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SEISMIC DESIGN FOR RESILIENT SOCIETY

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Abstract: Advances in seismic design technology today enable structural engineers to design buildings with a variety of seismic safety levels corresponding to different demands of the society. However, target of design is basically limited to secure life safety level within relatively short time span, i.e., serviceable life of each building. Aspects of constructing sustainable and resilient cities, which consists of buildings with long life, are not taken into account in general.
Strong earthquakes occur at intervals that are longer than life of individual building or people. On the other hand, as life of cities is obviously much longer, the corresponding seismic action is stronger than the design action and may cause serious damage in buildings designed for their life only. Taking these into account, we have to design each building for earthquakes considering the life of cities in order to secure continuity of urban activities over disastrous earthquakes.
However, there are problems to be solved in order to implement such seismic design. In this paper, factors in seismic engineering that hinder to realize long life city are identified and discussions on future steps of structural engineers to contribute in constructing sustainable and resilient society are indicated.

DEVELOPMENT OF SEISMIC DESIGN METHOD

Starting with a simple seismic resistant design where strength of building structures only is the bases for seismic performances, new technologies and design methods to provide various levels of seismic safety in buildings have been studied and developed. They are grouped into:

Seismic isolation where seismic energy input to building is remarkably reduced;

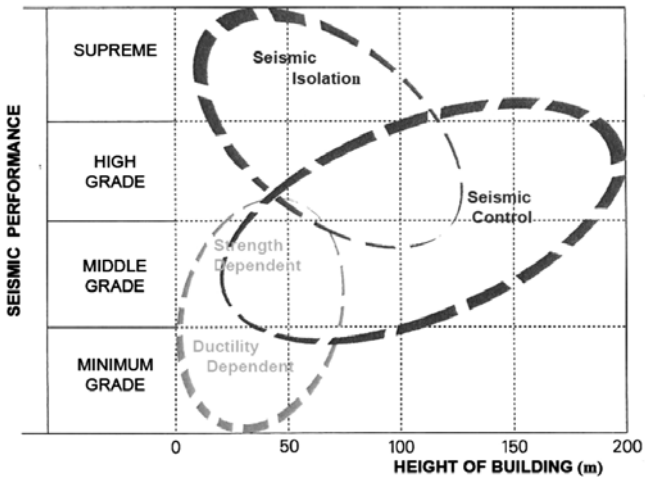
Passive control system where energy absorption devices of various types are installed;

Orthodox strength dependent system where seismic safety is mainly provided by the strength of structures; and

Ductility dependent system where seismic safety is mainly provided by ductility of structures.

Making use of these design methods, buildings of various types and structural characteristics are being built. The difference in design method usually produces difference in seismic performances. Among the listed design methods, seismic isolation can realize the highest seismic performance of buildings and, generally speaking, the order of the above list indicates decreasing performances.

Although we should not be too haughty of our present technology nor forget that there are certain limits of scope of application in each design method, it is possible to state that the structural engineers today can provide appropriate design solutions to demands for any level of seismic performances in buildings with a variety of height if only characteristics and intensities of design input earthquake ground motions are defined. *Fig. 1* on the next page shows which design method can realize what level of seismic performance in buildings corresponding to their heights. In *Fig. 1*, seismic performance is classified into four (4) levels. The seismic performances here mean those of buildings as a whole and not limited to structural issues. The "minimum" level corresponds to the level of performance which can be obtained by satisfying requirements of the Building Standard Law and Enforcement Order only and design target for this level is to ensure life safety under very rare (expectation for approx. 500 years) seismic action.



Figuer 1 Design Method and Seismic Performance

SEISMIC ISOLATED BUILDINGS

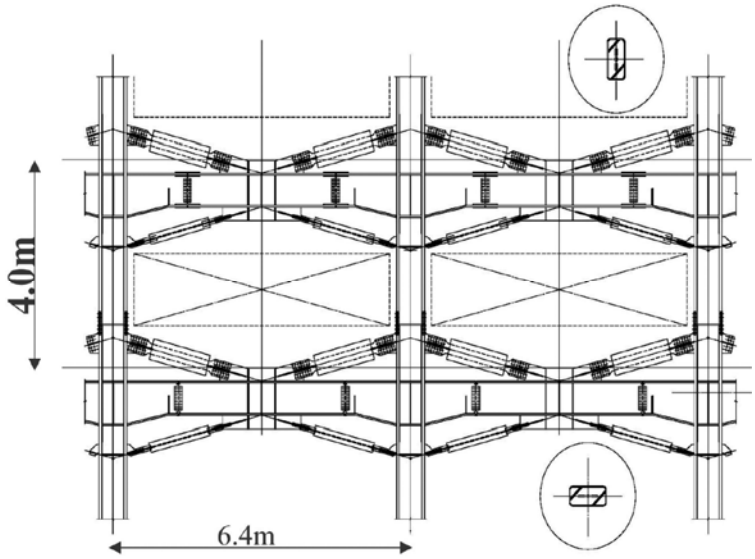
We have more than 5,000 seismic isolated small houses and more than 1500 seismic isolated buildings such as big apartment, computer centre, hospital, school and government in Japan. In our campus, 20 story steel building was constructed on the seismic isolation devices 4 years ago.

PASSIVE CONTROLLED STRUCTURES

After Kobe earthquake in 1995, more than 80% of new constructions of tall buildings are designed using passive control system. We have many kinds of supplemental damping devices such as Buckling Restrained Braces, Viscous Damping Walls and Oil Dampers. We designed three passive controlled steel tall buildings in down town Tokyo about 10 years ago. Many buckling restrained braces were installed to the 40 story steel structure as shown in the photographs.

Figuer 2 Seismic Isolated Steel Tall Building in Tokyo Institute of Technology

Figuer 3 Three Steel Tall Buildings Installed Buckling Restrained Braces



Figuer 4 Steel Columns, Steel Beams and Buckling Restrained Braces

Figuer 5 Construction of Frames and Installing Buckling Restrained Braces

COST INCREASE FOR PERFORMANCE ENHANCEMENT

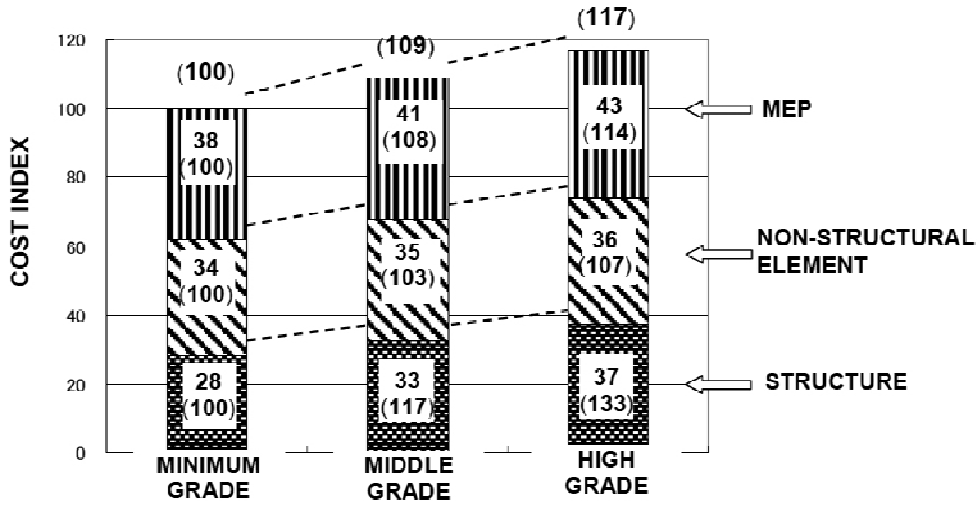
As prescribed, the development in structural design methods makes it possible to realize remarkably high seismic performances. Consequently, targets of seismic design today are of great variety including life safety, functionality after seismic action, damage mitigation, etc. In addition, objects of design are not limited to structures but include all elements consisting buildings. However, there are still bottlenecks in popularizing such high performances in the society. It is the problem of the construction cost increase.

The enhancement of seismic performances is not

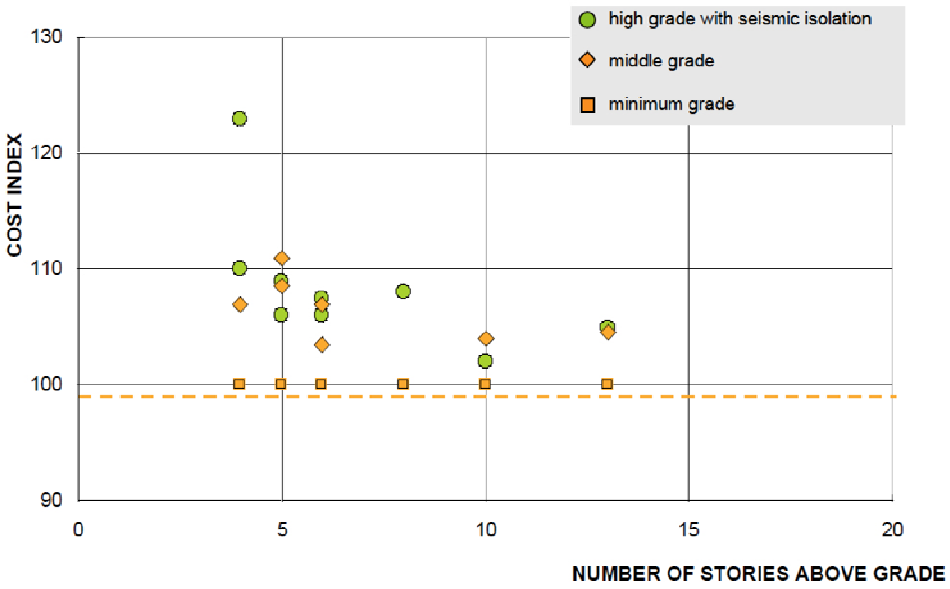
achieved without increase in their construction cost. As the seismic performance is not limited to structural safety, cost increase is inevitable not only in structure but also in cladding, finishes, and MEP system.

An example of calculation of increase in cost associated with enhancement of seismic performance of a model building designed with strength dependent system is shown in *Fig. 6*. Here, minimum grade, middle grade and high grade corresponds performance of life safety, limited function secured and main function secured respectively after very rare earthquakes. Design seismic strength of a middle grade and high grade building is 125% and 150% respectively of that of minimum grade building. It should be noted that increase in total construction cost is influenced by types of the buildings and cost allocations for various works. *Fig. 6* shows results of a case study on just an example model building which is based on relatively old data and a fairly conservative estimation taking into account possible increase in non-structural elements and MEP system.

Fig. 7 shows results of another example calculation. Nine (9) model buildings with various numbers of stories are designed to have seismic performances of minimum grade, middle grade and high grade with base isolation and their construction costs are compared. Although there is relatively high fluctuation, several to 30 percent cost increase is necessary to achieve high seismic grade by introducing seismic isolation system compared with buildings with minimum seismic performances.



Figuer 6 Seismic Performance Upgrading and Cost Increase



Figuer 7 Construction Cost Index (Minimum Grade = 100)

WIDESPREAD MOMENT-RESISTING FRAME STRUCTURE

The spread of performance based seismic design philosophy has positively affected in improving seismic performances of buildings. However, due to lack of sufficient understanding of damage levels in buildings caused by strong earthquakes, the developments in seismic design technology sometimes resulted in increase of rather vulnerable buildings of which the structural design is too much focused on satisfying the minimum requirements of codes and standards.

Diversification in seismic design method does not necessarily result in reduction of potential earthquake damage in buildings. The most representative example is the excessive reliance on structural ductility. It is possible to evaluate ductility of structures more precisely today and obviously the result of the evaluation in moment resisting frames is more reliable than that in frames with shear walls. This fact tends to increase risk of misunderstandings that the most popular and simple moment-resisting frame system without shear walls or vertical braces is the best type of structures as their characteristics and seismic performance can readily be calculated. The structures which can be easily analyzed and designed are not necessarily those with preferable performances. These are the most rational structures in a sense but they are the ductility dependent structures. Their seismic performances are provided mainly by capability of structure to support vertical loads in large deformation ranges where there is high potential that finishing, claddings, MEP systems, etc. are seriously damaged. In fact, their coefficient of structural characteristics, ***Ds***, which is equivalent to inverse of ***R***-factor, is from 0.25 to 0.30. On the other hand, ***Ds*** in the buildings with strength dependent earthquake resistant system are from 0.45 to 0.55. It is obvious that ultimate lateral shears in the ductility dependent buildings are less and damage in the buildings will be serious once they are hit by strong earthquakes even if the life safety requirements are satisfied.

The revised Building Standard Law (BSL) went into effect in this June and stipulations in the revised law and relevant regulations require more precise evaluation and calculation with high accountability on the characteristics of earthquake resisting elements, especially those of shear walls. These requirements are intended to and perhaps efficient to prevent falsifications in structural calculation but contain high risk of a side effect to facilitate design of ductility dependent buildings with high potential of seismic damage.

In the current seismic design regulation in Japan, intensity of very rare seismic action expressed in terms of standard shear coefficient, ***Co*** = 1.0 is 5 times that of rare earthquakes for which ***Co*** = 0.2. Although there is a certain possibility that ground motions due to strong earthquakes may partly exceed this design condition, most buildings in urban areas will be hit by the ground motion within this bound. As the result, buildings with strength dependent resisting system suffer serious damage only in limited zones where quite intense ground motions occur but those with simple moment-resisting frames suffer the same level of damage in wider areas. It is understood that design targets in current BSL are to maintain functionality for rare earthquakes and life safety for very rare earthquakes. The people seems to understand that all buildings are designed to possess the same level of performances as a minimum standard stipulated by BSL and no explicit difference exists excluding special cases. However, the actual damage in buildings will be not same as considered.

Today, damage control issues are often highlighted and PML has become an important factor to evaluate seismic performance. In addition, business continuity issues after earthquakes in various types of facilities are frequently discussed. On the other hand, however, it is a quite unfavourable trend from the viewpoint of design for durable, sustainable and resilient buildings that the simple moment-resisting frame structures, in which large plastic deformations under intense seismic motions is predicted, are becoming widespread.

DESIGN SEISMIC ACTION FOR BUILDING AND CITY

The prescribed two problems, namely, cost increase necessary to enhance performance and widespread of ductility depending structures are the factors which may hinder the effort to mitigate earthquake damage in buildings. These problems are even more serious when we consider issue of how to keep functionality of urban activity over disastrous earthquakes and to realize sustainable and resilient cities.

Earthquakes are natural phenomena and the most fundamental problem in seismic design of buildings is that we cannot predict precisely what the intensity of the critical earthquake is and when it occurs. In this context, it is perhaps a rational engineering judgment considering impacts on construction cost, not to take into account explicitly the maximum possible earthquake that is with very low probability of occurrence in designing individual building. As such earthquakes will occur only quite rarely, this is an appropriate approach from probabilistic viewpoint and works well to ensure a certain level of seismic safety of each individual building against design seismic actions established based on the life of the building. However, this design philosophy concerning seismic action will be a risky choice from the viewpoint of creating sustainable and resilient cities due to the synergy effect of two factors, namely: expected life of cities is much longer than that of buildings; and buildings should be treated as being not replaceable but component parts of cities when seismic actions are concerned.

Although the serviceable life of each building is 60 years or less in general, the life of a city is much longer and ranging from several hundreds to over a thousand years. The risk of strong earthquakes in the life of a city is much higher than that of each building. In other words, the critical earthquakes to be considered in discussing the continuous functionality of cities throughout their expected life should be much stronger

than that to be considered in securing safety of each building only. Under ordinary situation, each building is deemed to be a replaceable part of a city. Buildings can be replaced one by one as the end of the life comes and sustainability of the city will be secured even if design life of each individual building is shorter than that of the city. However, the same principle cannot be applied in case of very rare earthquakes. If a very rare and strong earthquake hit a city, most of the buildings there will suffer serious damages and the function of the city will be lost for a considerably long period.

There may be argument that importance factor can provide some solutions to the problem. Concepts of importance factor are not stipulated in BSL but increase of required ultimate lateral shear for important governmental facilities and buildings accommodating hazardous materials are stipulated in "General Seismic Design Standard for Governmental Building with Commentary". Such increase is efficient in mitigating probable damages of important facilities and in improving social preparedness for emergency operation immediately after earthquakes. However, the improvements are limited to performance of so classified important facilities. All remaining buildings are out of scope of application. When discussing sustainable and resilient cities, seismic performance of not only facilities for emergency operation but also ordinary buildings for maintaining urban functionality is the key issue.

LIMIT OF LEGAL CONTROL

Despite all of the prescribed arguments, it is not easy to design individual buildings to be free from any damage for the maximum possible seismic action which we cannot predict when to occur only because they are basic components of a city. If the buildings are not subjected to strong ground motion for several decades until end of their life, we can't help being blamed that we have forced our clients to make useless additional investment. In Japan, it is a common understanding that the average life of ordinary buildings is 40 years or less. Provided that these buildings are designed to withstand strong ground motions that occur once in 400 years, as they are demolished and rebuilt 10 times in the 400 years and it means that only one out of the 10 is hit by the design earthquake and demonstrate the fruit of seismic design. The rest 9 buildings end their life without experiencing design seismic action and it will be judged that they are over-designed for seismic safety.

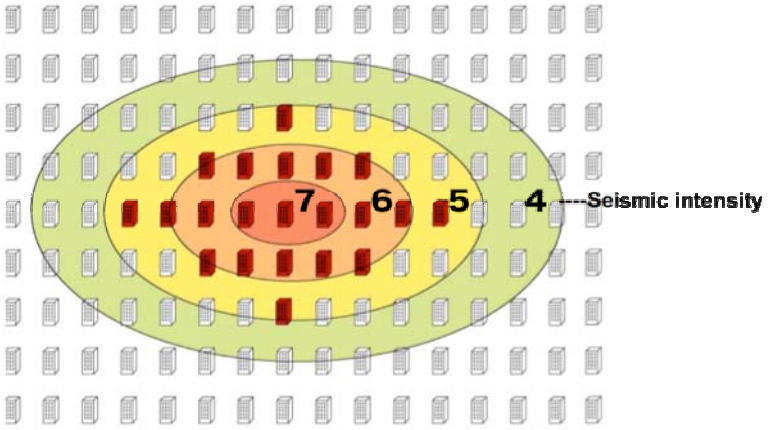
Under this situation, it seems that the restriction or control by laws or codes will be most effective to construct sustainable and resilient cities through enhancing required minimum seismic performance level of buildings. However, there are limits also in laws and codes and it is difficult to regulate obligations of owners or private companies to make their buildings having higher level of seismic performance beyond the target of life safety within their expected life because such regulation involves extra financial loads on the owners and/or private companies as explained before. If the government put such requirements, it may be deemed an infringement of the people's right to control their own property, which is protected by the Constitution of Japan. Consequently, not the preservation of functionality nor property but life safety level by preventing failure or collapse only is required for very rare intense earthquakes in BSL.

NEEDS FOR SUPREME SEISMIC PERFORMANCE WITHOUT COST INCREASE

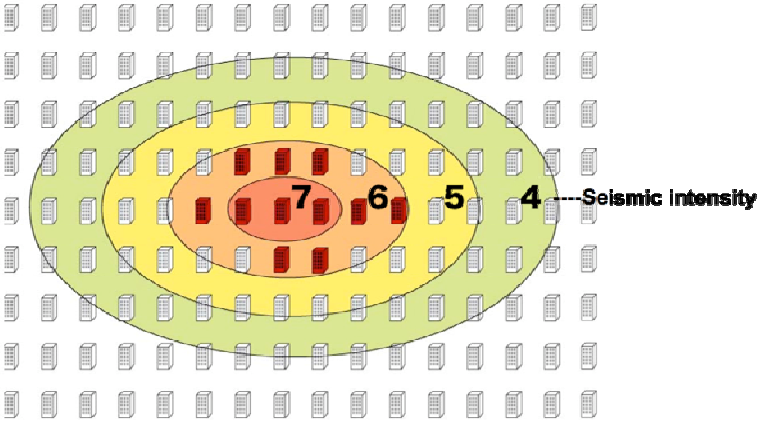
Recently, concepts of performance based design are often discussed and issues such as PML and BCP are becoming more popular in structural engineering. Other methods to evaluate seismic performances are being studied and developed from various aspects. At the same time, we need to have practical methods to respond various requests for enhancement of seismic performance.

The prescribed arguments call for the development of structural systems which realize supreme seismic performance without or with very slight increase of cost compared with those required in ordinary buildings. If substantial increase in cost is not required, then, it is rational to design buildings which suffer substantially no damage from very rare earthquakes and such design will be accepted by the society. As the results of enhancement of seismic performance of individual building in a city, the performance of the city itself will be improved remarkably. Development of such structural system will make it reasonable to design buildings for the seismic action based on the return period corresponding to the life of a city, say 1000 to 2000 years. Of course we should be aware of the fact that our knowledge is still limited and further researches and studies are necessary to identify the seismic actions corresponding to such long return periods.

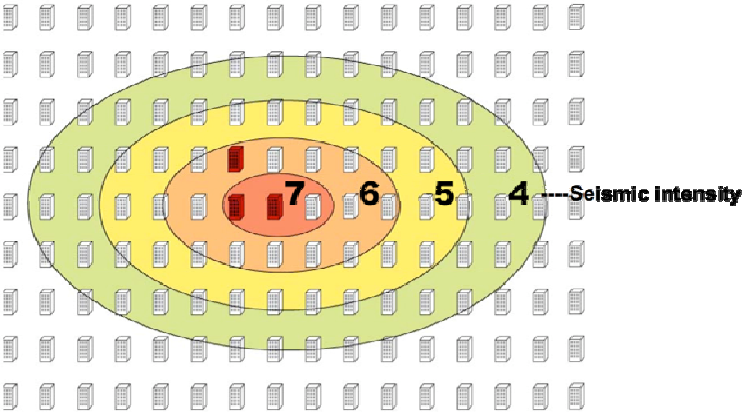
Today, studies of seismic engineering in the countries or areas where risk of destructive earthquakes is high should be focused on developing the technology to realize supreme seismic performance. Since the methods of reinforced concrete and steel structures were introduced to Japan in approximately 100 years ago, lots of buildings had been designed and constructed based on the methods. They have suffered from various earthquakes and it seams that the limit of seismic performances obtained based on such orthodox technology is becoming evident today. We are at the time to make effort to enhance seismic performance of cities by enhancing those of individual buildings. What we are requested today is to seek not for cost reduction keeping same performance level but for higher performance level without cost increase and to promote building structures with higher seismic performance which contribute to develop a long lasting therefore sustainable and resilient society.



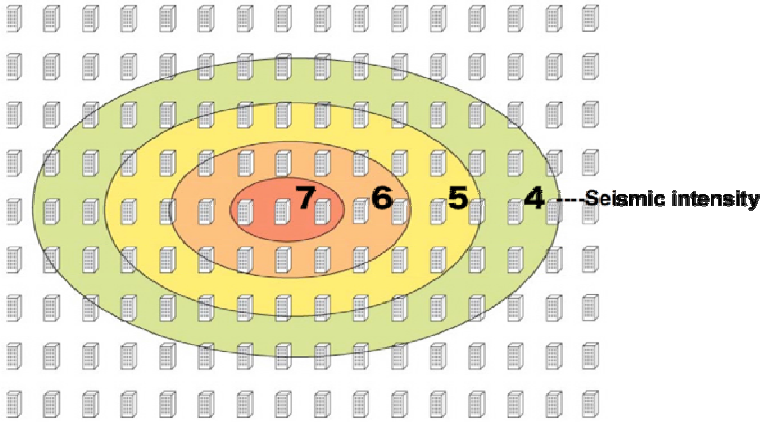
Figuer 8　Damages of buildings in the city after big earthquake, in the case that all buildings were designed as ductile frame structure.



Figuer 9　Damages of buildings in the city after big earthquake, in the case that all buildings were designed as strength oriented structure.



Figuer 10　Damages of buildings in the city after big earthquake, in the case that all buildings were designed as passive controlled structures.



Figuer 11 All buildings were designed as seismic isolated structures.

CONCLUDING REMARK

Sustainability and resilience are obviously two of the most important and common key-words all over the world today. The most important role of structural engineers in this relation is perhaps to contribute by providing long-lasting buildings. Especially in areas where risk of destructive earthquake is high, the key issue is to secure functionality of cities over earthquakes of the intensity corresponding to their life but there are obstructions for the implementation. The most serious obstruction is the increase in cost required for this purpose. Therefore, we should changeover the direction of technology development from "cost reduction keeping same performance level" to "higher performance level without cost increase". In addition, we should note that it is one of the important duties of structural engineers to explain the true merits for clients and all stakeholders of enhancing the seismic performances of buildings.

Finally, one other important issue should be pointed out. It is the increasing risk brought about by the advance in civilization. Torahiko Terada, a famous scientist and essayist once stated that the more the civilizations advance, the more the disasters evolve. One of depopulated areas in Japan, Noto Peninsula district was hit by an earthquake in March 2007. One month was necessary to provide the temporary houses for the refugees. It is predicted that 10 years will be necessary for the same purpose in case a strong earthquake hit Tokyo even if there are sufficient spaces for temporary houses. The structural engineers, based on the knowledge in physics, mathematics, structural dynamics, etc, and complying with the laws, have been striving effort to complete many project for satisfaction of request from society. Transportation system such as railways and roads, life lines including water, gas and electricity supply and lots of buildings have been constructed. The large cities so constructed are highly efficient and active in normal situation. They have provided bases for activating economy and spaces for people to enjoy modern civilization. As the result, excessive concentration of population as well as social function to main cities has been brought about. The excessive concentration is most remarkable in Japan. Among the total population of 80 million in Germany, only 3.4 million (4%) is living in the largest city, Berlin and there are many other active cities all over the country. In US, 8.2 million among the total population of 290 million is in New York and there are also many large cities. On the other hand, approximately 25% of total population of Japan is living in Tokyo and the surroundings. Once Tokyo is damaged by destructive earthquakes, the whole country may be put into functional disorder for a long period. It is obvious that the social system of Japan is quite vulnerable strong earthquakes.

The pursuits of excessive concentration to mega cities inspired by people's demand and facilitated by activation of economy, high efficiency obtained by the concentration, highly controlled traffic network and pleasant social life supported by mass use of energy, all these will produce contrary effects to weaken the resistance against natural disasters.

Perhaps most of the citizens including engineers are honest in their activities. However, we shall perceive and alarm today that civilization resulted from integration of individual honest activity creates a high risk society and start actions in our discipline to mitigate such risk.