ANTI-CATASTROPHE: PERFORMANCE OF INFRASTRUCTURE SYSTEMS FOR SOCIAL RESILIENCE AFTER EXTREME EARTHQUAKE EVENTS

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Abstract

After the 2011 Tohoku earthquake and tsunami, infrastructure played an important role in recovery activities. It has been shown that even if infrastructure systems are damaged by extremely severe natural disasters, their subsequent recovery to the minimum required level can make significant and essential contributions to the resilience of the community affected by extreme natural disasters. In addition to simply strengthening the seismic performance of infrastructure systems, it is crucial to ensure their performance improvement after they have been damaged. The realization of such performance is called "anti-catastrophe." To implement seismic design with this concept in mind, it is essential to consider severe infrastructure damage scenarios, propose effective countermeasures, and verify structural performance. Input ground motions should be meticulously tested as part of the design for this specific purpose. The design concept based on anti-catastrophe is applicable to a wide variety of structures. However, different structures require different design methodologies.

In this session, anti-catastrophe-oriented seismic design will be introduced from the viewpoint of ground motions and various infrastructure systems, namely reinforced concrete structures, geotechnical structures, lifelines, transportation networks, and their combinations. For each of the structure types, the concept of "anti-catastrophe" is described with their backgrounds, design methods, and actual cases of structural damage caused by severe disasters.

Keywords: Anti-Catastrophe, Seismic Design, Community Resilience, Input Ground Motion, Risk Governance

1. Introduction

After the 2011 Tohoku earthquake and tsunami, infrastructure played an important role in recovery activities. It was observed that even when infrastructure systems are damaged by extremely severe natural disasters, if they recover to the minimum required level, they can make significant and essential contributions to the resilience of the affected communities. In addition to simply strengthening the seismic performance of infrastructure systems, performance improvement is crucial after the actual damage has occurred. The concept of resilience has garnered the keen interest of engineers. Resilience-based designs have been developed and published in various forms, including guidelines from the American Society of Civil Engineers (ASCE) [1]. One of the essential elements of these methodologies is uncertainty.

For example, Operation Comb, which played a crucial role in providing access to areas that were completely destroyed by the 2011 Tohoku earthquake and tsunami, was not prepared prior to the earthquake [2]. Therefore, we must consider Knightian uncertainty, and not risk, in the preparation efforts for severe disasters. Knight presented the concept of uncertainty for which quantifiable information, such as probability, is missing [3], while risk is a quantifiable uncertainty. Resilience engineering considers serious risk, but we must also prepare for unpredictable severe disaster situations for which only insufficient knowledge is currently available. We call this concept “anti-catastrophe.” When designing a structure seismically with this concept in mind, it is essential to consider severe scenarios of infrastructure damage, propose effective countermeasures, and verify their performance. Input ground motions should be meticulously designed for this specific purpose. Design based on the anti-catastrophe concept is applicable to a wide variety of structures. Different structures, however, require different design methodologies.

This paper is structured as follows. The Introduction is followed by the “Resilience” section, which reviews the concept of resilience and then extends that concept to the main concern of this study, which is “anti-catastrophe.” This concept is elaborated upon in the third section, “The Anti-Catastrophe Concept.” This section discusses the aims of anti-catastrophe and defines the catastrophes that we are concerned with. The next section, “Seismic Design for Anti-Catastrophe”, presents the framework of the seismic design employed to realize the concept of anti-catastrophe. It also gives a brief description of the elements comprising the framework. The section on “Risk Governance” emphasizes the importance of community in the development of anti-catastrophe, and explains how risk governance is an essential factor in encouraging the community to participate in the disaster management and recovery process. The last section provides a summary of the paper.

2. Resilience

Resilience is widely recognized as an essential part and parcel of earthquake disasters. Resilience-based design has been discussed. For example, the *Journal of ASCE Structural Engineering* published a special issue titled “Resilience-Based Analysis and Design of Structures and Infrastructure Systems” in 2016. It covered a wide variety of research topics. One of the topics involved structural performance. Echevarria et al. [4] discussed the seismic performance of RC bridge piers retrofitted with concrete-filled fiber-reinforced polymer tubes. Chandrasekaran et al. [5] discussed the effect of the retrofit material on the performance of bridges in the multihazard context. Rodgers et al. [6] proposed and validated the performance of damage avoidance design. Their main concerns involved the improvement of seismic performance. These technologies have made significant contributions with regard to safety in the context of earthquake disasters. Strictly speaking, however, they are not associated with recovery or resilience.

Other topics discussed in the special issue included the quantification of resilience. Cimellaro et al. [7] investigated the recovery of water supply networks. Cimellaro et al. [8] quantified resilience by integrating the resilience curve, which had been proposed by Bruneau et al. [9]. Similarly, Alipour et al. [10] discussed the effect of the deterioration of road networks on the resilience of the transportation network. Reed et al. [11] presented a method to estimate the resilience of electric power supply networks. They modelled the elements of the network using a single-degree-of-freedom system. Quiel et al. [12] proposed a method to estimate the recovery process while considering a wider variety of aspects. Quantification was conducted by integrating the recovery curve of Bruneau et al. [9]. These studies attempted to improve the efficiency of the recovery process. Retrofitting of structures has also been evaluated from the same viewpoint; thus, it is implicitly assumed that the recovery process after the occurrence of a disaster is determined in advance.

However, planned action may not be possible in the wake of very severe natural disasters. In the case of the 2011 Tohoku earthquake, for example, the Ministry of Land, Infrastructure and Tourism (MLIT), Japan, conducted Operation Comb to provide access to areas that had been totally destroyed by the tsunami. The operation made a significant contribution to the recovery of these areas. This strategy was unplanned because the disaster situation was totally unexpected, and the originally planned strategy was almost useless. Disasters are termed as serious disasters when they involve certain unexpected factors. It is impossible to predict the damage before the earthquake, let alone quantitatively evaluate resilience.

The anti-catastrophe concept requires the community to consider the situation after infrastructure has suffered physical damage in the aftermath of a very serious disaster. Because a large amount of uncertainty must be accepted, the anti-catastrophe concept does not require optimized management or accurate prediction of the recovery process, but the identification of the essential mechanism by which the disaster inflicts damage on the community.

The MLIT reports that the voluntary contribution of human and physical resources by the construction companies was an essential factor for the success of Operation Comb. Such collaboration with the community is also essential for the resilience of infrastructure. In the aforementioned special issue of the ASCE journal, Burton [13] and McAllister [14] presented proposals based on community resilience. Park et al. [15] remarked upon the importance of the community's capacity to respond to catastrophic events. Thus, quantification of the resilience of the infrastructure requires consideration of their contributions to the community's recovery activities.

3. The Anti-Catastrophe Concept

3.1 Objectives

The anti-catastrophic property of a structure can be defined as the capacity of the structure to contribute to the resilience of community even when it is exposed to conditions that exceed the design parameters of the structure. We cannot completely prevent the damage caused by extremely intense disasters. However, if the community can take appropriate action for recovery after the disaster, it could be regarded as being resilient. Anti-catastrophe is consistent with this idea.

From the viewpoint of the technical issues concerning structural design, the anti-catastrophic concept could be regarded as an advanced version of the safety factor, which demands that a particular margin be considered in the estimation of structural performance to avoid accidents due to fluctuations in the properties of the structure. However, while discussing the anti-catastrophic property, we need to assume larger and more complex uncertainties.

Infrastructure is exposed to significant uncertainties due to the natural environment. Structures are typically constructed on site, which implies that their quality is not strictly controlled. Thus, the structure itself has relatively large inherent uncertainty. This discussion is applicable to seismic design, where external uncertainties with regard to the ground condition, input ground motion, spatial distribution of liquefaction, etc. are inherent, as are the internal uncertainties with regard to the nonlinear dynamic behavior of damaged structures. A conventional and practical solution to handle such uncertainties can be found in the seismic design of RC piers. When exposed to seismic ground motion, RC piers are more likely to suffer bending failure than shear failure, because bending failure is preferred to shear failure in terms of ductility. It is broadly recognized that this approach works efficiently, but this mechanism is not perfect when the intensity of the ground motion is very high; the anti-catastrophic concept applies to such cases.

The concept of anti-catastrophe thus applies to very severe natural disasters, which have a very low probability of occurrence but for which countermeasures must be planned nonetheless. Accurate estimation of probability is not required, but it is necessary to understand what changes may occur beyond those the structure is specifically designed for. This approach is identical to that utilized in the design of RC piers, namely designing the bending failure to be dominant. The probability of bending failure preceding shear failure is not explicitly discussed; the main concern relates to the mechanism that determines the behavior of the RC piers when these failure modes occur.

3.2 Catastrophe as a phase transition

In a previous report about the implementation of the anti-catastrophe concept [16], the author proposed three axes to extend the domain to be considered in structural design: *time, space, and phase*.

Extension in terms of *time* indicates that we must consider the situation immediately after the disaster, short-term and long-term recovery process situations, and so on. Extension in terms of *space*, which can be also understood as extension in terms of *scale*, indicates the consideration of wide-scale disasters, the effects on lifeline networks, and the like. These factors are also discussed in several papers in the special issues of the aforementioned ASCE journal [17]. We discuss the extension in terms of these phases in the next sub-section.

Many studies on resilience discuss how the strength of the infrastructure may be raised against external forces via design and construction methods, so that the structures can resist earthquake events of high intensity but low probability. The anti-catastrophic concept, however, emphasizes how to prevent catastrophes while accepting that the structure will sustain damage.

Catastrophes in the anti-catastrophe concept refer situations that are essentially different from those before the disaster occurs. Its governing mechanism should be fundamentally different from that under ordinary situations (i.e., before the disaster occurs). It is necessary to identify the change in the governing mechanism. Therefore, we define the emergence of a catastrophe as a change in phase or a phase transition from the ordinary phase to the catastrophic phase.

The term “catastrophe” as per the anti-catastrophe concept denotes a very rare event, one whose occurrence probability is almost negligible. Thus, the anticipated cost due to such an event could be small, thereby causing an underestimation of its impact and insufficient budget allocation. At the same time, preparation for extreme disasters can be very costly. These considerations indicate that we should not expect full protection or prevention against such catastrophes.

Since we cannot predict the occurrence of catastrophic situations, they involve large uncertainty. Therefore, countermeasures must be robust so that structural performance is not significantly affected by the variations in various factors, such as the external force, or the structural and environmental conditions. Rather than optimizing the measure against some specific catastrophic events, we should be prepared to function under a wide variety of possible scenarios.

It is impossible to prepare for all possible damage scenarios, however. We should thus identify the most critical scenarios that could emerge after severe damage, and take appropriate countermeasures to prevent such scenarios. To effectively prevent the emergence of catastrophes, it would be effective to identify the root cause or the fundamental factors shared by those scenarios, and take action against them. For example, damage to bridge supports can trigger ripple effects on a wide range of infrastructure networks. In this sense, retrofitting bridge supports should be an effective way to prevent the initiation of damage cascades leading to catastrophic disasters. Even if the supports suffer damage, anti-catastrophe design should allow them to recover swiftly and resume service. Even if the service resumes partially but immediately after the disaster, it would be regarded as contributing to the resilience of the community.

4. Seismic Design for Anti-Catastrophe

4.1 Overview

Seismic design for anti-catastrophe is not intended to provide perfect protection against external forces that are more intensive than those considered by conventional design. It is aimed to prevent catastrophic situations that could be triggered by events that exceed the situations assumed in ordinary seismic design. For this purpose, it is essential to extend the scope of consideration in the design process.

We can think of millions of possible scenarios as extensions of the scope. To select scenarios to which the anti-catastrophic approach must be applied, we need to consider the effect of damage to the infrastructure on the community in each scenario, including the possible secondary or ripple effects on the community, the severity of the resultant situation, and difficulty in recovery. The scenarios must be evaluated at multiscale scopes to identify all possible issues. For example, damage to bridge supports (at the bridge scale) may lead to girder failure of the bridge and in turn limit recovery activities, because such damage will hamper access to the affected areas (at the transportation network scale). Thus, it is necessary to implement such an abstract process as part of the structural design.

Implementation of the anti-catastrophic property requires the identification and management of the governing mechanism and critical factors of the damage. Advanced technologies should be utilized even if the design methodologies are not completely established. This aspect requires highly technical discussions by engineers.

Improvement in the seismic performance of infrastructure will surely contribute to resilience. However, in cases of severe disasters in which the anti-catastrophic property of infrastructure must be exploited, structures alone cannot provide perfect protection, and the community's active participation in activities such as evacuation is essential. Similarly, functioning infrastructure is crucial for the community to participate. Recovery or reconstruction activities need transportation networks to ensure access to the affected areas. Thus, both elements are dependent on each other.

To make community participation effective, it is necessary that the community is aware about the performance of the infrastructure. It is not realistic to expect the community to understand the technical discussions related to structural design. Therefore, the design frameworks should consider the ease of information sharing between engineers and lay people in the community.

4.2 Design Framework

Let us propose a design framework for the anti-catastrophe concept. It consists of the following five stages:

- Performance Definition: This stage should plainly describe the assumed disaster scenarios with circumstantial situations, such as social conditions, and explain how the structures are supposed to behave in those disaster scenarios.
- Situation Setup: This stage involves determining the external conditions of the design. These conditions should be considered as damage scenarios. Input ground motions are not required but can be used to analyze the behavior of the damaged structures.
- Conceptual Design: This stage involves determining the core concept of the design while considering various factors, such as the socio-economic conditions, geographical conditions, and seismic environment.
- Structural Design: This stage requires us to determine the details of the structural design and exploit all relevant advanced technologies.
- Verification and Validation: At this stage, we should check that the design procedure is consistent with the performance defined in the first stage, and that the design procedure meets all engineering-related requirements.

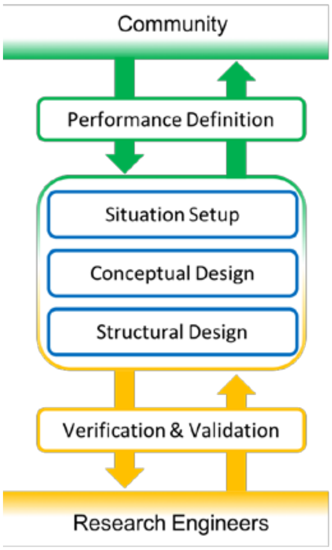

Fig. 1 Design framework for the anti-catastrophe concept.

The various stages of the design framework are presented in Fig. 1. “Situation Setup,” “Conceptual Design,” and “Structural Design” are the elements of the main design procedure, and they are bridged to the community via “Performance Definition” and to the engineers via “Verification and Validation.” Thus, the communication path between the community and the engineers is defined. Moreover, it is intended that the design information be shared between lay people and engineers.

“Situation Setup,” “Conceptual Design,” and “Structural Design” are the core tasks of conventional seismic design. They are technical and professional tasks, which must be conducted by engineers. Collaboration with the community is essential to realize the anti-catastrophe concept, but it is difficult for ordinary community members to understand such outputs. For that purpose, “Performance Definition” plays an important role, because the implementation of the engineering technologies is described plainly in the output of “Performance Definition.” The validity of the description is confirmed in the last of the five stages: “Verification and Validation.”

Moreover, to ensure that the defined performance is realized, it is necessary to conduct various technical analyses. Newly developed technologies for which design methodologies are not yet established should not be avoided simply because of this shortfall if they are effective for seismic safety. Simultaneously, if such technologies are utilized, it is necessary to conduct specific and reliable investigations to evaluate the performance of those technologies. Similarly, we need to confirm that design conditions, such as external force, disaster scenario, and the role in the recovery process, are consistent with the objectives of anti-catastrophe design. These analyses and investigations should be carried out in the “Verification and Validation” stage.

The design framework shown in Fig. 1 would enable lay people in the community, the engineers working on the structural designs, and research engineers, who are familiar with the most advanced theories and methodologies, to share their ideas about the performance of the structures that are designed for anti-catastrophe.

4.3 Components of the Design Framework

(1) Performance definition

As the name suggests, performance definition defines the desired performance in the structural design. For the purpose of risk governance, which will be discussed later in the paper, a plain description is desirable so that it can be understood and accepted by the community.

This definition must explain the necessity for the anti-catastrophic property. As explained previously, anti-catastrophe is a function beyond the necessary performance of the structure, and the reason for the selection must be clarified. The most convincing reason would be the assured role of the concerned structure in the recovery process after the disaster. Moreover, existing structures under poor maintenance could suffer serious damage and might deserve the consideration of the anti-catastrophic concept, because doing so could mitigate the effects of damage at a smaller cost than that entailed for perfect retrofits or reconstruction.

The following issues must be considered:

- Seismic environment: Scientific information in this regard includes the estimated occurrence probability of earthquakes, locations of active faults, and damage estimation.

- Social environment: Since anti-catastrophe is supposed to contribute to the resilience of the community, information on the social conditions is essential. It should include hazard estimation, a regional disaster management plan, and the various resources available for the recovery of the community. It may also include data on human resources as well as the capacities of construction companies and heavy industries.
- Recovery scenario: Although it is impossible to quantitatively predict the recovery process, the recovery plan baseline and a long-term view of the recovery process (such as future plans of the community) should be prepared in advance. They define the various conditions, such as financial or social support in the recovery process, which are essential to determine the priorities and limitations associated with the infrastructure recovery.

(2) Situation Setup

The design conditions should be defined. Input ground motion is the essential item to be defined for conventional seismic design. However, estimation of the ground motion in future earthquakes involves huge uncertainty. For rare and strong earthquake events in particular, prediction of ground motion is almost impossible. On the other hand, even if the input ground motion is not specified, the possible damage to the structures could be inferred based on structural analyses. Even if the time history of the ground motion is not available, one can consider the effect of essential factors such as ground condition and frequency characteristics to a sufficient level. Such analyses yield reliable information about possible damage for design purposes. Such damage scenario analyses do not provide the quantitative value of the damage. However, they can identify the fundamental mechanism to be considered in the seismic design, namely robustness against the fluctuations of the input ground motion. This information is sufficient for the design. Therefore, this stage is intended to determine the situation, not the external force or ground motions.

The above discussion, however, does not exclude the option of utilizing information on input ground motion as follows:

(a) Stress test with virtual input motions

To identify possible damage scenarios, dynamic analyses assuming excessively strong external forces could be an effective tool. It is preferred that the ground motion information have a scientific foundation in terms of seismology, and in recent proposals, such as STREST [18, 19], the fault parameters are considered while assuming certain types of earthquakes. However, the input motion information for such purposes should be designed so as to reveal the weak points of the structure, and these aspects should be determined from the engineering point of view.

(b) Consideration of the phases of earthquake events

It is possible to multiply some factors to increase the amplitude of the ground motion, but it is difficult to rationally determine these multiplication factors. To generate *excessively strong* ground motions, it is possible to assume which phase of the earthquake event will exceed the design assumption. By analyzing the seismological conditions, we estimate the earthquake scenario that could occur if some conditions are changed. This aspect is called a phase, and we consider the effects of changes in factors such as the size of the fault rupture, moment magnitude (energy release), and ground conditions.

In both cases, the objectives of the analysis are to identify the weak points and damage scenario, and to discuss effective countermeasures to mitigate the effects of vulnerability. This exercise does not require that structures must resist these excessively strong ground motions.

(3) Conceptual/Structural Design

These stages are similar to those in the conventional design procedure. Anti-catastrophe design does not aim to resist unexpectedly strong external forces, but to prevent the phase transition of the community to catastrophic situations. Therefore, it is essential to understand the dominant mechanism of the damage development process, and take action against the root cause of that process. This task is inevitably ambiguous, because severe damage is governed by complex mechanisms, which are sensitive to various conditions. Therefore, the design analysis does not require accurate reproduction of the damage phenomena, but it is essential to estimate the robust mechanisms required to prevent an increase in the seriousness of the damage. Computer simulation (e.g., Monte Carlo simulation) is encouraged as a tool, not only for the accurate simulation of the damage phenomena, but also for the estimation of the effects of uncertainty.

Conceptual design determines the fundamental concepts of the design, namely the macroscopic design requirements related to structural types, level of external force, and alignment of roads.

It is essential to use the most advanced technologies for structural design, because anti-catastrophe design must consider extremely severe damage. Even if newly developed technologies are not authorized and their design methods are not yet established, they should be adopted based on scientific discussions, and theoretical and experimental verification. It is essential that the results of such analysis are made freely available to third parties (i.e., the public).

(4) Verification and Validation

This stage ensures that the design is consistent with the realization of the performance defined in “Performance Definition.” It consists of the following two elements:

(a) Verification

This sub-stage verifies that all the procedures in the design process are appropriate and reliable from the viewpoint of science and engineering. External force is defined with sufficient rationality, and nonlinear dynamic simulations are appropriate to analyze the physics of the damage scenarios being considered. The performance of the newly developed technologies should be checked thoroughly as well. This process is essential to exploit the advanced technologies and scientific findings in practical design. It also enables information sharing between the design and research engineers.

(b) Validation

This sub-stage ensures that all necessary and sufficient conditions to realize the performance described in “Performance Definition” are investigated as part of the design process. It is verified that all damages are properly assumed and that the recovery scenarios are consistent with the social conditions. Moreover, this subs-stage is intended to ensure that the derived conclusion is robust against various uncertainties.

These processes are essential for the community to be able to trust the information presented in “Performance Definition.” They should be conducted by a third party so that objectivity is assured. These processes also encourage information sharing between designers, research engineers, and the community.

5. Risk Governance

5.1 Community Resilience

To ensure resilience, it is essential for the community to have the capacity to participate in the recovery process. Bruneau's framework, which is intended to quantitatively evaluate resilience based on the recovery curve, is based not only on the recovery of the structure and other infrastructure, but also on the community itself. The National Institute of Standards and Technology (NIST) applies the resilience concept to lifelines [20, 21]. NIST has also published a guideline for community resilience. [22] From the view point of structural engineering, the aforementioned special journal of the ASCE intensively discusses the behavior of structures as well as the performance of the infrastructure system (including road networks and lifelines). Thus, close collaboration with the community and the infrastructure system as a whole is essential to ensure effective resilience of infrastructure. This thought process also applies to anti-catastrophe design.

5.2 Encouraging investments in disaster prevention

Implementation of anti-catastrophe requires a resilient community. Engineers must share various types of information with the community and ensure that the community understands the concept. This would inculcate a positive attitude within the community.

Firstly, the anti-catastrophic concept must be accurately understood. We must prevent the community from misunderstanding anti-catastrophe as a compensation for the insufficient seismic performance of the structure.

Conversely, anti-catastrophe can improve the reliability of the infrastructure in the wake of severe disasters. Anti-catastrophe enhances the effectiveness of disaster prevention activities within the community. Thus, this justifies investments in disaster preparation and prevention, which in turn would encourage investment in disaster-related activities, such as development of business continuity plans for companies and organizations.

Anti-catastrophe can provide grounds for local and national governments to allocate and expend additional resources on disaster preparation as well as infrastructure maintenance. It will encourage construction industries to increase their investments in the preparation against severe disasters, which is one of the most essential factors associated with infrastructure resilience.

5.3 Risk perception

Risk-related information dissemination about severe disasters can cause anxiety and overreaction among community members. Thus, we should ensure that all risk-related information is perceived appropriately to avoid causing panic and instead encourage people to take proper action. Risk governance is thus essential to guide the community to recognize and take advantage of the anti-catastrophic property of the infrastructure. It requires to analyze not only physical conditions such as intensity of earthquakes, but also social aspects such as people's concern, and manage the community's perception and attitude. Renn [23] showed the framework that consists from five components: pre-assessment, risk appraisal, tolerability & acceptability, risk management, and risk communication.

6. Summary

This paper presented the concept of anti-catastrophe and clarified the factors that should be implemented to ensure social resilience in the community after very severe earthquakes.

The anti-catastrophic concept requires one to consider aspects that are not explicitly discussed in conventional structural design by extending the scope of seismic design over three axes: time, scale, and phase.

We also emphasize upon the importance of collaboration within the community. Resilience requires the participation of community members, and the anti-catastrophe concept can encourage the community to contribute to resilience. Their inter-dependency should be recognized.

We presented the five stages of the design procedure. Three of these stages are the same as those in conventional design. Moreover, with regard to the anti-catastrophe concept, it is essential to enable communication between the community and engineers, because doing so will guide the community to take appropriate action while allowing the engineers to implement advanced technologies without hesitation.

Lastly, we emphasized the importance of risk governance. We should exploit the community's risk perception in a positive direction. In other words, risk-related information should be provided in such a manner so as not to scare the community, but encourage it to take appropriate risk management actions.

In the future, it will be necessary to conduct research to understand how the concept of anti-catastrophe may be extended to other areas, such as considering multihazard damages, and the maintenance and deterioration of structures, as well as becoming relevant to other types of natural disasters [24].

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