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"ANTI-CATASTROPHE" CONCEPT IN JAPANESE SEISMIC DESIGN CODES

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Abstract

In light of the serious tsunami disaster during the 2011 Tohoku earthquake and the subsequent severe accident at the Fukushima-Daiichi Nuclear Power Plant, the preparedness of infrastructures such as railway structures, highway structures and port structures to unexpected events became a big issue among civil engineers in Japan. In the conventional seismic design of these structures, basically two kinds of design ground motions, namely, the level 1 and 2 design ground motions are considered and the structures are designed so that they fulfill respective performance requirements through verification. In particular, significantly intense ground motions from shallow crustal and subduction earthquakes have been considered as the level 2 design ground motions. However, it is still necessary to consider the performance of structures to unexpected events and its consequences, mainly because of our insufficient knowledge of natural phenomena and of the performance of structures itself. Therefore, the authors proposed a new design concept called the "anti-catastrophe design concept". In this concept, 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. In order to contribute to the establishment of the "anti-catastrophe" design concept of structures, the design standards for railway structures, highway structures, and port structures in Japan are reviewed. In all of these codes, the necessity to consider the performance of structures to unexpected events and its consequences are recognized. For the railway structures, devices have been developed for the anti-catastrophe design including the "dead weight compensation mechanism". For the highway structures, "unseating prevention devices" have widely been used in the design of bridges. For the port structures, efforts are being made to improve the performance of breakwaters after they are affected by extreme tsunamis. 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. However, as mentioned above, the Japanese engineers seem to put more emphasis on the development of measures or devices to cope with this issue. It should be noted that our knowledge is quite limited in terms of the performance of a structure or of a structure-environment system subject to extreme events. Obviously more effort is needed to understand the performance of structures to extreme events. To this end, every kind of available tools should be used. For example, model tests and numerical simulations could be useful. On the other hand, it is not reasonable to think that the performance of such devices or measures should always be evaluated quantitatively. Sometimes, other human abilities such as intuition and insight could be useful in developing measures and devices. As an example, although we do not know the detailed stress history of unseating prevention devices during an earthquake, they have widely been used in the design of highway bridges in Japan and some of those devices performed well in the past earthquakes. After all, we should mobilize all kinds of human ability, ranging from intuition or insight to more sophisticated engineering skills, to cope with the issue of the preparedness of structures to unexpected events.

Keywords: Anti-catastrophe design; design code; unexpected event; extreme event; consequence

1. Introduction

In light of 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 such as railway structures, highway structures and port structures to unexpected events. The authors formed 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, basically two kinds of design ground motions, namely, the level 1 and 2 design ground motions are considered and the structures are designed so that they fulfill respective performance requirements through verification. In particular, the level 2 design ground motion is determined by taking into account severe ground motions from shallow crustal and subduction earthquakes and the structures are designed so that the ultimate limit state is not exceeded. In this process, less attention has been paid to the performance of structures subject to a strong ground motion exceeding the level 2 design ground motion and to its consequences.

In light of the lessons learnt from the 2011 Tohoku earthquake, however, the working group recognized the necessity to consider the performance of structures under unexpected events and its consequences mainly because of the following two reasons.

1. The level 2 design ground motions may be exceeded during the design working life of a structure irrespective of the method that is used to determine the level 2 design ground motion because of our insufficient knowledge of natural phenomena.
2. Structures may exhibit unexpected performance leading to damage even when the level 2 design ground motion is not exceeded.

Therefore, the working group proposed a new design concept called the “anti-catastrophe design concept” [1]. In this concept, 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 working group has started developing a framework for the design of structures based on this concept [1].

In the “anti-catastrophe design”, a scenario involving a collapse of a structure is considered, irrespective of the strength of the structure. Then, the performance not only of the structure itself but also of the structure-environment system is considered. Based on the expected consequences, possible measures are taken not only in the process of structural design but also during planning. For example, when we discuss the ability of a breakwater to delay the inundation of tsunamis, the tsunami-affected region including the breakwater is considered as a system. When we discuss the redundancy of a transportation system, the road network is considered as a system. Although simulations of tsunami inundation have been conducted in the practice of regional disaster planning in Japan, what’s new about the “anti-catastrophe design” is that it is conducted in the process of designing structures, probably under the leadership of engineers, thereby making it possible to take appropriate measures in the design and planning.

The relationship between the conventional seismic design and the anti-catastrophe design can be shown as in Fig. 1. As shown in Fig. 1, the conventional seismic design is based on the process of verification of the performance of structures for design ground motions (blue). There are events, however, that cannot be controlled by the conventional seismic design (red). These events can be regarded as the “complementary set” being a set of events that are complementary to those controlled by the conventional seismic design. These are the target of the anti-catastrophe design.

Fig. 2 schematically illustrates the seismic performance of structures with and without anti-catastrophe design. Structures with only conventional seismic design show sufficient performance up to the level 2 ground motions, but damage could significantly increase for excessive seismic actions (blue broken line). On the other hand, we could imagine an ideal structure for which damage does not increase for excessive external forces (red line). In the anti-catastrophe design, engineers will take measures with both hardware and software so that the actual performance of structures approaches to the red line.

While the “anti-catastrophe design” is a new concept, the working group noticed that the necessity to be prepared for unexpected events has long been recognized among diligent engineers. In addition, the seismic design codes have been improved since the occurrence of the 2011 Tohoku earthquake and now we can find descriptions about the preparedness of structures in the face of unexpected events in these codes. It would be meaningful to review the seismic design codes in Japan and to understand how these codes are trying to assess the issue of the preparedness of structures in an unexpected event.

In order to contribute to the establishment of the "anti-catastrophe" design concept of structures, Japanese design standards for railway structures, highway structures, and port structures are reviewed in this article, with special reference to their recent trends. Design examples are presented in which "anti-catastrophe" design concept is considered implicitly or explicitly both before and after the 2011 Tohoku earthquake. In addition, the "anti-catastrophe" design concept is discussed in the context of international trends of structural design.

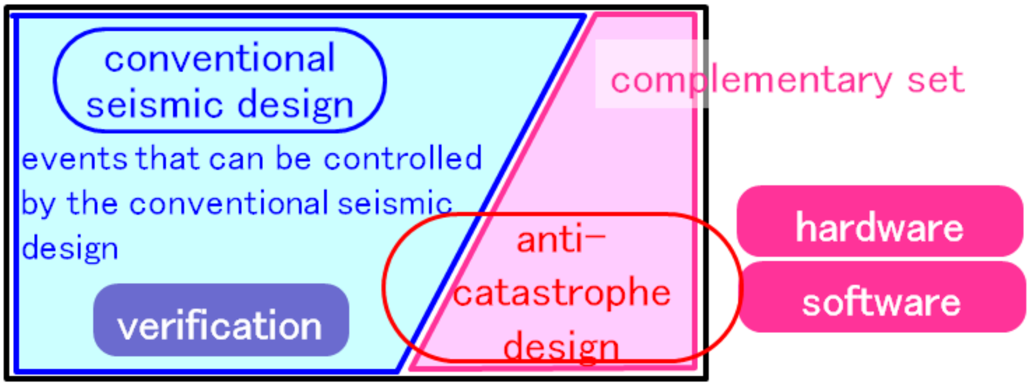

Fig. 1 – The relationship between the conventional seismic design and the anti-catastrophe design

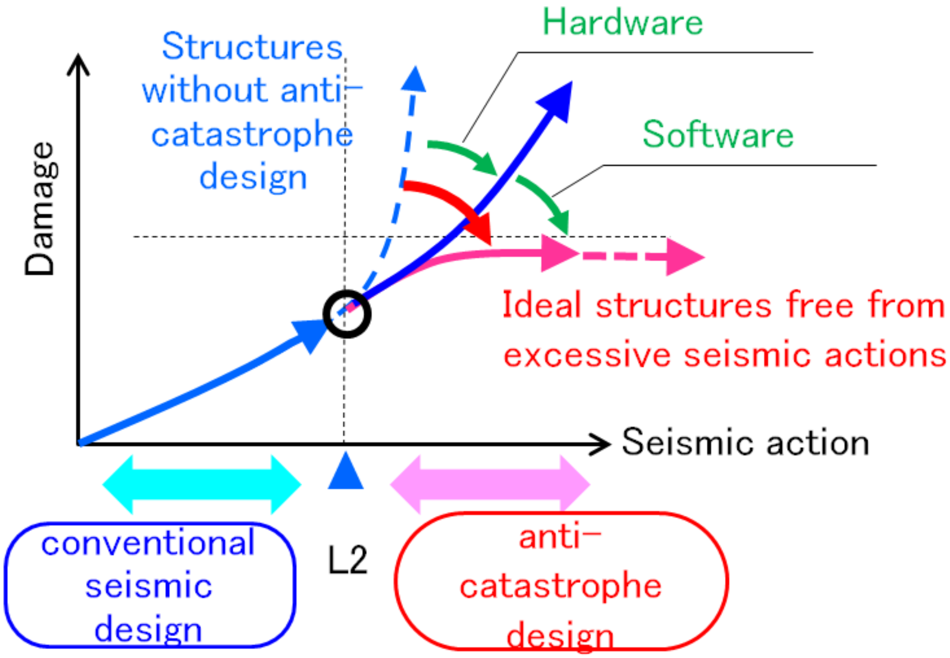

Fig. 2 – Seismic performance of structures with and without anti-catastrophe design

2. Railway structures

2.1 Principles of preparedness of structures to unexpected events

In the seismic design of structures in Japan, significantly intense ground motions have been adopted as the level 2 design ground motions, referring to the near-source ground motions in Kobe during the 1995 Kobe earthquake and other damaging ground motions including those from subduction earthquakes. However, it is important to acknowledge that, after all, the level 2 design ground motions are based on the judgment of a group of skilled engineers and they do not represent the strongest possible ground motion from a physical point of view at the site. Therefore, the level 2 design ground motions may be exceeded during the design working life of a structure irrespective of the method used to determine the level 2 design ground motion. This recognition is the important starting point for the "anti-catastrophe design".

The revised version of the seismic design standards for railway structures [2], published in 2012 after the Great East Japan Earthquake, addresses these issues, stating "the possibility of the occurrence of a ground motion exceeding the level 2 design ground motion cannot be denied". Then the revised version states the principles of preparedness of structures in unexpected events, saying "because railway structures bear highly public nature and their functionality is quite important for human life and social/industrial activities, in the seismic design of structures, in addition to considering safety and restorability, a structure should be designed so that the structure or the structure-environment system does not exhibit catastrophic situation even in an unexpected event". These expressions constitute the basis for our definition of the "anti-catastrophe design" stated in the introduction of this article, although the design standards for railway structures [2] do not use the term "anti-catastrophe" explicitly. It is also stated in the design standard [2] that, because verification methods have not been established for this purpose, the preparedness in unexpected events should rather be considered in structural planning.

2.2 Descriptions related to "anti-catastrophe design" in the design standards

We can find more detailed descriptions about the preparedness of structures in unexpected events in the design standards for railway structures [2]. In the following, two examples are described.

It is well known that shear failure of a concrete structure is brittle and unfavorable compared to bending failure. The design standards for railway structures [2] recommend a structure that fails in bending rather than in shear. Let us assume two types of structures that do not fail under the level 2 ground motion; however, one exhibits bending failure and the other exhibits shear failure under a ground motion that exceeds the level 2 ground motion. If we do not have to consider the possibility of the occurrence of a ground motion exceeding the level 2 ground motion, there is no difference between these two types of structures. However, in fact, the level 2 ground motion could be exceeded. Therefore, the former structure is preferable. Thus, the above expression in terms of the preferred failure mode can be regarded as related to the preparedness of a structure in an unexpected event.

The design standards for railway structures [2] also recommend that the environment of a structure should adequately be planned so that it allows for rapid restoration of the structure when it is subject to earthquake damage. In particular, based on past experiences of damaging earthquakes, the rapidity of the restoration is largely dependent on the availability of a service road or a space under elevated tracks. Therefore, the standards recommend reserving an access route or a yard for the restoration work. The standards also recommend that the damage to a structure should be restricted to a member or a portion of a structure for which inspection and restoration can easily be carried out.

2.3 Recent efforts to improve preparedness of structures in unexpected events

After the publication of the latest version of the design standards for railway structures [2], more efforts have been made to improve the preparedness of structures in unexpected events. In the following, two examples are described.

One example is the so-called "dead weight compensation mechanism" [3], which was recently proposed by the Railway Technical Research Institute (RTRI). The concept of this mechanism is shown in Fig. 3. The blue columns in Fig. 3 are ordinary columns and the red columns are the "dead weight compensation columns". The ordinary columns undergo conventional seismic design for the level 2 ground motion. On the other hand, the dead weight compensation columns only bear the vertical forces and are free from the horizontal forces due to the inertia force acting on the slab. Therefore, we could expect that the dead weight compensation columns should remain intact even after the action of excessive seismic forces. Thus, even when the ordinary columns are damaged and collapse as shown in Fig. 3, the dead weight compensation columns will support the slab.

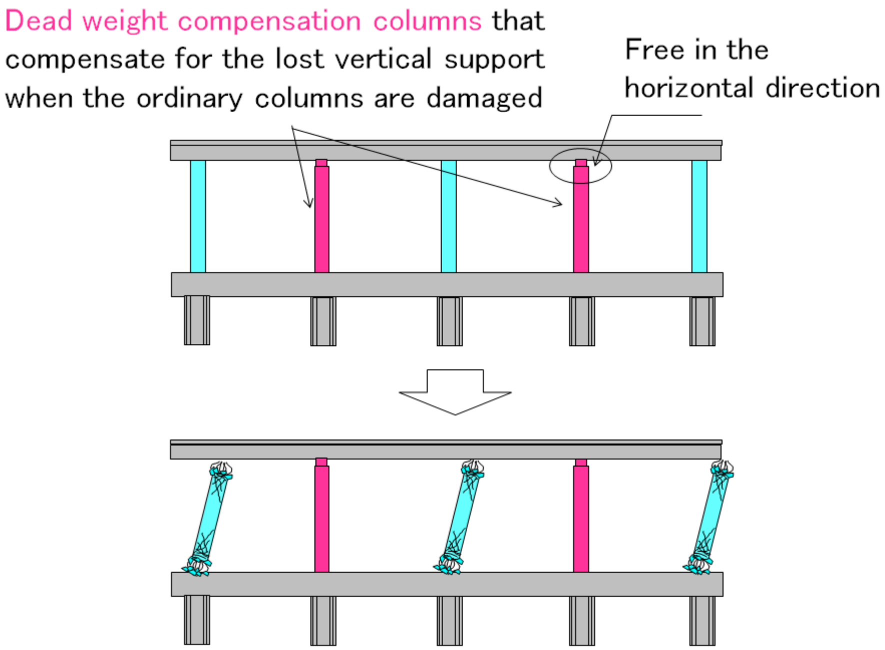

Fig. 3 – Dead weight compensation mechanism [3]

Table 1 – Feasibility study on the dead weight compensation mechanism [3]

Type of structure	Bar arrangement of ordinary columns	
	Longitudinal bar	Transverse reinforcement
Ordinary structure	5-D32	D19@150
Structure with dead weight compensation mechanism	7-D32	D19@100

Nishimura et al. [3] investigated the feasibility of this mechanism for a rahmen elevated bridge with one layer and 5 spans. According to the results, if four out of twelve ordinary columns are replaced with the dead weight compensation columns, for instance, horizontal forces acting on the ordinary columns increase and the strength of the ordinary columns should be increased. However, this increase can be covered by only a small number of additional longitudinal bars as shown in Table 1.

Another example is the control of the direction of structural collapse. In case of structural collapse, its consequences may largely be dependent on its direction. Saito et al. [4] proposed to control the direction of structural collapse to prevent loss of lives, to avoid interrupting emergency transportation, and to reserve access routes or spaces for restoration (Fig. 4). The direction of structural collapse may be controlled by adequately determining the relative strength of the members that constitute the structure [4].

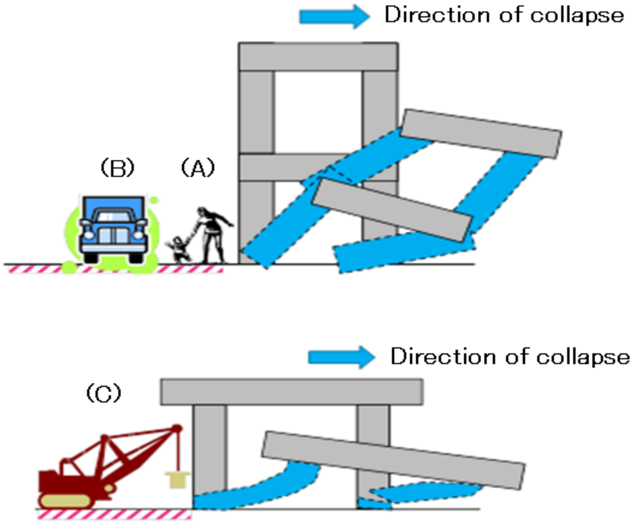

Fig. 4 – Control of the direction of structural collapse [4]. Controlling the direction of collapse may contribute to prevent loss of lives (A), to avoid interrupting emergency transportation (B), and to reserve access routes or spaces for restoration (C).

3. Highway structures

3.1 Principles of preparedness of structures to unexpected events

The design specifications for highway bridges in Japan have been published in several volumes. The volumes I, II, III, IV, and V are devoted to common aspects, steel bridges, concrete bridges, substructures, and seismic design, respectively. The latest version was published in 2012.

Published after the 2011 Great East Japan Earthquake, the latest version of the specification involves descriptions related to the principles of the preparedness of structures in unexpected events [5]. The specification points out that failure of one member of a bridge may cause the collapse of the whole structure if the structure is not appropriately designed. It requires the engineers to pay attention to this fact while designing the structures. It should be noted that the statement is not specific to earthquakes but it applies to all other unexpected events. The statement is accompanied by commentaries [5]. The followings are the essence of the commentaries.

In the design of bridges, various actions that could affect the structure during the design working life are considered. However, the specification admits that the bridges may be subjected to unexpected external loads during the design working life and may be damage. It should be noted that, in the design of highway bridges in Japan, the level 2 design ground motion is considered, just as in the design of railway structures. Therefore, the above statement is equivalent to the expression “the possibility of the occurrence of a ground motion exceeding the level 2 design ground motion cannot be denied”, which is included in the seismic design standards for railway structures [2] and discussed in 2.1. This recognition is important as the starting point for the “anti-catastrophe design”.

The specification points out the importance of taking measures to avoid “extremely unfavorable situation” in an unexpected event. Therefore, although the specification does not use the term “anti-catastrophe” explicitly, one can conclude that the concept of “anti-catastrophe design” has already been introduced in the design specifications for highway bridges in Japan. It should be noted that, if the bridge is closed for a long time for fear of collapse or the bridge is forced to be demolished, it is called an “extremely unfavorable situation” even when the bridge has not actually collapsed.

The specification also admits that it is difficult to propose a unified criterion in terms of what kind of measures should be taken, because this issue requires comprehensive judgment based on a consideration of other important aspects such as costs and workability. Therefore, the specification just recommends that the engineers consider the possibility of unexpected events, and take measures whenever appropriate, instead of specifying verification methods.

3.2 Unseating prevention device [6]

When a highway bridge is subject to extremely large ground motions, a bearing failure may take place, resulting in deck unseating. To prevent such an unfavorable situation, “unseating prevention devices” have widely been used in the design of highway bridges in Japan [6]. Some of those devices actually succeeded in preventing deck unseating in the past earthquakes. Fig. 5 shows an example of such device. The figure shows an unseating prevention device installed at Ono Bridge, Miyagi Prefecture, Japan, after the July 26, 2003, Northern Miyagi Prefecture earthquake (M6.4) [7, 8]. During the earthquake, all the bearings on the abutments and the piers suffered significant damage such as shear failure of anchors. As a results, the girder displaced in the axial direction 0.2 m at maximum. After the earthquake, tensile force was acting in the PC cable of the unseating prevention device connecting the superstructure and abutment. Therefore, the investigation team concluded that the unseating prevention device efficiently prevented the unseating of the superstructure. As another example, Fig. 6 shows an unseating prevention device installed at Kiyamagawa Bridge, Kumamoto Prefecture, Japan, before and after the

Fig. 5 – Unseating prevention device installed at Ono Bridge, Miyagi Prefecture, Japan, after the July 26, 2003, Northern Miyagi Prefecture earthquake [7, 8].

Fig. 6 – Unseating prevention device installed at Kiyamagawa Bridge, Kumamoto Prefecture, Japan, before (left) and after (right) the April 16, 2016, Kumamoto earthquake.

April 16, 2016, Kumamoto earthquake (M7.3). Since the girder is slightly skew, concrete blocks were installed to prevent excessive displacement in the longitudinal and transverse directions in preparation for bearing failure. During the earthquake, all the steel bearings on the piers suffered significant damage such as failure of pin connections. As a result, the girder hit the concrete blocks, but the device succeeded preventing unseating. In the context of this article, the unseating prevention device is one of the most typical devices for “anti-catastrophe design”, because it is installed in preparation for unexpected events such as extremely large ground motions.

On the other hand, the design specification for highway bridges [6] also suggests some cases where the installation of the unseating prevention devises can be omitted. According to the specification, the installation can be omitted for bridges where the displacement of the superstructure in the axial direction is restricted because of structural characteristics. From a perspective of the “anti-catastrophe design”, such structures are preferable, because their structural characteristics contribute to avoiding the unfavorable situations created by deck unseating. Therefore, selecting one of these types of structure in the process of structural planning can be regarded as one example of “anti-catastrophe design”.

According to the specification [6], the displacement of the superstructure in the axial direction is restricted in the following cases.

1) A bridge with a continuous girder supported by abutments at both sides is one of the structures where the installation of the unseating prevention device can be omitted, because even if the bearings are damaged and the displacement of the superstructure in the axial direction occurs during an earthquake, the superstructure will soon collide with one of the abutments, and further displacement will be restricted because of the reaction of the abutment and the backfill soil.

2) A bridge with a continuous girder supported by at least four elastic bearings or fixed bearings in the axial direction as shown in Fig. 7 is one of the structures where the installation of unseating prevention device can be omitted, because this type of structure will exhibit sufficient redundancy. It should be noted that the inertia force should uniformly be distributed over different bearings in this type of structure because, if the inertia force is supported only by a few bearings, the failure of the bearings is anticipated, which may result in a successive failure of a larger part of the structure. According to the specification, the inertia force supported by one bearing should not exceed 50 % of the total inertia force.

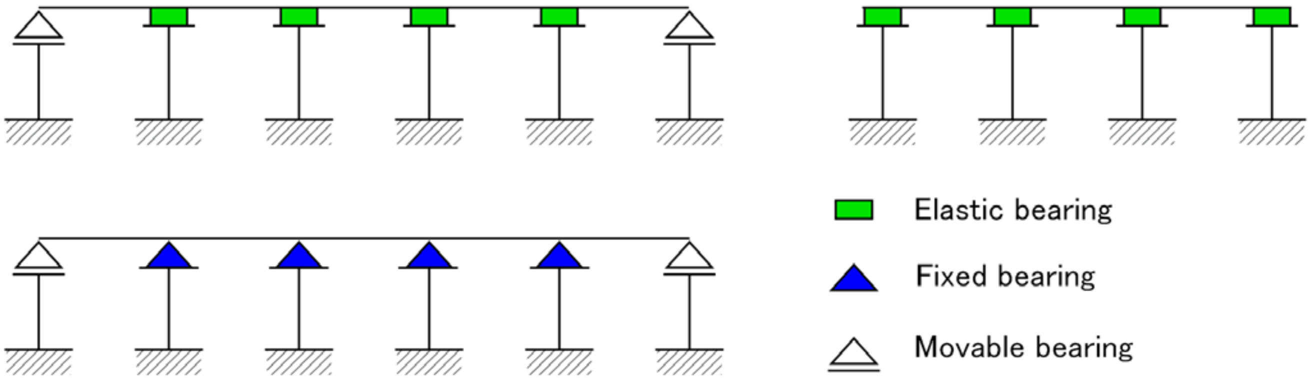

Fig. 7 – A bridge with a continuous girder supported by at least four elastic bearings or fixed bearings in the axial direction

3) A rahmen bridge rigidly supported by at least two piers as shown in Fig. 8 is one of the structures where the installation of the unseating prevention device can be omitted, because it is not realistic to expect a total rupture of the rigid supports and the separation of the superstructure and substructure.

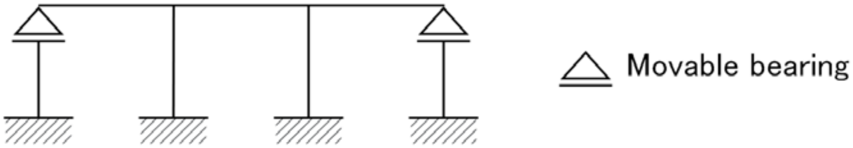

Fig. 8 – A rahmen bridge rigidly supported by at least two piers

The specification [6] also calls attention to some cases where the rotation of a deck may lead to unseating of the deck. Fig. 9 shows curved bridges with different plan views. (a) shows an unfavorable plan view where $AB<AH_1$ and the rotation of the deck may lead to unseating of the deck. (b) shows a favorable plan view where $AB>AH_2$ and the rotation will be restricted due to the existence of neighboring decks or abutments. Therefore, in the context of this article, selecting a plan view in (b) instead of (a) in the process of structural planning can be regarded as one example of “anti-catastrophe design”.

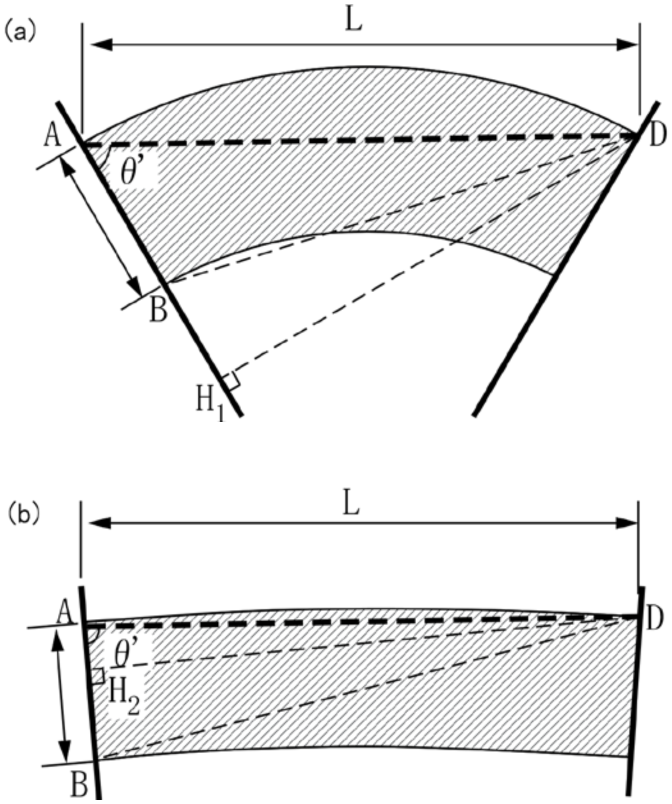

Fig. 9 – Curved bridges with different plan views. (a) shows an unfavorable plan view where $AB<AH_1$ and the rotation of the deck may lead to unseating of the deck. (b) shows a favorable plan view where $AB>AH_2$ and the rotation will be restricted due to the existence of neighboring decks or abutments.

4. Port structures

4.1 Design tsunami

In light of the serious tsunami disaster during the 2011 Tohoku earthquake, the technical standards for port structures in Japan [9] were partially revised in 2013 [10]. In the revised version, the term “design tsunami” was introduced for the first time. The design tsunami is defined as “a tsunami that has a low probability of occurrence during the design working life of a structure and that will have a significant effect on the structure”. The design tsunami should be determined based on past records or numerical simulations [10].

For the design tsunami, the port structures are intended to protect not only human life but also properties. For this purpose, the concept of multiple protection is encouraged, where the effects of every structure including breakwaters and tide embankments should be integrated and utilized for the protection. It is believed that, although the original purpose of the breakwaters is to keep the calmness of the port for ordinary ocean waves, the breakwaters can contribute to reducing the tsunami energy efficiently depending on their distributions.

The performance verification for breakwaters or tide embankments for the design tsunami are basically conducted by applying a tsunami force and by assessing their stability against such failure modes as sliding, overturning, and instability of underlying ground. The applied force on the breakwater is dependent on the occurrence of overflow, because overflow is allowed for a breakwater.

4.2 Tsunami exceeding the design tsunami

The design of breakwaters or tide embankments for the design tsunami mentioned above corresponds to the conventional seismic design shown in blue in Fig. 1. On the other hand, the design for a “tsunami exceeding the design tsunami”, which was also newly introduced in the technical standards for port structures in Japan in 2013 [10], can be regarded as one example of “anti-catastrophe design”, in the context of this article.

Although the original purpose of the breakwaters is to keep the calmness of the port as mentioned in 4.1, it is believed that the breakwaters can contribute to reducing the height of tsunami that arrives at the protection line including tide embankments and to delay the arrival time. For example, according to the numerical simulation conducted by the Port and Airport Research Institute [11], the Kamaishi Tsunami Breakwater contributed to reducing the tsunami height at the inner part of the bay by about 40 % and delaying the time of overflow at the tide embankments by about 6 minutes, although the breakwater finally collapsed. This amount of time will have a significant effect in assisting the tsunami evacuation.

For a tsunami exceeding the design tsunami, the port structures are intended to assist human evacuation and to reduce damage to properties as much as possible. For such a tsunami, of cource, the most important action is evacuation. However, if the breakwater is robust enough and it takes sufficiently long time before its collapse, the breakwater will be able to assist the evacuation activity.

From such a point of view, the technical standards for port structures in Japan partially revised in 2013 [10] addresses the performance requirements of a breakwater for a tsunami exceeding the design tsunami. The revised technical standards states: “In terms of the performance requirement of a breakwater for which the consequence of failure is significant including loss of life and property or significant negative effects to socio-economic activities, when it is subject to a tsunami exceeding the design tsunami, the collapse of the structure should be delayed as much as possible”. For a tide embankment with equivalent importance, similar performance requirement is stated in the revised technical standards.

For the purpose of realizing a robust breakwater, various methods have been proposed including embankment widening and scour protection. For the verification of the methods, hydraulic model tests and numerical simulations are used.

As mentioned above, in the design for a “tsunami exceeding the design tsunami”, not only the performance of the structure itself but also of the structure-environment system, which is the tsunami-affected region including the breakwater in this case, is considered as a system. Then, based on the expected consequences, possible measures are taken. Therefore, the design for a “tsunami exceeding the design tsunami” is one example of a true “anti-catastrophe design”, in the terminology of this article. In the future, if the positive effects of various measures to improve the breakwater robustness are evaluated through tsunami inundation simulations and evacuation simulations in terms of their contribution to assisting evacuation activities, the effectiveness of the measures will be recognized more widely.

5. Discussion and Conclusions

As mentioned above, in light of the serious tsunami disaster during the 2011 Tohoku earthquake and the subsequent severe accident at the Fukushima-Daiichi Nuclear Power Plant, the preparedness of infrastructures such as railway structures, highway structures and port structures in unexpected events became a big issue among civil engineers in Japan. The authors formed 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, basically two kinds of design ground motions, namely, the level 1 and 2 design ground motions are considered and the structures are designed so that they fulfill respective performance requirements through verification. In particular, significantly intense ground motions from shallow crustal and subduction earthquakes have been considered as the level 2 design ground motions. However, it is still necessary to consider the performance of structures under unexpected events and its consequences, mainly because of our insufficient knowledge of natural phenomena and of the performance of structures itself. Therefore, the working group proposed a new design concept called the “anti-catastrophe design concept”. In this concept, 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 working group has started developing a framework for the design of structures based on this concept.

While the “anti-catastrophe design” is a new concept, the working group noticed that the necessity to be prepared to unexpected events has long been recognized among diligent engineers. In addition, the seismic design codes have been improved since the occurrence of the 2011 Tohoku earthquake and now we can find descriptions about the preparedness of structures in unexpected events in these codes. In order to understand how these codes are trying to assess this issue and to contribute to the establishment of the “anti-catastrophe” design concept of structures, the design standards for railway structures, highway structures, and port structures in Japan are reviewed, with special reference to their recent trends.

In all of these codes, the necessity to consider the performance of structures under unexpected events and its consequences are recognized. For the railway structures, devices have been developed for the anti-catastrophe design including the “dead weight compensation mechanism”. For the highway structures, “unseating prevention devices” have widely been used in the design of bridges. On the other hand, the design specification for highway bridges suggests some preferable structures where the displacement of the superstructure in the axial direction is restricted and unfavorable situations such as deck unseating can be avoided. For the port structures, efforts are being made to improve the performance of breakwaters after they are affected by extreme tsunamis.

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 [12], where the engineers are requested to evaluate the consequence of structural failure. However, as mentioned above, the Japanese engineers seem to put more emphasis on the development of measures or devices to cope with this issue, probably because “the unexpected events” are much more realistic in Japan than in any other country on the globe. In addition, some of the devices have already performed well during past large events.

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. So far, our main concern was to evaluate the performance of structures subject to “design ground motions”. Thus, less attention has been paid to the performance of structures subject to a strong ground motion exceeding the design ground motions. 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. For example, model tests and numerical simulations could be useful, as they have been useful in the study of robust breakwaters in the field of port engineering.

On the other hand, it is not reasonable to think that the performance of such devices or measures could always be evaluated quantitatively. Sometimes, other human abilities such as intuition and insight could be useful in developing measures and devices. As an example, although we do not know the detailed stress history of unseating prevention devices during an earthquake, they have widely been used in the design of highway bridges in Japan and some of those devices have performed well in the past earthquakes.

After all, we should mobilize all kinds of human ability, ranging from intuition or insight to more sophisticated engineering skills, to cope with the issue of the preparedness of structures to unexpected events.

6. Acknowledgements

The authors would like to thank the members of the “anti-catastrophe design” working group, the Earthquake Engineering Committee, the Japan Society of Civil Engineers, for fruitful discussions.

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