SEISMIC DESIGN FOR “ANTI-CATASTROPHE”
— A STUDY ON THE IMPLEMENTATION
AS DESIGN CODES —

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This paper presents a design concept of “anti-catastrophe” and proposes a framework of seismic design code for that concept. It proposes that the domain to be considered in the design should be extended in terms of three dimensions: phase, time, and space. We discuss the conditions required for the implementation of “anti-catastrophe”-oriented design. Since concepts of “anti-catastrophe”-oriented design is significantly different from that of conventional design, it is proposed to introduce “Category of Design” (CoD). We then present a design framework which consists of five stages. We also discuss institutional conditions required for this new design codes from the viewpoint of risk governance.

Key Words: anti-catastrophe, seismic design code, extreme events, resilience, risk governance

1. INTRODUCTION

After the 2011 off the Pacific Coast of Tohoku Earthquake (which will be referred to as “2011 Tohoku Earthquake” hereafter), anticipation of extreme events has become a great concern in Japan. The role played by the infrastructures in the recovery activity after the severe disaster is recognized. The Operation Comb (The Operation Kushinoha)3, which succeeded in providing access roads to the severely damaged coastal area quickly after the earthquake, was highly appreciated. The cooperation of multimode transportation, maritime transport, railways, and flights, which contributed supply of oil to the Tohoku Area, was also reported by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). Many infrastructures utilized in these operations were actually damaged. However, their damage was not critical and thus they were operational after proper repair. These events indicate that infrastructure can contribute to the resilience of the society, if they are not critically damaged and that their contribution can make considerable difference.
After the 2016 Kumamoto Earthquake, the number of evacuees exceeded 180,000 at its peak on the day after the main shock. This indicates the importance of the support for the community. Investigation of damage to infrastructure by the 2016 Kumamoto Earthquake indicates that appropriately designed structure could avoid critical damage and would be able to make contribution to the recovery process after severe earthquakes\(^2\).

It is not a totally new concept for engineers to assume a situation beyond the capacity intended in the design. The concept was, after the 2011 Tohoku Earthquake, partially adopted in the design code of railroad structures\(^3\). Many types of technologies based on a similar concept were available even before the 2011 Tohoku Earthquake. It was not clear, however, how those technologies should be stated in the design code. Since it was not explicitly specified in the design specification, it must be conducted based on engineers’ judgment, paying attention to the economic rationality to avoid overspecification.

Accountability is important for infrastructure, since their cost is paid by public budget. For the implementation of “anti-catastrophe” property, it is necessary to clarify the concept of “anti-catastrophe” and explicitly specify it in the design codes. This paper organizes the required elements for the “anti-catastrophe” property to be specified in the design codes, providing the theoretical foundation.

### 2. “ANTI-CATASTROPHE” CONCEPT

#### (1) Core concept of “anti-catastrophe”

The idea of “anti-catastrophe” property is understood as the high ductility of structures, when they are exposed to extremely strong external force. However, they are not equivalent with simply strong or ductile structures.

The Operation Comb shows that infrastructures can essentially contribute to the recovery process or resilience of the society, if they are not severely damaged. MLIT (The Ministry of Land, Infrastructure, Transport and Tourism) reported that The Operation Comb was possible owing to the following three factors:

1) Quick and clear decision was made about the procedure and order of rehabilitation of roads.
2) Local construction companies devoted their resources to this operation.
3) Retrofit of bridges prevented the occurrence of severe and irreparable damage.

It should be noted that factors that are not directly related to the reduction of structural damage are included.

As this case indicates, “anti-catastrophe” is not solely the property of structures; it also represents the disaster response capacity of various organizations. The scope for the implementation of the “anti-catastrophe” property should include the whole community.

#### (2) Extension of the scope of design

The “anti-catastrophe” requires consideration of the aspects that were not explicitly discussed in the conventional seismic design. We need to widen the scope of the situation to be considered in the design process. Let us introduce the three dimensions to deliberate on for the extension: a) Phase, b) Time, and c) Space.

##### a) Phase dimension: situation after the structures are damaged

After the Tohoku Earthquake, the role and contribution of seawalls and breakwater are recognized. The Japanese design codes of those structures declare that those structures should have “ductile property,” so that they can contribute to the mitigation of damage due to tsunami whose height exceeds the specified value of the design tsunami\(^5,6\). Similarly, in the seismic design, importance of ductility has gained recognition and it is mentioned in the Japanese design code of railroad structures\(^7\). These design codes request to pay attention to the situation after the structures are seriously damaged, which had not been explicitly mentioned in the previous design codes, so that appropriate countermeasure for such situation can be taken. It is the core concept of “anti-catastrophe.”

##### b) Time dimension: fast and efficient recovery

Resilience has been discussed for decades in various fields including disaster management\(^8,9,10\). Bruneau et al.\(^9\) presented the framework to quantify resilience capacity. They denoted the performance of infrastructure in the community by the performance ratio \(Q(t)\), which was supposed to drop and recover after the disaster as shown in Fig. 1. Then they defined the Resilience Loss function as:

\[
R_L = \int_{t_0}^{t_f} [100 - Q(t)] dt
\]

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**Fig.1** Performance recovery of infrastructure after the damage (%). Time \(t_0\) denotes the moment of damage\(^9\).

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This simple formulation explicitly considers the time after the event, and it can evaluate the contribution of infrastructure in the recovery process.

There are other similar approaches for the evaluation of resilience. For example, Bocchini et al. quantified resilience as:

$$ R = \frac{1}{t_1 - t_0} \int_{t_0}^{t_1} Q(t)dt $$

(2)

This emphasizes the efficiency of the recovery from the damage. We should select the appropriate index, depending on what aspects of contributions to quantify in the design process.

c) Space dimension: multi-scale approach in terms of physical space and system domain

The design should discuss not only the performance of the unit of infrastructure, but also the performance of the infrastructure system so that it can play a key role in the recovery process of the whole community. For that purpose, infrastructure design concept should expand the domain to consider:

- Physical space, so that the role of the infrastructure during the recovery process of the regional community can be taken into account, and
- System domain, so that the network of infrastructure can perform as a whole infrastructure system.

After the 1995 Kobe Earthquake, the Japan Society of Civil Engineers (JSCE) proposed the design concepts based on their studies, in which “seismic performance of the system of infrastructure” was discussed. The concept presented in this paper is consistent with that idea of JSCE.

The domain of the system should be defined in various manners in different scales depending on the concerned function. The design of girder restrainers of the bridge, for example, should pay attention to the behavior of the whole bridge structure as a structural system, while the required performance level of the bridge should be determined based on the evaluation of the transportation network covering a broad area. On the other hand, design of the seawall requires the consideration of the people’s evacuation, that is, the function of the community as a social system.

(3) Definition in relation to the current seismic performance

How should we define “anti-catastrophe” in relation to the concept of current seismic design? The “anti-catastrophe” property is to assure the function for the situation after the disasters. It is supposed to encompass the concept of conventional seismic performance.

However, “anti-catastrophe” is not just the enhancement of Safety, Serviceability, and Recoverability, which are conventionally considered as elements of seismic performance.

It is clearly classified as another independent property that should be added to these three elements. This indicates that seismic design can independently adjust the level of seismic performance in terms of Safety, Serviceability, Recoverability, and “anti-catastrophe.” Even the structure with low recoverability or safety can be equipped with high “anti-catastrophe” property. Those structures can provide part of their function even after they are severely damaged. This may be useful for the seismic design of existing structures, which had been designed with old design codes.

Let us also discuss the relationship to other concepts of seismic performance. Bruneau et al. listed the following 4Rs as elements of resilience:

Robustness. Strength, or the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function.

Redundancy. The extent to which elements, systems, or other units of analysis exist that are substitutable, i.e., capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality.

Resourcefulness. The capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some element, system, or other unit of analysis; resourcefulness can be further conceptualized as consisting of the ability to apply material (i.e., monetary, physical, technological, and informational) and human resources to meet established priorities and achieve goals.

Rapidity. The capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption.

These 4Rs are applicable for “anti-catastrophe”. Robustness is obviously essential to deal with uncertainties of severe situations induced by earthquakes. Redundancy is also necessary to prepare some alternative functions for the structure to work, or sufficient margin to the external force. We would like to emphasize the importance of Resourcefulness, which is not just about the amount of available resource, but also about the capability to judge and manage the resource allocation in the response to the situation. Resourcefulness is not the physical condition of the structure, but it should be included as seismic performance. Rapidity is close to the concept of recoverability, which explicitly discusses the time factor.

The discussion about them are further elaborated in the White paper on the SDR grand challenges and by Renschler et al., as the property that considers the contribution of social capacity. They pay attention to the recovery, which is defined as $R$ in Equation (2). It corresponds to Resilience, which is also
essential for “anti-catastrophe”. Resilience is correlated to the factor Time among the three dimensions of “anti-catastrophe”, and it is also associated with Phase and Space. It evaluates the influence on secondary damage and recovery. It also considers the effect on the community. The concept of Sustainability, which has been widely accepted for a longer time, shares a similar idea. Sustainability should be considered in the gradual deterioration such as aging of infrastructure, while “anti-catastrophe” for instantaneous damage such as collapse due to earthquakes. They are consistently complementary with each other.

3. CONDITIONS FOR IMPLEMENTATION OF “ANTI-CATASTROPHE”-ORIENTED DESIGN

This section discusses the required conditions to implement the concept of “anti-catastrophe” in the design of structures.

(1) Framework of performance-based design

The quality of “anti-catastrophe” property is not only determined by physical conditions, but is also dependent on the context, such as the expected role of the structure after the disaster, importance of the structure in the infrastructure system, and available resources for the structure.

The first task of the design for “anti-catastrophe” property is to determine the performance of the structure in the circumstances expected after the disasters. It is followed by the essential task to define the design concept that will form the baseline of the detail design.

Since it is highly context-dependent, it is not practical to prescribe all applicable options in the design code. This procedure is similar to that of the performance-based design approach, in which the performance of the structure should be appropriately determined considering various factors. For the implementation of “anti-catastrophe”, the design code should not take the prescriptive style, but that of the performance-based design method.

(2) Qualitative validation

It is desirable to verify the legitimacy of the design by numerical simulations. However, “anti-catastrophe” property becomes effective in an extreme case that exceeds the assumption of the seismic design, and it is not always possible to simulate the whole phenomenon precisely.

For example, the behavior of the bridge whose RC columns suffer buckling due to extremely strong ground motions is difficult to reproduce accurately. It is almost impossible to predict which column will be damaged, and how seriously due to what type of ground motion. This implies that we cannot rigorously verify the performance of the “anti-catastrophe” mechanism to prevent the secondary damage after the buckling of (some of) the PC columns.

Even when details of the behavior of the damaged structures are not precisely known, we should still be able to identify critical problems and propose countermeasures, since “anti-catastrophe” property should be essentially robust against changing situations.

It is not intended to discourage detailed analysis. For newly developed design methods and technologies, established procedure for performance evaluation may not be available. However, lack of authorized verification procedure should not hinder employment of advanced methodologies, if performance can be rationally verified. It should be accepted that high accuracy of analysis is not necessary, if essential mechanism is well understood and verified through reliable measures, including theoretical analysis, experimental investigation, or survey of past damage cases.

It is accountability that matters. We should promote disclosure of the information including the methodologies and data utilized for the validation. If quantitative value of some evidence is not available, lack of data itself should be disclosed.

(3) Institutionalization

As discussed above, it is difficult to quantitatively evaluate the contribution of “anti-catastrophe” property before severe earthquakes actually occur. Even if it is evaluated, it could be underestimated, because “anti-catastrophe” concept is for rare events that have very low occurrence probabilities. It may not be an easy task to justify the “anti-catastrophe”-oriented design from the viewpoint of conventional cost-benefit analysis. Therefore, it should be explicitly required in the design codes.

At the same time, attention should be paid to the consistency with the current seismic design codes. Seismic design codes in Japan have been improved for decades and they also have already realized several concepts of “anti-catastrophe” property. The logic of those existing design codes should not be disturbed or ruined by a newly introduced “anti-catastrophe” concept.

4. CATEGORIES OF DESIGN

There are significant differences in current seismic design and the “anti-catastrophe”-oriented design, because they had been developed for different purposes.

Current seismic design requires that structures
should satisfy specific conditions. Response of structures exposed to specified external force must be strictly under the specified value. On the other hand, “anti-catastrophe” requires structures to be resilient in various situations. Structures with “anti-catastrophe” property are not supposed to lose their fundamental function even when they are under unassumed conditions.

The “anti-catastrophe”-oriented design is different from the conventional methods in the following aspects:

1) The design of the “anti-catastrophe” structure takes into account the structure performance beyond the state that is considered as the limit state (which should not be exceeded) in the conventional design code. Because uncertainty and complexity of the structural behavior are much more severe beyond the limit state, a reliable simulation method to verify the design has not been established.

2) Consideration of the time line after the disaster. In evaluating of the role of the structure during the recovery process, circumstantial conditions after the disaster should be determined in advance and must be checked in several scenarios. It is affected by even social factors; thus, verification of the design is even more difficult than 1).

3) In requires discussion of not only the scale of the unit of the target structure, but also the larger scales of infrastructure systems and the community. For this purpose, engineering designers should participate in the earlier stage of the design process, where general concept of the target structure is determined.

Since current design and design for “anti-catastrophe” differ in many points, their design codes are therefore different. These different design concepts should be clearly defined to avoid confusion. For that purpose, we propose to introduce the class of “Category of Design” (CoD). The current design is classified as “Category of Design I” (CoD-I) and the design for “anti-catastrophe” as “Category of design II” (CoD-II).

However, if the current seismic design and CoD-I are regarded as rigorously identical, it raises inconsistency with the current design, because the current design already includes some technologies corresponding to the “anti-catastrophe” concept. If such technologies are labeled as specifically for “anti-catastrophe”, they may be regarded as unnecessary for ordinary seismic design and may not be utilized. Such situation must be avoided. Therefore the boundary between CoD-I and CoD-II should be different from the boundary between conventional seismic performance and “anti-catastrophe” property.

This concept is shown in Fig. 2. There are two blocks labeled as “Design” (top) and “Performance” (bottom).

The top block shows the concepts of seismic design, where Level 1 and Level 2 are included in the “Category of Design I.” The dotted vertical line separates the “Category of Design I” and “Category of Design II.”

The bottom block illustrates the concept of seismic performance. The left part consists of three elements of current seismic design: Safety, Recoverability, and Serviceability. They gradually merge to the right part labeled as “anti-catastrophe”. Note that the left and right parts are not distinctly separated.

It should be noted also that the vertical dotted line separating “Category of Design I” and “Category of Design II” in the top block is located above the domain of “anti-catastrophe”. It means that some of the “anti-catastrophe” is covered by CoD-I of the design codes.
In practice, the position of the border between CoD-I and CoD-II should be different for different infrastructures, depending on various factors such as their roles in the society, the level of seismic performance of existing structures, physical conditions such as seismic environment, and social circumstances such as budgetary constraint and consistency with current design codes. The final decision should be made by the owner or the code writers who are in charge of and responsible for the management of the corresponding infrastructure.

5. FRAMEWORK OF “ANTI-CATASTROPHE”-ORIENTED DESIGN METHOD

This section proposes a basic framework for “anti-catastrophe”-oriented seismic design for the design codes. The concept of “anti-catastrophe”-oriented seismic design is similar to that of the performance-based design. Assuming that the framework of the performance-based design should be suitable for “anti-catastrophe”, we propose a framework which consists of five stages:

(i) Definition of anti-catastrophe performance To clearly define the targeted performance.

(ii) Situation setup To determine damage types, circumstantial conditions, and input ground motions.

(iii) Conceptual design To determine general design concept.

(iv) Structural design To design the details.

(v) Verification and validation To confirm that stages (i) to (iv) are correct and consistent.

First, in stage (i), we define the target performance of the structures expected after they are severely damaged. Since the main objective of “anti-catastrophe” is to contribute to the recovery of the infrastructure systems and the community, not only technical aspects, but also social environments should be taken into consideration.

Then, technical issues of structural design are discussed in stages (ii) to (iv), such as evaluation of external force and response of structures. In the design for “anti-catastrophe” property, extreme situations that are more severe than those in the ordinary design are assumed. In addition to protection against the disasters, response and recovery after the disasters should be explicitly within the scope of design.

In the last stage (v), the whole design process is to be reviewed. Besides verifying that analyses and evaluations are correct, consistency of the whole design stages should be validated.

The design process does not have to follow the order of (i) to (v), because the cycle of the whole process should be iterated, exchanging feedback and adjusting to each other, until they converge into the final output.

In the following sections, we describe stages (i) to (iv), clarifying essential elements of CoD-II that must be included in each stage.

(1) Definition of anti-catastrophe performance

Since the design procedure takes the same framework as the performance-based design, the performance this design aims at must be determined as the first step. It should clearly specify what performance is to be realized in what situations. Since the defined performance must be feasible and reasonable, it must be derived based on the discussion considering various aspects including engineering and management.

First, we need to identify the social needs: what role the structure is expected to play. In the aftermath of the disaster, infrastructures are expected to support various activities to support the recovery of affected community. Possible contribution of infrastructure is dependent on the condition of the society, which includes its vulnerability and capability. The regional disaster management plan of the area should also be taken into consideration.

To determine conditions for “anti-catastrophe”, extreme situation must be assumed. For those purposes, it would be helpful to extend the discussion to the dimensions of phase, time, and space (see Section 2. (2)). It must also be recognized that some structures do not require “anti-catastrophe” property, because of their limited role in the recovery from serious disasters.

We also have to think of technical feasibility and rationality. The performance defined above must be feasible. Therefore, feasibility of all following stages should be roughly estimated in terms of budget, time, technologies, and other factors. As physical conditions, scientific information such as seismic environment, ground conditions, locations of active faults, and past earthquake records, should be taken into consideration. Most of these factors are already considered in the current seismic design, but extreme situations assumed with rational scientific reasoning are not considered. Although they are essential for the design for “anti-catastrophe”, they are not explicitly included in the conventional design scheme.

In the context of catastrophe, not only the structure of our concern, but also other structures and the whole community must suffer some damage. Therefore, when recoverability is discussed in the design for “anti-catastrophe”, social condition should be given more emphasis than it is in the current seismic design.

As introduced above, the Operation Comb after the 2011 Tohoku Earthquake was possible only with the help of management factors, such as appropriate decision of administration and contribution of con-
struction companies based on the agreement. It would be advisable to consider those factors in the design stage.

It is also essential to consider the social conditions to maintain the performance and condition of the infrastructures. Availability of monitoring data, original design documents, capability of society and organization for maintenance management, such as preparation for the emergency response, skills, and budget for the infrastructure maintenance, must be important factors. They are external conditions and have only secondary effect on the structures, but they can be considered as elements of the performance of the structure in the design for “anti-catastrophe”. They do not make direct contribution but they correspond to Resourcefulness, one of the 4Rs for resilience.

In order to determine the required performance, the societal significance of the infrastructure in the aftermath of severe natural disasters must be assumed, considering various aspects. These aspects include engineering and management conditions, such as possible damage mechanism, technologies and capacity for the recovery, quality of maintenance, and availability of various resources including construction companies, labor, and heavy machineries.

(2) Situation set-up

The current seismic design determines the external force corresponding to the Levels 1 and 2, and structures are supposed to resist them. CoD-II considers the situation that exceeds the state (damage) assumed in CoD-I. For that purpose, Stress Test should be carried out to identify the damage or disaster that should be taken care of after the disaster.

Stress tests should be set up in multiple scales, using the following scenarios: 1) some devices get broken, 2) some structures collapse, and 3) the transportation network is disrupted. Emphasis should be put on how further severe damage and secondary effect can be prevented, and how functions of structures can be recovered in a short time.

One of the methods to set up the extreme situation is to consider extraordinarily strong external force, or strong ground motion that exceeds the L2 class ground motion.

In the past decades, the total number of strong motion records has increased due to the development of observation networks. It is widely accepted that ground motion can exceed the ones specified in the design codes.

Ground motion simulation methodologies also have advanced considerably. The influence of local site effects can be evaluated by various methodologies and it is possible to simulate strong ground motion at an arbitrary site with certain reliability. Therefore, we can synthesize a realistic worst-case ground motion by setting parameters intentionally tough for the structure. Such ground motions are usually not utilized in the seismic design, but should be suitable for the design to consider “anti-catastrophe”. Structural analysis using those ground motions can provide us with insights into the possible damage modes, for which we should prepare for. For the purpose of Stress Tests, it would be also possible to utilize ground motions that are generated by processing those recorded or artificially synthesized ground motions.

Another method is a scenario-based approach. Even if detailed analysis is not conducted, we can estimate the damage scenarios based on engineering knowledge. In some cases, we may skip the evaluation of external force and take severely damaged situation as the starting point of discussion.

It should be clearly stated that the situations assumed in this stage of the design are hypothetical virtual scenarios for Stress Tests to investigate the vulnerability of the structures under extremely tough condition. Since the situations are regarded as exceptional, lack of the countermeasure for such situations should not be regarded as omission with any legal responsibility.

(3) Conceptual design

This stage determines the design concept of the structure, such as selection of structural system of bridges and alignment of roads and structures. It is important information because it forms the outline of the details of structural design.

For efficient realization of “anti-catastrophe” property, the design concept should be appropriately determined considering various circumstantial conditions such as geological and geographical conditions, environmental conditions, disaster history, and specific characteristics of the expected disasters. Additionally, attention should be paid to a wider spectrum of factors such as the regional disaster management plan, and expected recovery process of structures.

One of the most important issues for CoD-II is the strategy on how the structure will manage the catastrophic situation.

Let us introduce some basic concepts of “anti-catastrophe” strategies. The requests on structures can be one of the following:

- To be stable even after severe damage: e.g., girder restrainer can still support the full weight of the girder.
- To be robust against changing conditions: e.g., low sensitivity to the change in parameters, and predictability of behavior even under uncertain conditions, or
- To be strong sufficiently against a very large external force: e.g., a structure that can resist an
external force that is much larger than the force specified in the design code.

The concept determines the baseline to discuss the required structural strength, function and state after the damage, required conditions for fast recovery, selection of construction site, and other elements of design. Thus, it defines the outline of the structural design.

This may correspond to “the creative process in designing large bridges”\(^{(18)}\). It is required for engineering designers to be involved in this stage to make, or support the people to make, decision appropriate from the viewpoint of “anti-catastrophe”-oriented design.

(4) Structural design

This stage is close to the procedure of the current seismic design based on structure mechanics and dynamics, where details of the structure are determined so that it realizes the specified property, based on the conceptual design. It is important to implement appropriate measures to prevent the situation from becoming physically or socially critical.

For CoD-II, the most advanced technologies should be utilized. Even if the evaluation/verification method applicable for such advanced technologies is not established yet, reliable and effective technologies should be admitted after thorough investigation and verification based on scientific knowledge. Lack of evaluation method should not discourage the employment of appropriate technologies.

(5) Verification and validation

For CoD-II, it is necessary to assure that all factors set for “anti-catastrophe” are effective and practically feasible. This final stage is supposed to make sure that the target performance of the presented design will work effectively in the assumed scenarios, paying attention to elements such as severe structural damage, response of communities such as evacuation, and also recovery of infrastructures and the society.

We verify that all of the previous stages are appropriately conducted. We also need to validate the consistency among stages (i) to (iv). Conditions presented in stage (i) must be realized in the succeeding stages (ii) to (iv), so that the performance defined in stage (i) can represent the “anti-catastrophe” property designated in this design.

6. RISK GOVERNANCE

The “anti-catastrophe” concept accepts a certain level of damage on structures. It means that the risk must be accepted and shared by the society. The “anti-catastrophe”-oriented design leaves high degree of freedom to designers’ judgment, because it allows for a wide range of technologies, which are not prescribed in the design code. Therefore, for efficient implementation of “anti-catastrophe”, we need an endogenous mechanism of risk control, where society can make decisions, set appropriate safety standards, and realize and sustain them.

As for the risk management, there have been various research works. Reason\(^{(20)}\) discussed the risk management of organizations. In those research works, elimination of causes of risk was regarded as an important factor.

In recent years, Hollnagel et al.\(^{(21),(22)}\) advocated Resilience Engineering, in which they defined Resilience as\(^{(22)}\)

The intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions.

It emphasizes the role of endogenous mechanism to maintain the society. This trend is also observed in the field of structural design. ISO 2394 has adopted the concept of risk-informed decision making in their recent revision\(^{(23)}\) in 2015.

The concept of risk governance regards the community as one of the essential factors\(^{(24)}\). It includes risk commutation and risk management. Our discussion is based on this definition hereafter.

The International Risk Governance Council (IRGC) reported that the risk governance can prevent or mitigate problems such as\(^{(25)}\):

- Inequitable distribution of risks and benefits between countries, organizations, and social groups
- Differing approaches to assessing and managing the same risk
- Excessive focus on high-profile risks, to the neglect of higher probability but lower profitable risks
- Inadequate consideration of risk trade-offs
- Failure to understand secondary effects and linkages between issues
- Cost of inefficient regulations
- Decisions that take inappropriate account of public perception
- Loss of public trust

They are all important issues when risk of extreme events is considered. The IRGC presents the risk governance framework consisting of five stages\(^{(25)}\): Pre-assessment, Appraisal, Characterisation and Evaluation, Management, and Communication. We consider how these elements should be utilized for the realization and management of “anti-catastrophe”-oriented seismic design.
(1) Pre-assessment

In this stage, it is requested to “clarify the various perspectives on a risk” (IRGC\textsuperscript{25}) and to “form the baseline for how a risk is assessed and managed” (IRGC\textsuperscript{25}).

It is essential for the “anti-catastrophe”-oriented design to understand how the society perceives the risk of infrastructure damage due to rare but severe earthquakes.

Seismic design codes request that infrastructures have seismic performance that can resist a certain level of severe ground motions. However, when it is exposed to earthquakes that have very low occurrence probability but can cause severe consequences, is the public responsible for the damage or accidents?

The “anti-catastrophe”-oriented design is not intended to protect the infrastructure perfectly against extremely strong earthquakes. It is supposed to prevent the further development of the damage and support the recovery. It means that it leaves a certain level of residual risk and this concept should be accepted by the society.

It has been discussed for a long time and there has never existed a right answer. However, efforts should be continued to establish a baseline that is consistent with the concept of “anti-catastrophe” so that it should be accepted by the society.

(2) Appraisal

This stage comprises “a scientific risk assessment” (IRGC\textsuperscript{25}) and “a concern assessment” (IRGC\textsuperscript{25}).

The “anti-catastrophe”-oriented design has characteristics that can give wrong impression. For example, it explicitly considers the situation where structures are damaged, so that we can discuss appropriate action to prevent further damage. It is intended to prevent critical damage and contribute to the recovery of the society, but it can be misunderstood that structures are left unsafe, aiming at other objectives such as economic efficiency.

Let us show another possible example. The design process may utilize very strong ground motion that exceeds the ones specified in the design codes. It may give the impression that the government does not take appropriate action, even though it recognizes the risk that such strong earthquake can occur.

These kinds of misunderstanding should be prevented. We should present scientific evidence to show the meaning and effectiveness of the analysis of critical situation of the structures and the society after a severe earthquake.

(3) Characterisation and evaluation

This stage is to evaluate “societal values” (IRGC\textsuperscript{25}) based on scientific facts to judge if the risk is “acceptable,” “tolerable,” or “intolerable” (IRGC\textsuperscript{25}).

As stated above, “anti-catastrophe”-oriented design admits residual risk. For the judgment of acceptability, we should consider various factors: reliability and accuracy of estimation of occurrence probability and magnitude of expected earthquakes, technical feasibility, reliability and financial cost of seismic design and construction, trade-off between convenience and safety of infrastructure, etc. If we just provide data, it may not lead to appropriate evaluation, because it has obviously a significant magnitude of uncertainty and probabilistic approach may not give appropriate idea. However, quantitative data may be misunderstood as evidence of occurrence of damage, and qualitative data may not be sufficiently convincing. We need communication to resolve such trade-off.

(4) Management

This stage is to design and implement “the actions and remedies to avoid, reduce, transfer, or retain the risk” (IRGC\textsuperscript{25}).

In order to maintain trust and support from the society, it is essential to implement the “anti-catastrophe”-oriented design in an efficient manner.

If it is overly applied to too many structures without clear criteria or with inappropriate priority, it will not gain the reputation as a special treatment, leading to the wrong impression that those without “anti-catastrophe”-oriented design are of a quality below the ordinary safety level.

If it is not applied to important structures that are necessary for the recovery activity, infrastructure system may not work effectively in the aftermath of severe earthquakes and this concept may lose trust. Efforts should be made to apply the concept to existing structures that were designed based on old design codes.

Besides the engineering efforts, it is also important to set up an institutional environment. Implementation of the design codes should be one of the most effective methods to encourage the adoption of “anti-catastrophe”-oriented design. It should be accompanied by efforts to build trust among stakeholders including the community, local construction companies, and local government, because their support is essential for the “anti-catastrophe” property of infrastructure to function effectively after the event.

(5) Communication

This stage emphasizes the importance of communication to “enable stakeholders and civil society to understand the risk” (IRGC\textsuperscript{25}) and to “recognize their role in the risk governance process” (IRGC\textsuperscript{25}).

Bi-directional information exchange between the government and the society is essential to establish
trust in the “anti-catastrophe” concept. It will help the government to have meaningful feedback from the society, and it will also encourage the society to recognize the risk and their own responsibility for the decision. It can prevent social amplification of anxiety and distrust, or diffusion of groundless and agitating rumors through the media and the Internet. These are essential conditions not only for the realization of “anti-catastrophe” property, but also sustainability of the policy of “anti-catastrophe”.

7. IMPLEMENTATION POLICY

The policy of risk governance suggests some policies required for sound implementation of “anti-catastrophe”-oriented design methods. Discussion requires further study, but let us make some proposals based on our current conception.

(1) Collaboration with the society

Pre-assessment process requires the government to understand the risk recognition of the society and associated factors. The risk communication process demands information exchange with the society. The output of these processes should be realized and it is possible only if the government and society will work together.

(2) Appropriate application

It must be understood that not all infrastructures require “anti-catastrophe” property. The application of “anti-catastrophe” concept should be selective. If it is abused without apposite selection, it may lead to misunderstanding that the structures without “anti-catastrophe” property are unsafe. Appropriate application consistent with the basic concept of “anti-catastrophe” should justify the discussion of Appraisal.

(3) Inspection by a third party

Since “anti-catastrophe”-oriented design process has a high degree of freedom, transparency is crucial. The idea is consistent with the aim of Characterisation and Evaluation. Objective reasoning and accountability for the appropriateness are required.

For example, it is possible to use intentionally weak input ground motion in the situation set-up. One effective measure to prevent such problems is the investigation of the design process by a third party. The organization should be free from the interest of private companies and therefore it should be a public or a non-profit institution.

(4) Information disclosure

Information disclosure is obviously important from the viewpoints of Management and Communication. Information such as the situation assumed in the design, which includes the input ground motions and other external loads, is of great concern of the society and it should be shared within the society. Government may hesitate to do this because, if new information such as the existence of active faults in the neighborhood is revealed, that may require a revision of the design and may cost a lot for retrofitting or even replacement, which can be significantly costly and physically difficult in the case of the infrastructure.

However, the framework of “anti-catastrophe”-oriented design should provide a tool to exploit qualitative discussion efficiently so that we can deal with such unexpected extreme situations rationally. We would like to expect that the discussion should become productive and provide good opportunity to gain trust from the society, which is essential for risk governance.

8. CONCLUDING REMARKS

This paper introduced the concept of “anti-catastrophe” that has been gaining attention in Japan after the 2011 Tohoku Earthquake. The “anti-catastrophe” concept is an essential and useful concept of a seismic design to deal with extremely severe conditions using practical solutions. The core concept is not totally new for advanced engineers, but it has not yet been widely utilized in ordinary design methodologies. We discussed the theoretical framework and the conditions required for the implementation of this concept in design codes.

Our discussion covers the foundational parts only. Further efforts are required for the realization and diffusion of this concept. For that purpose, we emphasize the importance of not only technical issues, but also social issues. Therefore, the concept of risk governance is presented as a framework to develop the strategy for the implementation. We hope that our discussion could contribute to making the society accept the “anti-catastrophe”-oriented design as an efficient and rational methodology to prepare for extreme disasters, which will enhance the role of the infrastructure as the foundation of social activities both during the ordinary times and times of emergency.

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REFERENCES


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