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Resilience and sustainability of a transportation network against geo-hazards

La résilience et la durabilité du réseau de transport contre géorisques

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ABSTRACT: Civil infrastructure systems, especially geotechnical assets, are vulnerable to climate change, and natural and man-made disasters. Resilience, which is the ability of a system to absorb, recover from, and adapt to disruptions so that the consequences are minimized, introduces a new paradigm to overcome challenges with such vulnerability. In this paper, a quantitative framework for the assessment of resilience and sustainability of geotechnical infrastructure is presented. Consideration of sustainability in infrastructure asset management in conjunction with resilience ensures that the human interventions for the purpose of building resilient infrastructure systems do not conflict with sustainability goals and result in more sustainable and desirable built environments. The new framework is demonstrated through a hypothetical case study based on a selected road network in the province of Ontario, Canada.

RÉSUMÉ : Les systèmes d'infrastructure civile, en particulier les actifs géotechniques, sont vulnérables aux changements climatiques, aux catastrophes naturelles et aux catastrophes anthropiques. La résilience, qui est la capacité d'un système à absorber, récupérer et s'adapter aux perturbations afin que les conséquences soient minimisées, introduit un nouveau paradigme pour surmonter les défis avec une telle vulnérabilité. Dans cet article, nous présentons un cadre quantitatif pour l'évaluation de la résilience et de la durabilité des infrastructures géotechniques. La prise en compte de la durabilité en conjonction avec la résilience dans la gestion de l'infrastructure garantit que les interventions humaines visant à construire des systèmes d'infrastructure résilients à de nombreux égards ne sont pas incompatibles avec les objectifs de développement durable. Environnement bâti souhaitable. Le cadre est démontré par une étude de cas hypothétique basée sur un réseau routier sélectionné dans la province de l'Ontario, au Canada.

KEYWORDS: Resilience, sustainability, assessment framework, road embankments, transportation network

1 INTRODUCTION

Over the last decade, the importance of sustainability in the built environment has been emphasized because of the growing awareness that there are limited resources on earth to fulfil human needs. The effort of the current generation to sustain and carefully consume available resources with the consideration of intergenerational equity has been a norm for sustainable development. In the recent past, increased frequency and magnitude of extreme events (i.e., natural and man-made disasters) and climate change effects have led to the realization that it is necessary to build resilience in civil infrastructure systems, ecosystems, communities, and other systems that are vital for fulfilling human needs and maintaining quality of life. Incorporation of resilience theory and sustainability science during the design, operation, and maintenance of critical infrastructure systems ensures that adverse environmental and socio-economic impacts on communities are minimized and sustainable development is achieved.

Geotechnical assets (e.g., embankments, tunnels, retaining structures, bridge foundations, dams, and pipelines), being important components of civil infrastructure systems, must be properly designed and maintained with resilience and sustainability considerations so that they are not only robust against climate change effects and extreme events, but also sustainable from social, economic, and environmental perspectives. To practically determine if geotechnical assets of interest are resilient and promote sustainability goals, a quantitative assessment framework is necessary.

In this paper, connections between sustainability and resilience are examined to find their similarities and conflicts, and a quantitative framework for the assessment of resilience and sustainability of geotechnical infrastructure is proposed. The framework is applied to a hypothetical case study of a transportation network consisting of road embankments.

2 SUSTAINABILITY AND RESILIENCE

2.1 *Sustainability in engineering*

Sustainability is mostly defined as development that “*meets the needs of the present without compromising the ability of future generations to meet their needs*” (Brundtland Commission 1987). Sustainability science introduces a perspective regarding directions on how the coupled human and natural system needs to be developed to continuously create and maintain prosperous social, economic, and ecological systems (Folke et al. 2002). To achieve sustainable development, the dynamic interactions between nature and society have to be understood, and interventions or human decisions for a better future have to be clearly defined (Clark and Dickson 2003; Gibson 2006; Redman 2014). For civil engineering applications, the philosophical definition of sustainability can be understood as a dynamic equilibrium between four Es – engineering design, economy, environment, and equity (Basu et al. 2014).

2.2 *Resilience in engineering*

The concept of resilience was first introduced in ecological studies by Holling (1973) in which resilience is defined as “*the measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables*”. Simply put, resilience is understood as the ability of a system to “bounce back” from a change or shock and still continue to function. Key characteristics of resilience are adaptation and transformation. Adaptation relates to the decision-making processes, collective actions, and learning capabilities to adjust a system to potential shocks, stresses or other changing conditions to maintain essential system functioning and allow continuous development (Nelson et al. 2007; Folke 2006). Moving the current thresholds or making a threshold more

difficult to reach may be the ways to practice adaptation (Walker and Salt 2006). On the other hand, transformability is the capacity of people to create a fundamentally new system when ecological, political, social, or economic conditions make the existing system untenable (Walker et al., 2004). In short, adaptation relates to an adjustment of the system in response to threats whereas transformation relates to a more pervasive and radical action when the system is near a threshold because of a major threat (Redman 2014).

For civil engineering applications, the concept of resilience can be characterized by robustness, rapidity, resourcefulness, and redundancy (Bruneau et al. 2003). Robustness is the ability to absorb and withstand external shocks. Rapidity is the speed of recovery from being disrupted or damaged to achieve an acceptable level of functionality. Resourcefulness is the capacity to identify problems, establish priorities, and mobilize resources (i.e., monetary, physical, technological, and informational resources). Redundancy indicates the extent to which existing elements or systems are substitutable. Many engineering systems are inextricably connected to the social, environmental, and economic systems (Basu et al. 2014); therefore, consideration of multiple dimensions of resilience is necessary to enable a holistic conceptualization of resilience from an interdisciplinary perspective (Rogers et al. 2012). Thus, the four characteristics of resilience (i.e., robustness, rapidity, resourcefulness, and redundancy) can be considered from four different points of view – technical, organizational, social, and economic (Bruneau et al. 2003; O'Rourke 2007).

In general, resilience can be quantified in terms of change in the system performance with respect to time, as given by:

$$R = \frac{1}{t_h} \int_{t_d}^{t_d+t_h} Q(t) dt \quad (1)$$

where R is the resilience, $Q(t)$ is the system functionality or performance function, t is the time, t_d is the time when disruption occurs, and t_h is the total inspection time.

2.3 Connections between sustainability and resilience

Many studies suggest that resilience is a pre-requisite to sustainable development because a resilient system has the capability to avoid surprises and continue to provide the goods and services that support the quality of life (Gunderson and Holling 2002; Walker and Salt 2006). Natural (e.g., climate change effects and natural disasters) and human-made (e.g., technological and geopolitical) changes will disrupt the cycles of materials and energy flows. Therefore, civil infrastructure systems and geotechnical assets, which consume vast amount of resources (e.g., natural and monetary resources), will be affected by such changes and significantly impact the sustainability (Basu et al. 2014; Fiksel 2006). A resilient civil infrastructure system ensures that the system has the capability to recover from a disrupted state in response to global changes and extreme events so that a desirable configuration can be maintained over a period of time. If goods and services are able to serve desirable development over extended periods of time, and the development does not jeopardize the functions of the system, then sustainability can be achieved (Folke et al. 2002; Li et al. 2015).

Sustainability envisions a continuously desirable future; however, resilience is not necessarily always desirable. A system in an undesirable state may exhibit high resilience and resist all efforts to shift the system out of that state (Walker and Salt 2006). For example, polluted water supplies, political dictatorships, fossil-fuel-based energy systems, which are not in favour of social welfare, can be highly resilient (Carpenter et al. 2001; Li et al. 2015). While sustainability focuses on examining future options to reach more desirable and durable futures,

resilience focuses on the process to build adaptive capacity to cope with unknown futures (Gibson 2006; Redman 2014). In other words, sustainability can be deemed to be the desirable objective of human development, whereas resilience thinking contributes in providing specific and practical ways to reach that goal (Li et al. 2015).

Considering the connections of sustainability science and resilience theory, an integrated framework for the assessment of both resilience and sustainability of geotechnical assets should consider two aspects. First, human interventions should not only be evaluated based on the effectiveness to improve resilience but also on their congruence with sustainability goals. Second, as civil infrastructure systems interact with environmental, social, and economic systems, sustainable development in a changing global environment requires resilience at multiple levels (Fiksel 2006). In the assessment framework, sustainability metrics can be used as criteria to ensure that the human interventions not only improve the resilience of the system but also help in achieving a desirable future state defined by the communities and key stakeholders. The framework should not only focus on the engineering aspects of the infrastructure systems but also incorporate interdisciplinary factors. For example, the socio-economic and environmental impacts should be considered along with the technical integrity of an engineering system.

3 INTEGRATED ASSESSMENT FRAMEWORK

An integrated framework for the assessment of resilience and sustainability is presented in this paper. The framework follows the structural thinking of the "Driver-Pressure-State-Impact-Response" (DPSIR) framework which evaluates the feedbacks amongst five components, i.e., driver, pressure, state, impact, and response, for a given system. The DPSIR framework was originally developed for analyzing environmental problems; however, it can be modified and reinterpreted to analyze engineering systems. The DPSIR framework is reinterpreted so that it satisfies the following objectives and is applicable to geotechnical infrastructure: (i) simulate hazard scenarios and quantify the response of geotechnical assets in terms of their limit states, (ii) evaluate the sustainability of geotechnical assets by capturing the social, environmental, and economic impacts of damaged geotechnical assets to critical infrastructure systems and societies, (iii) quantitatively assess the resilience of geotechnical assets considering the key characteristics of resilience (i.e., robustness, rapidity, resourcefulness, redundancy, adaptability, and transformability), and (iv) evaluate the effectiveness of response strategies implemented for improving the resilience of geotechnical assets. The details of the reinterpretation is available in Lee (2016).

4 RESILIENCE OF TRANSPORTATION NETWORK

The proposed framework is demonstrated using an example of a transportation network, consisting of road embankments, that connects two cities, London and Toronto, in the province of Ontario. Seven different geometric sections of embankments are considered for this case study. Figure 1 shows the schematic of the transportation network considered in this study.

4.1 Drivers and Pressures

The primary function of a transportation network is to provide mobility to the public. Therefore, in this problem, the driving forces are the factors that motivate human to attain mobility of passengers and goods to the destination point. Mobility can be affected by the user's behavior (i.e., travel distance and frequency of trips) and choice of transportation mode (i.e.,

private car ownership and use of public transport), which are also influenced by the demographics, economic needs (e.g., employment), leisure activities (e.g., tourism), development of technologies (e.g., satellite tracking for traffic conditions), energy availability (e.g., vehicle fuels), production and trade of goods, and policy making (Akhyani 2015). Identification of the drivers can help select the most important transportation networks within a jurisdiction that require resilience assessment. In this particular case, the choice of the network is made based on the fact that London-Toronto corridor is very important in Ontario from a socio-economic viewpoint.

In this study, five network links (i.e., link Nos. 2, 10, 17, 20, and 21 in Figure 1) are assumed to be affected by a flood scenario with 100 mm/hr of rainfall intensity, 6 hours of rainfall duration, and 100-year return period. It is also assumed that only 1/3 of the entire length of road embankments is affected.

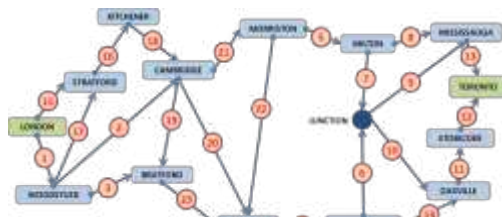


Figure 1. Schematic of London-Toronto transportation network

4.2 States

Resilience of the transportation network consisting of road embankments can be calculated using Eq. (1) with respect to appropriate multiple performance functions like the factor of safety (FoS) and settlement. The characteristics of resilience are represented by robustness, rapidity, resourcefulness, and redundancy properties.

Robustness of road embankments can be quantified in terms of the change in the ultimate limit state (ULS) and serviceability limit state (SLS) of embankments, which are represented by the FoS against slope stability and settlement, respectively. The rapidity aspect of resilience for the road embankments can be measured by the recovery of FoS and settlement with respect to time. Resourcefulness can be quantified by the ratio of construction costs required for implementing a response strategy to the government budget on highway management. The redundancy aspect of resilience can be represented by how ‘distributed’ the highway network is, and can be measured by its network entropy, which is an indicator of the heterogeneity of link attributes in a transportation network (Xie and Levinson, 2011). The more distributed the network, the higher the entropy, and the greater the redundancy.

4.3 Impacts and Responses

The impacts are quantified based on technical, environmental, economic, and social viewpoints using appropriate indicators. Table 1 briefly summarizes the description of the different impacts and the methodology used for the quantification.

Table 1. Description and quantification methods of impacts

Impact	Description	Methodology
Technical	Change in traffic volumes and travel times	Network flow optimization
Environmental	Air pollution	Life cycle assessment (LCA)
Economic	Construction costs for mitigation and repair	RSMears (2014) estimates
Social	Human health damage	LCA
	Change in leisure time	Network flow optimization

Five possible scenarios for the road embankments to cope with floods are outlined in Table 2. As a mitigation measure, toe berms can be constructed to improve the stability of road embankments. Rehabilitation can be practiced either by retrofitting (i.e., partial repair) to improve adaptability or by reconstruction (i.e., full repair) to achieve transformation.

Table 2. Response scenarios

Response scenario	Mitigation	Rehabilitation
1	No action	Retrofitting
2	No action	Reconstruction
3	Berm construction	No action
4	Berm construction	Retrofitting
5	Berm construction	Reconstruction

4.4 Results

The effectiveness of the five different response scenarios was evaluated based on (i) the resilience of the transportation network by considering performance functions like FoS, settlement, network entropy, and leisure time and (ii) the impacts of flooded road embankments that affect sustainability.

Normalized FoS, settlement, network entropy, and leisure time over 100 days of inspection and for different response scenarios outlined in Table 2 are shown in Figures 2, 3, 4, and 5, respectively. These functions were used as performance functions, $Q(t)$, to calculate the resilience of the transportation network using Eq. (1), and the results are summarized in Table 3. In general, Figures 2-5 show the progress of flood damage (i.e., instant decrease in performances), assessment period (i.e., assumed to be 15 days), and repair (i.e., effect of different response scenarios).

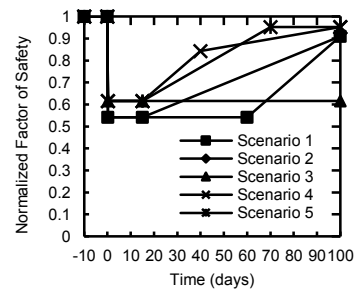


Figure 2. Normalized factor of safety of road embankments

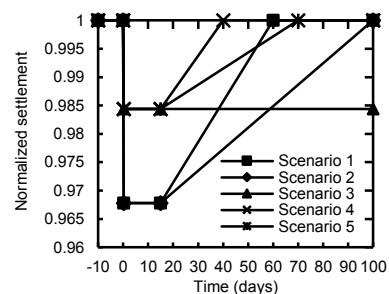


Figure 3. Normalized settlement of road embankments

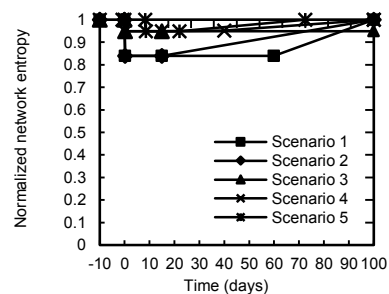


Figure 4. Normalized network entropy of transportation network

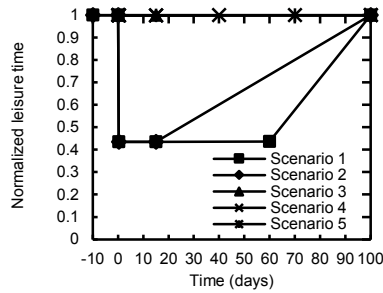


Figure 5. Normalized leisure time of road users

Table 3. Resilience of transportation network

Response scenario	Resilience (Eq. (1))			
	FoS	Settlement	Network entropy	Leisure time
1	0.690	0.904	0.904	0.436
2	0.699	0.908	0.908	0.675
3	0.617	0.949	0.949	0.150
4	0.814	0.963	0.963	0.999
5	0.810	0.978	0.978	0.999

Figure 6 shows the construction costs of mitigation and rehabilitation actions for different response scenarios. Figure 7 shows the normalized environmental impacts from construction activities such as the haulage and operation of machineries and haulage of embankment fills. It is evident that the haulage of fills predominates the environmental impacts. Human health impacts portray the same results as shown in Figure 7.

Considering all the characteristics of resilience, it is apparent that response scenarios 4 and 5 are the most resilient options (Table 3). However, from the sustainability point of view (i.e., considering the environmental and human health impacts), scenario 4 appears to be the best.

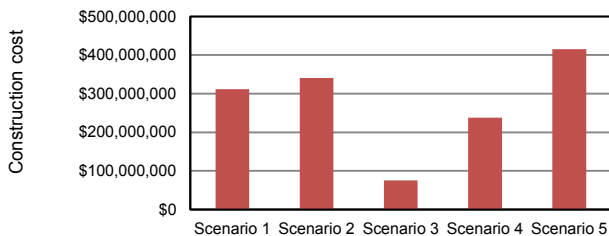


Figure 6. Construction costs for road embankments

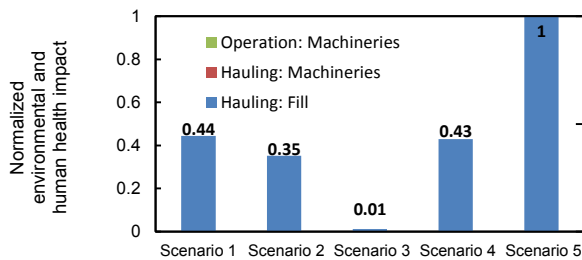


Figure 7. Normalized environmental and human health impacts

5 CONCLUSIONS

A quantitative framework for the assessment of resilience and sustainability of infrastructure systems affected by geo-hazards is presented in this paper. The framework is developed based on the DPSIR framework. It quantifies the resilience of geotechnical infrastructure using four resilience metrics which reflect the robustness, rapidity, resourcefulness, and redundancy aspects of resilience. The framework also uses relevant

sustainability indicators to estimate the environmental, economic, and social impacts of the damaged geotechnical infrastructure by given hazard scenarios. A hypothetical case study on a transportation network, consisting of road embankments subjected to flood scenarios, is used to demonstrate the suitability and applicability of the proposed framework in geotechnical engineering. In the case study, the resilience metrics and sustainability indicators are utilized to evaluate the effectiveness of five different response strategies with different combinations of mitigation and rehabilitation actions.

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