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System Resilience for Sustainable Development and Disaster Risk Reduction

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Abstract: In this paper, the resilience of a complex system is described as "the ability of a system to manage uncertainties, complexities and changing situations in a timely manner during its lifetime by retaining its objectives and goals." The following eight attributes of the resilient system were summarized: (1) absorbing changes; (2) adapting to changes; (3) restoring or transforming itself; (4) monitoring change or disturbance; (5) learning from experiences; (6) anticipating potential changes, needs, demands, and constraints; (7) managing complexity; and (8) coping with change.

Keywords: resilience, natural hazard, disaster risk, sustainable development.

1. Introduction

Almost ten years have passed since the 2011 earthquake off the Pacific coast of Tohoku, which led to the Fukushima Daiichi nuclear power plant accident and questioning of conventional engineering practice. Furthermore, the lessons learned have been discussed and implemented in actual engineering practice. The concept of resilience has attracted attention, being one of the lessons learned. However, the essence of resilience does not seem to be fully understood and implemented.

This paper aims to provide an understanding of "system resilience," mainly focusing on long-term management of a complex socio-technical system, sustainable development, and disaster risk reduction that is also consistent with and an extension of risk concept. Key attributes necessary for a resilient system are also discussed and summarized.

2. Conventional definition of "system"

Before discussing system resilience, the conventional definition of "system" is reviewed. In ISO 2394: 2015, for example, system is defined as a "bounded group of interrelated, interdependent, or interacting members forming an entity that achieves a defined objective in its environment through interaction of its parts and interactions of its parts with the environment." A system discussed here includes structural systems, and human and management systems as subsystems. This means that when the performance of a structural system is discussed, it is not a purely technological issue, but it should be discussed in a more complex context as a mixture of technology, human and organizational, and socio-economic factors (Furuta, 2015).

This conventional definition of the term system also implies that the system is identifiable, as well as all elements and subsystems, and the boundary of the system can be identified. It also assumes that the objective of the system can be clearly identified. These assumptions, however, have limitations when challenges of performance-based engineering of our time are discussed as it is done here.

3. Natural disaster risk

3.1 Risk

In the field of organizational risk management, risk is defined as the "effect of uncertainty on objectives" (ISO Guide 73:2009). This definition implies that the recognition of risk is dependent on the "objectives or expectations" of the organization. In other words, whether risk management succeeds depends on whether appropriate policies, goals, and objectives are set in the organization. Recognition of "uncertainty" is another important aspect of the concept of risk, especially in case of natural disaster risk.

In the field of engineering, risk is usually defined as "combination of 'the probability of an event' and 'its (negative) consequences'" (ISO Guide 51:2014). This definition facilitates quantitative estimation of risk compared to the definition of ISO Guide 73:2009.

3.2 Characteristics of natural hazards

The assessment of natural disaster risk includes the assessment of natural hazards, as well that of system resilience. The characteristics of natural hazards make the style of natural disaster risk management different from the typical risk management style. The characteristics of natural hazards that are important from the viewpoint of natural disaster risk management can be summarized as follows (e.g., Atomic Energy Society of Japan & Japan Association for Earthquake Engineering, 2019):

- Natural hazards exhibit uncertainties, both aleatory and epistemic. Estimation of rare natural events suffers especially from significant uncertainties, where the characteristics of the natural hazards are perceived differently among experts.
- The simultaneous occurrence of damage in space and time is the characteristic of large-scale natural events (Itoi et al., 2017).
- One natural event could trigger other events, for example, nuclear power plant accidents triggered by tsunami or landslides triggered by ground motion.

Identifying and estimating site-dependent characteristics of such natural hazards is also important when managing natural disaster risk.

3.3 Natural Disaster Risk Management

Considering the experiences regarding the 2011 earthquake off the Pacific coast of Tohoku, which caused vast damage, including the Fukushima Daiichi nuclear power plant accident, how to manage uncertainties is recognized again as one of the important issues in risk management (Itoi & Sekimura, 2017). A typical fault in case of decision making related to natural disaster risk management was postponing the decision until sufficient evidence is obtained, that is, waiting until uncertainty decreases and clear evidence becomes available. Decision making and its implementation should be agile, and they should be assessed periodically based on a long-term perspective, especially in the case of the management of safety-critical facilities (Itoi et al., 2016). In case of decision making, uncertainties, as well as complexities, tend to be trivialized to make it simpler. Rigorous approaches to analyze and treat uncertainties are also needed.

As for the treatment of risk, regarding prevention and mitigation measures as equally important is also crucial considering uncertainties of natural hazards. However, the conventional engineering practice still focuses on the prevention measures, that is, setting the limit state and design its performance so that the probability of exceeding the limit state is acceptably low. Mitigation measures include recovery measures.

4. System Resilience

4.1 Review of conventional definition

The term “resilience” is often used to discuss the capability of the system to absorb change or bounce back. In the field of engineering, the focus is on the features of the system to reduce failure probabilities, consequences from failures, and time to recovery (e.g., Bruneau et al., 2003).

Resilience is also understood as a conceptual framework composed of multiple dimensions (Carlson et al., 2012; Francis & Bekera, 2014). In Francis and Bekera (2014), it was summarized that absorptive, adaptive, and restorative capacities are the way how the system needs to respond to perceived or real shocks, and the objective of resilience is to retain predetermined dimensions of system performance and identity. The importance of adaptive and restorative capacities, in addition to absorption capability, is recognized when considering the effects of uncertainties.

Hollnagel et al. (2011) proposed the four potentials that a system performs in a resilient manner, that is, potentials to respond, monitor, learn, and anticipate.

The conventional understanding of system resilience based on the discussion can be summarized as shown in Figure 1.

Structural systems can mainly contribute to absorptive capacity, that is, prevention of accident and mitigation of the consequences of the accident. Human and organizational factors are mainly considered in the case of adaptive and restorative capabilities. The concept of resilience also implies that the performance of structure also depends on that of “cognition” consistent with the discussion in Section 2, although it is sometimes out of the scope of risk assessment of structures.

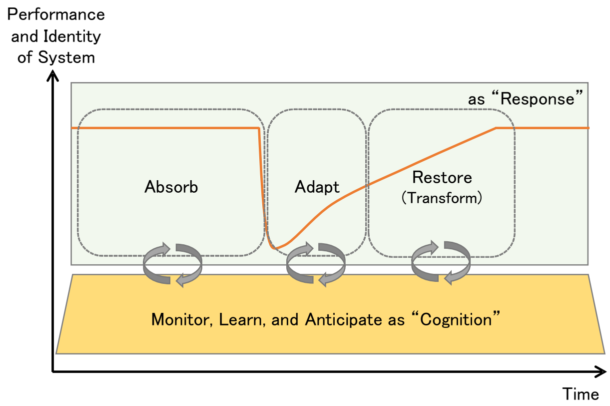

Figure 1. Resilience in previous studies.

4.2 Definition of system resilience under threat of natural hazards

As discussed in Sections 2 and 4.2, the performance of structures also depends on human and organizational factors. In the modern era, the range of stakeholders—related humans and organizations—is wide and sometimes cannot be specified clearly. Therefore, a system in modern era should be considered as an open and complex system. Not only complexity but also the variability of performance of the system, and that of its environment, should be managed.

In such a system, its objectives and goals, as well as responsibilities, are multifaceted, and they are not clearly identified. They are also not always consistent with each other, as the information to discuss them is incomplete, and it can be different for different subsystems.

Objectives, goals, and responsibilities can also change with time. Obsolescence of the system should also be recognized. Therefore, even if its objectives and goals, as well as responsibility are set, timely update is needed. The same is true for responsibilities.

In addition, it should be emphasized that it is impossible to fully capture the characteristics of the environment that the system is placed clearly, especially when external natural hazards are considered in the environment. The variety of stakeholders involved increases, including natural scientists that have the role to capture the characteristics of natural hazards and inform other stakeholders. An update of the knowledge on such natural hazards during the lifetime of the system is also important.

In case of such a system, especially under threat of natural hazards, the role of human and organization to manage complexity and cope with change is required that helps to bridge the gap between “cognition” and “response” of each stakeholder, as shown in the conventional definition of resilience in Section 4.1.

Based on the discussion so far, the key feature of system resilience under threat of natural hazards is summarized as “the ability of a system to manage uncertainties, complexities and changing situations in a timely manner during its lifetime by retaining its objectives and goals” (Itoi, 2020).

Attributes required for the resilient system can be categorized into responses, cognitions, and management. Attributes related to responses are (1) absorbing changes, (2) adapting to changes, and (3) restoring or transforming itself. Attributes related to cognition are (4) monitoring change or disturbance, (5) learning from experiences, and (6) anticipating potential changes, needs, demands, and constraints. To bridge cognitions and responses, attributes related to management — (7) to manage complexity and (8) to cope with change — are essential.

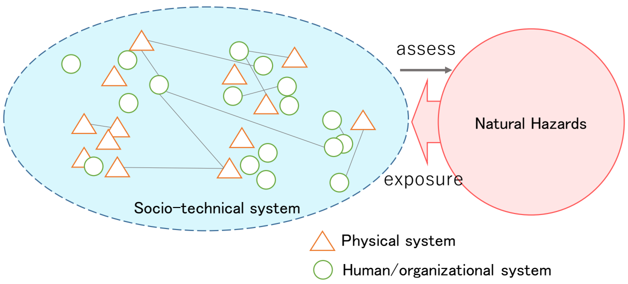

Figure 2. Schematic figure of socio-technical system exposed to natural hazards.

4.3 Safety-II perspective

The concept of Safety-II has also been proposed (Hollnagel, 2014), which focuses on things that go right, while conventional safety (“Safety-I”) focuses on things that go wrong. The concept of Safety-II is important when the performance of the system in developed society is discussed, where the occurrence of failure is relatively rare. In such cases, the conventional approach examining things that go wrong has limitations for the success of long-term system management.

It is also straightforward that the definition of system resilience under threat of natural hazards and vital attributes for it summarized in Section 4.2 is also applicable to Safety-II when managing uncertainties and variability in the system’s performance during a normal period.

5. Summary

In this paper, based on the experiences before, during, and after the 2011 Tohoku earthquake in Japan, as well as reviews of previous discussions on resilience, system resilience for sustainable development and disaster risk reduction were discussed and summarized to examine the future role of stakeholders, including academia in the field of risk assessment of structures. The concept of resilience is important to deal with change under uncertainties and complexities characteristic for modern era.

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