2 – Recorded (black) and synthetic (red) velocity waveforms at KBU and MOT for the 1995 Hyogo-ken Nanbu earthquake [5]. The source model by Yamada *et al.* [4] (Fig.1) was used.

The author’s observation is that such expectations for ground motion studies has decreased. For example, the 2002 version of the design specifications for highway bridges in Japan [8] stated “the level 1 and 2 design ground motions should be determined taking into account historical earthquakes, information on active faults, information on plate-boundary earthquakes, subsurface structures, ground conditions and the results of earthquake observations when the design ground motions can be appropriately evaluated based on such information”. This expression has been deleted in the 2012 and 2017 versions of the design specifications for highway bridges [9, 10]. Now the civil engineers are rather reluctant to incorporate the results of ground motion studies to the design of infrastructures.

The authors’ view is that this tendency was influenced by engineers’ suspicion about the maturity of ground motion studies. For example, Takahashi *et al.* [11] stated “the (long-term) prediction of earthquakes and tsunamis accompanies huge uncertainty; it is impossible to guarantee the safety of structures for sure against these events with our current technologies”. Kawashima [12], in his book, prepared a section entitled as “Characteristics of Strong Motions beyond Our Current Knowledge” and mentioned “strong motion predictions involves many unresolved aspects”. One of my colleagues once told me “How can we use the results of strong motion predictions when the occurrence of an earthquake of M9.0 cannot be expected in advance?” All of these comments are expressions of engineers’ suspicion about the maturity of ground motion studies.

3. What can ground motion studies really tell about future ground motions?

Based on the above observations, the question is "Can ground motion studies really contribute to the safety of the society?" The author's answer is "Yes, but probably in a different way from common expectations". In the following, the author's view will be summarized in terms of what ground motion studies can and cannot tell about future ground motions.

Generally speaking, strong ground motions are determined by three effects, namely, the source, path and site effects as shown in Fig. 3. The source effect can be defined as the characteristics of seismic waves generated at the earthquake source as a result of a rupture process on the fault. The path effect can be defined as the attenuation and deformation of seismic waves during their propagation from the source to the upper boundary of the seismological bedrock below the site. The site effect can be defined as the influence of sediments above the seismological bedrock on the seismic waves. The seismological bedrock can be defined as the layers having a shear wave velocity greater than or equal to 3,000 m/s and it is often composed of granite in Japan.

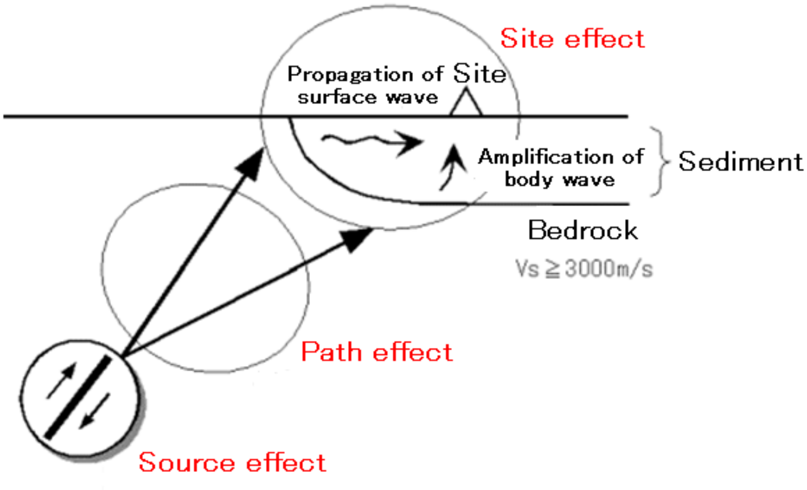

Fig. 3 – Source, path and site effects.

The existence of sediments below the site has significant effects on the amplitude, frequency content and duration of strong ground motions. It is important to recognize that the "sediments" involve not only shallower sediments with SPT N values smaller than 50 (shear wave velocities smaller than about 300 m/s) but also deeper sediments with N values greater than 50 (shear wave velocities ranging from 300-3,000 m/s). Seismic waves are mainly amplified due to the contrast of shear wave velocity. Because the contrast of shear wave velocity between the surface and the bedrock is sometimes as large as 20 (=3,000/150), seismic waves are significantly amplified by the existence of the sediments. The frequency content of strong ground motions is closely related to the thickness of the sediments. The relationship between the subsurface structure and the characteristics of ground motions is summarized in Fig. 4.

(1) At the outcrop of the seismological bedrock or a layer equivalent to it, ground motions are relatively weak.

(2) If the sediments above the seismological bedrock are thin, predominantly short period ground motions are observed, because the natural period of the sediments is short.

(3) If the sediments above the seismological bedrock are thick, predominantly long period ground motions are observed, because the natural period of the sediments is long.

(4) If the sediments have a closed shape, long duration ground motions are observed, because the seismic waves are easily trapped and continue reverberation within the sediments.

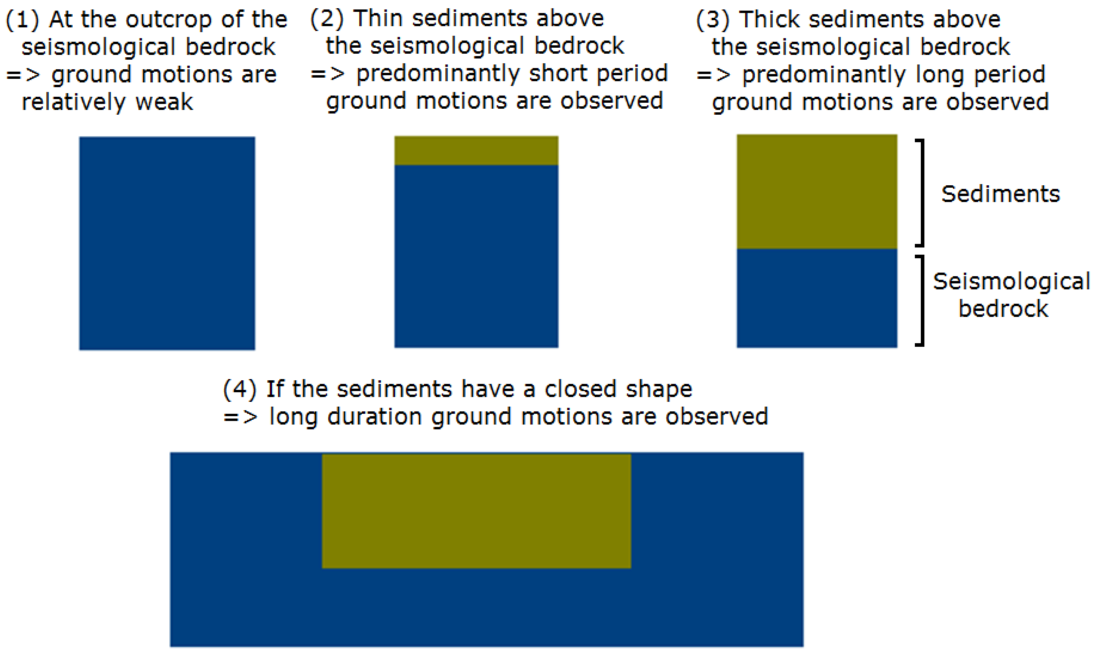

Fig. 4 – Relationship between the subsurface structure and the characteristics of ground motions.

There have been a lot of case histories in which earthquake ground motions were significantly affected by the existence of sediments. For example, it has been suggested that the “damage belt” in the City of Kobe during the 1995 Hyogo-ken Nanbu earthquake was generated partly because pulse-like ground motions with periods of 1-2 s were amplified by the sediments below the City of Kobe [13].

Fig. 5 shows another example of the importance of the site effect. The left panel shows the topography around the Port of Sakai, west Japan. Two observation stations, namely, Sakaiminato-G (Strong Motion Earthquake Observation in Japanese Ports) and JMA (the Japan Meteorological Agency) are located in the plains of Yumigahama Peninsula in the left-hand side of the photo. Other two stations, namely, SMN001 of K-NET [14] and SMNH10 of KiK-net [15] are located in mountainous Shimane Peninsula in the right-hand side of the photo. Observed peak ground velocities during the 2000 Tottori-ken Seibu earthquake (M_J7.3) for the plains of Yumigahama Peninsula were approximately 60 cm/s and four times greater than the values for the mountainous Shimane Peninsula (the right panel of Fig. 5). The difference can be attributed to the amplification of seismic waves due to the existence of the sediments in Yumigahama Peninsula. Thus, the relative amplitude between different stations is controlled by the subsurface structure.

Fig. 6 shows an example of the effect of the sediments on the frequency content of strong ground motions. At Hachinohe Port, both of the Fourier spectra from the 1968 Tokachi-oki earthquake (M_J7.9) and the 1994 Sanriku Haruka-oki earthquake (M_J7.5) are characterized by a peak at the frequency of 0.4 Hz (the period of 2.5 seconds). The former record is famous as the “Hachinohe wave” and was widely used for the design of port structures in Japan in the past. On the other hand, at Kansai International Airport, both of the Fourier spectra from the 1995 Hyogo-ken Nanbu earthquake and the 2000 Tottori-ken Seibu earthquake are characterized by a peak at the frequency of 0.2 Hz (the period of 5 s). The difference of the predominant periods can be attributed to the thickness of the sediments down to the bedrock at each observation station. Thus, it is preferable to avoid constructing a structure with a natural period of 2.5 s near the strong motion station at Hachinohe Port. Similarly, it is preferable to avoid constructing a structure with a natural period of 5.0 s at Kansai International Airport. It is impressive to observe that the spectra from different earthquakes at the same station are so close to each other if we consider the fact that all of the four earthquakes introduced here were large earthquakes and presumably accompanied their own complicated rupture processes. To the author, these observations mean that the site effects are so overwhelming that they mask the difference of the source spectra.

The photo was kindly provided by the 8th Regional Coast Guard Headquarters, Japan.

Fig. 5 – The topography around the Port of Sakai, west Japan (left) and the velocity waveforms for the fault-normal component recorded around the port during the 2000 Tottori-ken Seibu earthquake (M_J7.3).

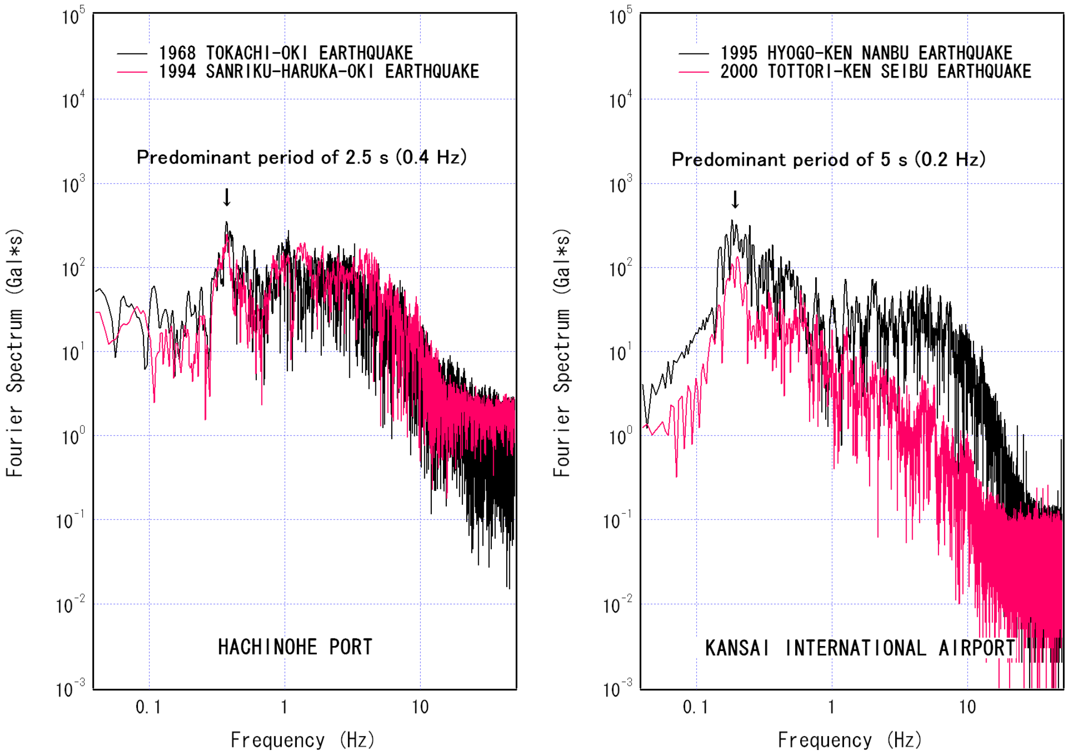

Fig. 6 – Fourier spectra of past major strong motion records obtained at Hachinohe Port (NS component) and Kansai International Airport (Runway-normal component).

To summarize, what ground motion studies can tell about future ground motions includes the relative amplitude between different sites and the site-specific predominant frequencies. Of cause the site-specific predominant frequencies will be affected by the nonlinear behavior of the soil especially at a higher frequency range. However, the site-specific predominant frequencies at a lower frequency range are rather robust and, above all, much more robust compared to other ground motion characteristics.

On the other hand, it is necessary to admit that the absolute amplitude of ground motions accompanies significant amount of uncertainty as suggested by Takahashi *et al.* [11] and Kawashima [12], mainly because the location and size of a future earthquake involve significant uncertainty. The 2011 Tohoku earthquake (M9.0) unexpectedly occurred without any warning from seismologists. The occurrence of the earthquake indicates that, by March 11, 2011, sufficiently large stress and strain have been accumulated along the Japan Trench off Miyagi through off Ibaraki, which could cause an M9.0 event at any time. It took at least 500 years for the stress and strain to be accumulated, indicating that both the stress and strain were at a sufficiently high level at least for several decades before the 2011 earthquake. Nobody noticed this accumulation before the earthquake, although the accumulation was going on along the Japan Trench which was under extensive investigations. In addition, among large crustal earthquakes in Japan between the 1995 Hyogo-ken Nanbu and the 2016 Kumamoto earthquakes, the 2000 Tottori-ken Seibu earthquake (M_J7.3), the 2005 West-off Fukuoka Prefecture earthquake (M_J7.0), the 2007 Noto Hanto earthquake (M_J6.9), the 2007 Chuetsu-oki, Niigata, earthquake (M_J6.8) and the 2008 Iwate-Miyagi Nairiku earthquake (M_J7.2) all occurred at a location where an earthquake of a comparable size was not hypothesized before the occurrence of the earthquake.

4. Can ground motion studies contribute to the safety of the society?

Given the limitations above, the author still believes that ground motion studies can contribute to the safety of the society in the following way:

(a) By appropriately investigating the site amplification factor at a construction site [16], we can prepare site-specific design ground motions that are consistent with the amplification characteristics at each site. This will enable us to efficiently strengthen structures within our limited budget.

(b) By appropriately investigating the site amplification factor at a construction site [16], we can prepare site-specific design ground motions that are consistent with the site-specific predominant frequencies. This will enable the engineers to select a structure suitable for each site, thereby reducing the risk arising from the coincidence of the natural frequency of the structure and the predominant frequency of strong ground motions.

(c) As mentioned above, the results of ground motion studies cannot be used to specify the upper limit of ground motions that will be experienced by a structure. However, engineers are sometimes requested to design a structure for a scenario earthquake similar to a past damaging earthquake occurring in a different place. This is presumably because past damaging earthquakes that had significant impact on the society such as the 1995 Hyogo-ken Nanbu earthquake or the 2011 Tohoku earthquake can be a standard and people (taxpayers or stakeholders) can relatively easily agree upon hypothesizing a similar scenario. This is why an M9.0 class earthquake has been hypothesized along the Nankai Trough after the 2011 Tohoku earthquake (M9.0) by the Cabinet Office. Similarly, an M7.8 earthquake has been hypothesized north-west-off Hokkaido, which is similar in size with the 1993 south-west-off Hokkaido earthquake (M7.8). Recall that ground motion studies have been successful in reproducing strong ground motions during past damaging earthquakes. Therefore, the results of ground motion studies will be extremely useful for determining design ground motions if such scenarios are considered.

(d) Based on ground motion studies, we can specify sites or regions susceptible to extremely strong ground motions because of their subsurface structures. This information can be used by decision makers to put priority on strengthening structures that are located in susceptible regions or to locate important facilities such as hospitals in less susceptible regions.

5. Why are we reluctant about using the results of PSHA?

Probabilistic approaches tend to be considered as a standard tool to cope with uncertainty. In the following, the author will explain why the Japanese engineers are so reluctant about using the results of probabilistic seismic hazard analyses (PSHA) to evaluate the safety of structures.

We are reluctant because of our experience of past damaging earthquakes in Japan. The 2011 Tohoku earthquake (M9.0) unexpectedly occurred without any warning. In addition, most of large crustal earthquakes in Japan between the 1995 Hyogo-ken Nanbu and the 2016 Kumamoto earthquakes occurred at a location where an earthquake of a comparable size was not hypothesized before the occurrence of the earthquake. These facts indicate that the reliability of PSHA is still in question. Kawashima [12] mentioned “Based on our common sense, it is totally meaningless to mention such values as 10^{-4}/year or 10^{-6}/year as the probability of failure”. The author completely agrees with this opinion.

PSHA is based on many probabilistic models that are difficult to validate. Probabilistic approaches are sometimes considered as a tool to “objectively” determine the design ground motions without any “judgement”, however, it is not true. When we look at the results of PSHA, “judgements” have been already done in terms of what kind of probabilistic models should we use.

Theoretically speaking, there are two major drawbacks in using PSHA for determining design ground motions.

(1) PSHA is based on many probabilistic models that are difficult to validate. For example, the occurrence of an earthquake may be assumed to follow a Poisson process. In a given region, earthquakes may be assumed to be uniformly distributed. A quantity may be assumed follow a Gaussian distribution. All of these probabilistic models are difficult to validate. Let us consider an ordinary-looking dice. It is a common practice to assign a probability of 1/6 to each pip. Then, to make sure that the dice is not a loaded dice, we can cast the dice again and again, maybe 1,000 times, until the law of large numbers starts to apply. Sometimes the test reveals that the dice is actually loaded. A similar test for the probabilistic models used in PSHA is difficult. Let’s assume a region comprising of subregions A1+A2+A3+A4+A5+A6. Let’s assume that scientists do not find any specific reason to assign different probability of earthquake occurrence to the subregions. Then the PSHA will be conducted based on the assumption that the probability is uniform. However, decades later, earth science may be much more advanced and it may be found that the probability is actually 6:0:0:0:0:0 instead of 1:1:1:1:1:1, which implies that the results of initial PSHA was wrong. To fully validate the probabilistic models, it is necessary to wait until the law of large numbers starts to apply. However, this is unrealistic in terms of earthquakes. Thus, there is no way to decide whether the results of PSHA is correct or not.

(2) Even if we can assume that the probabilistic models used in PSHA are all correct and, accordingly, the results of PSHA are all correct, it does not necessarily mean that it is reasonable to determine design ground motions according to the results of PSHA. The design working life of an infrastructure is usually 50 years or 100 years, which are too short for the law of large numbers to apply. The distribution of ground motions within the design working life will be completely different from those predicted by the maps. PSHA can only contribute to reasonable construction of infrastructures when we can wait until the law of large numbers starts to apply.

6. Can ground motion studies contribute to anti-catastrophe design?

Let’s go back to the topic of anti-catastrophe design. One of the most important ingredients of the anti-catastrophe design is to understand the performance of a structure or a structure-environment system under extreme external forces to understand its consequences. In this respect, the anti-catastrophe design is oriented in the same direction as the “risk-informed design” proposed in the revised version of ISO2394 [17], where the engineers are requested to evaluate the consequence of structural failure.

It should be noted that our knowledge is quite limited in terms of the performance of a structure or a structure-environment system subject to extreme events. Obviously more effort is needed to understand the performance of structures under extreme events to develop reliable measures or devices. To this end, every kind of available tools should be used. While simplified methods such as the alternative load path (ALP) method [17] could be useful, sophisticated methods such as model tests and numerical simulations could also be useful, as they have been useful in the study of robust breakwaters in the field of port engineering [2].

To perform shake table tests or earthquake response analyses, input ground motions exceeding design ground motions are definitely needed. For such a case, the results of ground motion studies will be useful. Even in an extreme case, the amplitude, frequency content and duration of strong ground motions will be different depending on the subsurface structure as shown in Fig. 4. For example, if the structure is located on the seismological bedrock or a layer equivalent to it, it will be exposed to predominantly short period ground motions. If the structure is located on a thick sediment, it will be exposed to predominantly long period ground motions. Different ground motions can mobilize different damage mechanism. Ground motion studies can contribute to anti-catastrophe design by providing a group of realistic site-specific ground motions. Each of those ground motions should accompany explanations by an engineering seismologist in terms of its reality, instead of accompanying a probability value that cannot be validated.

7. Conclusions

After the serious tsunami disaster during the 2011 Tohoku earthquake and the subsequent severe accident at the Fukushima-Daiichi Nuclear Power Plant, civil engineers in Japan have been discussing the preparedness of infrastructures to unexpected events. They proposed a new design concept called the “anti-catastrophe design concept”, where a structure is said to be “anti-catastrophe” when the structure or the structure-environment system does not exhibit catastrophic situation even in an unexpected event. The author joined the working group as an engineering seismologist. Therefore, the question that the author had to face was “Can ground motion studies contribute to this new design concept?” In this article, the author tried to answer the question by reviewing the current situations faced by ground motion studies in Japan and by discussing what ground motion studies can really tell about future ground motions.

After the 1995 Hyogo-ken Nanbu (Kobe) earthquake, there were high expectations for ground motion studies among civil engineers in Japan. The proposals issued by the Japan Society of Civil Engineers were in favor of incorporating the results of ground motion studies to the design of infrastructures. The author’s observation is that such expectations for ground motion studies have decreased and that the tendency was influenced by engineers’ suspicion about the maturity of ground motion studies. Based on the above observations, the question is “Can ground motion studies really contribute to the safety of the society?” To answer this question, the author’s view was summarized in terms of what ground motion studies can and cannot tell about future ground motions. Ground motion studies can reliably tell about the relative amplitude of ground motions between different sites and the site-specific predominant frequencies. On the other hand, it is necessary to admit that the absolute amplitude of ground motions accompanies significant amount of uncertainty as suggested by insightful engineers, mainly because the location and size of a future earthquake involve significant uncertainty. Given the limitations above, the author still believes that ground motion studies can contribute to the safety of the society by preparing site-specific design ground motions that are consistent with the amplification characteristics and the site-specific predominant frequencies at each site. On the other hand, because of our experience of past damaging earthquakes in Japan, the Japanese engineers are reluctant about using the results of PSHA to evaluate the safety of structures.

To understand the performance of structures under extreme events, every kind of available tools should be used. Ground motion studies can contribute to anti-catastrophe design by providing a group of realistic site-specific ground motions that can be used in shake table tests or earthquake response analyses.

8. Acknowledgements

The author would like to thank the National Research Institute for Earth Science and Disaster Resilience (NIED, https://doi.org/10.17598/NIED.0004), the Japan Meteorological Agency (JMA) and the Committee of Earthquake Observation and Research in the Kansai Area (CEORKA) for providing important strong motion data. Professor Sumio Sawada advised me to use the story of a loaded dice in this context.

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