Resilience Assessment in Geotechnical Engineering

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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ABSTRACT

Impacts of inevitable disasters and climate change have been major concerns for the safety and sustainability of communities in the recent past. In an effort to reduce these impacts, development of resilience in civil infrastructures is becoming crucial. Conceptually, resilience is the ability to absorb, recover from, and adapt to shocks or changing conditions. The current practice for infrastructure asset management needs to incorporate this concept of resilience in order to reduce or prevent the detrimental consequences not only to the physical infrastructure systems, but also to communities and other systems vital for fulfilling human needs. For example, consequences can include environmental impacts caused by an incident and rehabilitation construction activities, increased costs for the asset management, and degradation in the quality of life. Therefore, resilience thinking needs to be practiced for designing and managing civil infrastructure systems so that they are resilient to external stresses such as climate change and natural disasters. Despite the awareness that resilience can be a key to resolve the difficulties with extreme events and climate change and that geotechnical assets serve as crucial components in critical infrastructure systems, research in the resilience of geotechnical assets is lacking. To put resilience thinking into practical applications in geotechnical engineering, a quantitative-based framework suitable and applicable for geotechnical assets is necessary.

A quantitative resilience assessment framework applicable for geotechnical assets is proposed in this thesis. Driver-Pressure-State-Impact-Response (DPSIR) framework is adopted in developing the framework. It quantifies the impacts of damaged geotechnical assets to the relevant civil infrastructure network subjected to hazard scenarios. It also evaluates which strategic planning for mitigation and rehabilitation against the hazards is the most effective way for improving the resilience of the geotechnical assets. Metrics which reflect robustness, rapidity, redundancy, and resourcefulness aspects of resilience are developed for the evaluation. Environmental, economic, and social impacts are also concurrently considered to understand the trade-offs between the response strategies and their implementation consequences. The proposed framework is demonstrated using a case study on road embankments in a transportation network connecting London and Toronto in the province of Ontario.

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CHAPTER 1. INFRASTRUCTURE RESILIENCE - MOTIVATION

The concept of resilience was first introduced in ecology 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*". In the context of infrastructure, resilience is the ability of a system to withstand disruptions and continue to function by rapidly recovering from and adapting to the disruptions (National Infrastructure Advisory Council, 2009). The disruptions to physical infrastructure systems are typically climate change, and natural and man-made disasters which can cause catastrophic damage to the infrastructure systems and have negative impacts on societies if not dealt with properly. The necessity of developing resilience in civil infrastructure systems is becoming more evident as the effects of climate change become apparent and the frequency of natural disasters increases. Climate change gradually alters the load and resistance conditions of physical infrastructure systems that can accelerate the deterioration of the physical structures. Disasters, either natural or man-made, have the capability to destroy critical infrastructures and cause detrimental effects to societies. Therefore, there is a need for efficient maintenance of civil infrastructure systems to prepare for and respond to both gradual and instantaneous deterioration of the systems. Incorporation of resilience thinking in infrastructure management can be the key solution to overcome challenges with unavoidable disruptions. For example, the reliability and robustness of infrastructure systems can be enhanced so that the ability to absorb external shocks can be increased; systems can be designed to improve redundancy in order to maintain their operability and rapidly recover even after disruptions occur; and tactical responses regarding emergency management and resource allocation can be planned in advance to better cope with future potential disruptions.

Traditional risk management with fail-safe perspective has dominated the design strategies of engineering systems. Reliability of engineering systems on the ability to withstand external stresses has been the primary concern in the traditional risk management. However, risk-based approaches are only appropriate for events that can be foreseen or forecasted under usual scenarios (Korhonen and Seager, 2008). Until now, domination and overconfidence of fail-safe perspective led to a lack of safe-fail preparations (Park et al., 2011). For example, the failure of Fukushima nuclear reactors in Japan was caused by earthquake and subsequent tsunami, even though the plant was designed to resist anticipated natural disasters. The main problem was that the nuclear plant was not designed such that it can cope with big surprises (Onishi and Glanz, 2011). Fukushima incident, Hurricane Sandy, Hurricane Katrina, and terror attacks in urban cities, show that there is a serious limitation in ability to predict unforeseen disasters and be able to resist all surprises. It is impossible to design engineering systems that are foolproof against all possible threats. Systems should be ensured that it is inherently capable to recover to its functionality irrespective of the nature or magnitude of disaster it is subjected to (Basu et al., 2014). Clearly, practicing only fail-safe approach in designing engineering systems is not sufficient, and a different perspective is necessary. Resilience-based approach contains a safe-fail perspective which is concerned with minimizing the consequences when unusual, unexpected, and unforeseen events are revealed (Korhonen and Seager, 2008; Park et al., 2011). It emphasizes the ability to recover from unforeseen disasters rather than resisting all possible disasters.

It is especially important that the concept of resilience is studied in geotechnical engineering because geotechnical assets often play essential roles in civil infrastructure systems but are very vulnerable against external shocks. For example, embankments, bridge foundations, and tunnels are vital components of transportation infrastructure which provides essential mobility service to the public. Soil being the weakest of all the civil engineering materials, vulnerability of these geotechnical assets against hazards is among the highest. Moreover, critical infrastructures being inoperable because of geotechnical failures can significantly influence the functioning of other interdependent critical infrastructures (Rinaldi et al., 2001). For example, closure of a transportation network can affect access to medical care, emergency services, and food and fuel supply from which their impacts propagate to other critical infrastructures such as electric power generation, telecommunications, and water supply facilities (Min et al., 2007). Naturally, public safety, economy, and quality of life are connected to the conditions of the geotechnical infrastructure to a large extent. Therefore, there is a huge potential for geotechnical engineers to improve resilience not only in the physical infrastructure systems but also in communities.

In order to practically implement resilience thinking in geotechnical engineering, there is a need for a framework that can quantitatively measure the resilience of geotechnical infrastructure. Various resilience metrics and sustainability indicators can be incorporated into the framework to conduct a comprehensive analysis. The framework can be utilized as a decision-making tool for choosing the most resilient geotechnical option among competing alternatives and for evaluating the effectiveness of various response tactics to alleviate the impacts of disruptive events. The objectives of this study are to propose a framework which quantitatively assesses the resilience of geotechnical infrastructure and to demonstrate the framework using a case study. The specific aim of this research study is to demonstrate the suitability and adaptability of the proposed framework to measure the resilience of geotechnical infrastructure through an example problem.

In this thesis, chapter 2 discusses the concept of resilience in different disciplines like ecology, social science, economy, and engineering. A literature review on qualitative and quantitative resilience frameworks is also presented. Chapter 3 proposes a new resilience assessment framework applicable to geotechnical infrastructures. Chapter 4 demonstrates the proposed framework using a case study on a road network in the province of Ontario. Finally, chapter 5 presents the concluding remarks.

CHAPTER 2. REVIEW OF RESILIENCE CONCEPT AND ASSESSMENT

2.1 Resilience in different disciplines

Since Holling (1973) first introduced the concept of resilience in ecology, it has been used in many other disciplines with modifications to suit the needs of the different disciplines and their applications. Therefore, resilience lacks a universal definition which is one of the challenges behind putting resilience thinking into real-life practice. In order to evaluate the applicability of resilience concept in geotechnical engineering, it is important to study the concept developed from various disciplines so that different perspectives on and complex aspects of resilience are understood. In this chapter, the concept of resilience, as applied in different disciplines like ecology, social science, economy, and engineering, are discussed in brief. Further, the existing resilience assessment frameworks are outlined in brief.

2.1.1 Ecological resilience

Two different perspectives exist in defining ecological resilience. Biological sciences have been contributing in the development of ecological sciences while physical and engineering sciences have been involved in shaping environmental sciences (Holling, 1996). Thus, ecological resilience has been defined from both biological and engineering perspectives.

Pimm (1984) defined resilience as the speed of a system to return towards its equilibrium following a perturbation. This definition focuses on maintaining efficiency of a function, constancy of a system, and predictability near a single steady state. It emphasizes resisting disturbances and changes in order to conserve or recover what the system originally contained. This is an engineering perspective of ecological resilience to achieve fail-safe design. Instead of assuming a single steady state, Holling (1973) introduced the concept of multiple stability domains in natural systems, and defined ecological resilience as the ability of a system to absorb changes and still persist under threats. This definition focuses on persistence, change, and unpredictability. It is perceived that a disturbance to ecological systems can lead to another stability domain or regime. Instead of recovering the system after a perturbation, which the ecological resilience with engineering perspective focuses on, renewal of system is considered here. This is the biologists' perspective to achieve safe to fail design (Folke, 2006; Holling, 1996).

The concept of having multiple equilibriums in ecosystems can be explained using a topographic analogy (Figure 1). Three systems with different resistance and resilience are shown in Figure 1. The ball represents the system state, and the basins represent the stability domains. Equilibrium exists when the ball remains at the bottom of the basin, and disturbances to the system cause the ball to move away from its equilibrium and to a transient position (Gunderson, 2000). The bottom of the basin is the optimal state of the ecosystem, representing the lowest potential energy at which the system maintains order (Mu et al., 2011). Adding resistance to a system causes the system to be highly controlled, to operate within a narrow band of possible states, and to be designed to resist shocks from its equilibrium (Landscape 1 in Figure 1). It has the ability to recover from small perturbations; however, it may be vulnerable to large perturbations. A resilient system, on the other hand, functions across a broad spectrum of possible states, and it is capable of surviving large perturbations (Landscape 2 in Figure 1). A system with multiple equilibrium points is more resilient than a system with a single equilibrium because it can tolerate larger perturbations by shifting into a different equilibrium states but still remain in the same landscape (Landscape 3 in Figure 1) (Fiksel, 2003). Therefore, ecological resilience with engineering perspective is characterized by the slope of the basins. The steeper the basin is, the faster the ball returns to the bottom of the basin (i.e., to the stable state). Ecological resilience with biological perspective is characterized by the width of the basin and the number of basins (Gunderson, 2000).

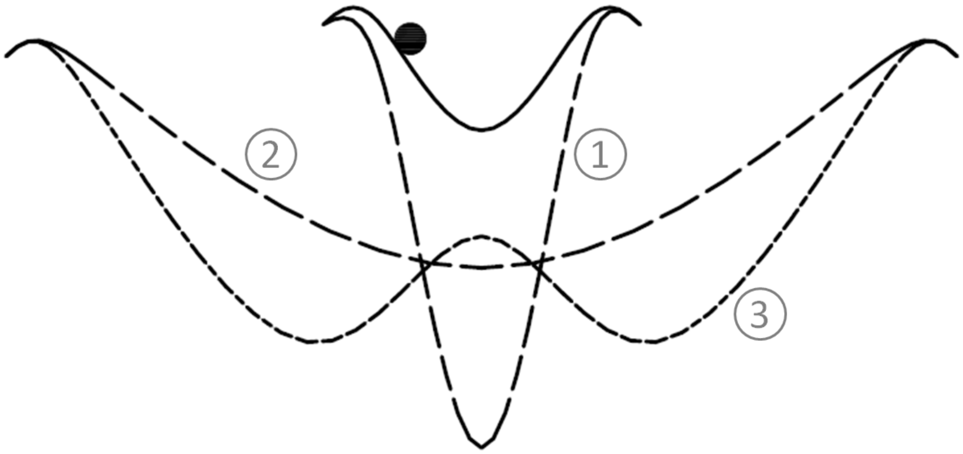

Figure 1. Stability landscapes (after Mu et al., 2011)

Recent studies on ecological resilience suggest that human society and natural systems are strongly interconnected; therefore, resilience should be considered for combined social-ecological systems as opposed to only ecological systems. The two ecological resilience definitions stated above mostly focus on the persistence and robustness to disturbances. However, it is important to realize that disturbance brings opportunities to evolve the systems towards a positive direction by renewing the system and following new trajectories. Hence, resilience in social-ecological systems focuses on adaptive capacity and transformability. Adaptive capacity or adaptability is the capacity of people in social-ecological systems to build resilience through collective actions. It relates to learning capabilities and allows continuous development while sustaining with change (Folke, 2006). With reference to the stability landscapes (Figure 1), adaptive capacity refers to the ability of the ball to remain in a stability domain as the shape of the domain changes (Gunderson, 2000). Transformability is the capacity of people to create a fundamentally new social-ecological system when ecological, political, social, or economic conditions make the existing system untenable (Folke, 2006; Walker et al., 2004). In terms of stability landscapes, transformability refers to the ability of the ball to cross its threshold and shift to a new different desirable landscape. Carpenter (2001) identified three properties of resilience in social-ecological systems: (i) the amount of change the system can undergo and still remain within the same domain of attraction, (ii) the degree to which the system is capable of self-organization, and (iii) the degree to which the system can build the capacity of resilience that reflects the learning aspect of system behaviour in response to disturbances.

Dynamic development of complex adaptive systems with interactions across temporal and spatial scales is an important aspect of resilience (Folke, 2006). Dynamical systems, such as social-ecological systems, pass through four characteristic phases: (i) rapid growth and exploitation, (ii) conservation, (iii) collapse or release, and (iv) renewal or reorganization (Carpenter, 2001). Gunderson and Holling (2002) developed the concept of adaptive cycles or panarchy in which the processes and patterns in ecosystems transform from one phase to another. The rapid growth or exploitative phase is characterized by rapid colonization of recently disturbed areas. The system can absorb a wide range of disturbances because of high ecological resilience. In the conservation phase, material and energy are accumulated and stored. The system's connectedness increases, eventually to become over-connected and increasingly rigid in its control. In the release phase or creative destruction phase, a disturbance influences the structure that has accumulated in the previous phases. Disturbances, such as forest fires, droughts, insect pests, release the tightly bound accumulation of biomass and nutrients that was developed in the conservation phase. Lastly, in the reorganization phase, the system becomes most vulnerable to changing stability domains. The system can easily be moved from one state to another, and it is disconnected from the processes that facilitate and control growth. A new exploitative phase is followed after the reorganization phase, and the adaptive cycle continues in a loop. The transformation from one phase to another flows unevenly. Biological time from the exploitation phase moves slowly to the conservation phase, rapidly to the release phase, rapidly to the reorganization phase, and rapidly back to the exploitation phase. Accumulated resources can leak away from the system as the system shifts from the reorganization to the exploitation phase because of the collapse of organization (Gunderson and Holling, 2002).

2.1.2 Social and economic resilience

The concept of resilience has been widely used in social sciences and applied to community development, disaster management, economy, and psychology. Social resilience is applied to social groups or individuals, such as communities, to examine their response to crisis such as social, economical, or environmental change. Social stresses can include political violence, economical crisis, and change in the physical environment (Adger, 2000; Kimhi and Shamai, 2004). The individuals or groups are forced to adapt to changed conditions, and positive response to such changes is social resilience or community resilience. Adger (2000) defined three properties of social resilience: resistance, recovery, and creativity. Resistance is the capacity of a community to withstand a disaster and its consequences. It can be measured by the degree of disruption that the community can accommodate without undergoing long-term changes. Recovery is the ability of a community to rebound from the disaster, and it can be measured in terms of the time efficiency for recovery. Creativity relates to the ability of a community to learn from the disaster experience and attain a higher level of functioning (Adger, 2000; Kimhi and Shamai, 2004; Maguire and Hagan, 2007). Longstaff et al. (2010) highlighted the need for developing resource robustness and adaptive capacity for building resilient communities. Resource robustness refers to the availability of resources that can improve the performance, diversity, and redundancy of communities. For example, resource robustness in terms of performance indicates how well the resources accomplish or support an essential function of communities. A community with high diversity in resources indicates that multiple options for accomplishing the essential functions exist. Redundancy in resources means that there are back-up resources available in case failures occur. Adaptive capacity in community resilience is understood as the ability of individuals and groups to (i) store and remember experiences and local knowledge, (ii) use the experiences and knowledge to learn, innovate, and reorganize resources in order to adapt to changing environmental demands, and (iii) connect with others inside and outside the community to communicate experiences and lessons learned, to self-organize or reorganize in the absence of direction, or to obtain resources from outside sources.

The ability to improve community resilience depends on interdependent levels. For example, the physical integrity of built environment and critical lifeline infrastructures need to be protected by means of building codes and maintenance actions for a community to recover from social stresses. The economic, business, and administrative continuity needs to be ensured, and the recovery of emergency management and social institutions are necessary. In addition, the community needs to ensure that organizations have the necessary capacities to utilize the resources in a way that minimizes disruption and facilitates higher level of functioning (Paton and Johnston, 2001).

Social resilience with a geographical perspective (i.e., disaster resilience) is concerned with the social and economic impacts of natural disasters to social groups within a community, city, or urban environment. Disaster resilience takes into account unique geographical conditions and different level of exposure to natural disasters of communities or cities. It is defined as the capacity of hazard-affected bodies to resist loss during disaster and to regenerate and reorganize after the disaster in a specific area in a given period of time (Zhou et al., 2010).

Economic resilience is defined as "the *inherent and adaptive responses to disasters that enable individuals and communities to avoid some potential losses*" (Rose, 2004). Economic resilience focuses on the response behaviour to external shocks rather than mitigation or preparedness. Two types of economic resilience are considered — inherent resilience and adaptive resilience. Inherent resilience relates to the ability to recover from external shocks under normal circumstances (i.e., from shocks that are expected). For example, inherent resilience is the ability of markets to reallocate resources in response to price signals. Adaptive resilience, on the other hand, is the ability to apply ingenuity and resourcefulness to recover from crisis situations. For instance, the economy of a market can be strengthened by providing information to match suppliers and customers (Rose, 2004).

Psychological resilience is the capacity of behavioural adaptation of human beings under challenging or threatening circumstances. The concept of resilience is widely applied in child development, and psychological resilience is described in terms of internal states of well-being. Similar to social resilience, psychological resilience is concerned with the ability to resist and recover from a trauma. Three properties of psychological resilience are identified by Masten et al. (1990) — psychologically resilient children under adverse circumstances display (i) good outcomes despite high-risk status, (ii) sustained competence under threat, and (iii) recovery from trauma.

2.1.3 Engineering resilience

The concept of resilience as applied in engineering disciplines mostly follows the definition provided by Pimm (1984), which focuses on the robustness against disruption and the speed of recovery. As stated by Holling (1996), engineering resilience assumes a single (global) equilibrium and focuses on maintaining stability near the equilibrium. Bruneau et al. (2003) used the concept of engineering resilience in seismic analysis, and defined community seismic resilience as the ability of social groups to mitigate hazards, contain the effects of disasters during occurrence, and recover in ways so as to minimize social disruption and mitigate the effects of future earthquakes. Seismic resilience of critical lifelines or facilities, such as water and power lifelines and hospitals, was examined by Bruneau et al. (2003) because such facilities are crucially responsible for community well-being.

In consideration of emergency management for the built environment, infrastructure resilience has been drawing attention because functions of infrastructure are vital for communities. The

National Infrastructure Advisory Council (2009) defined infrastructure resilience in terms of the ability of the infrastructure to reduce the magnitude, impact, or duration of a disruption. Infrastructure resilience is defined as the ability to absorb, adapt to, and/or rapidly recover from a potentially disruptive event. According to Bruneau et al. (2003) and Francis and Bekera (2014), a resilient system should reflect the following three properties: (i) reduced failure probabilities or increased absorptive capacity, (ii) reduced consequences from failures, and (iii) reduced time to recovery or increased adaptive capacity. A resilient system should reflect a reduced likelihood of being damaged or failure from disruptions. In other words, the ability to absorb damage propagation without catastrophic failure should be increased. Furthermore, consequences, such as social and economic impacts, should be reduced. Recovery of a resilient system from a disrupted state should be attained in a timely manner, which indicates increased ability to adapt.

The concept of resilience in infrastructure engineering corresponds to the preparedness and response of a system against disruptive events. Preparedness is mostly associated with the abilities to proactively mitigate the effects of the disruptive events by arranging adequate resources and devising strategies prior to the disruption. Lack of preparedness includes (i) lack of understanding and information on the effects of a disruptive event, (ii) failure to appreciate the scale of the rescue task, (iii) lack of appreciation of the damage caused to communication mechanisms, (iv) lack of situational awareness, and (v) lack of coordination (Perelman, 2007). Two types of response — absorption and recovery — can be expected after the event of disruption (Francis and Bekera, 2014; Ouyang et al., 2012). Absorption is the immediate response of an infrastructure system in which the system withstands the disruption, and recovery is the organizational efforts to rapidly repair the damaged system and the consequential effects propagated to other systems (e.g., communities). Figure 2 shows a typical degradation and recovery of system functionality over time. Absorption of shocks is reflected by the degradation of the system functionality at the event of disruption (from time t_d to t_a in Figure 2). The recovery efforts can be initiated immediately post-disruption; however, the system functionality can be unchanged for a certain period of time (from time t_a to t_r in Figure 2) until adequate resources are collected and response strategies are organized (this is the assessment stage). Ultimately, it is expected that the system functionality recovers to an acceptable level for its normal operation (from time t_r to t_f in Figure 2).

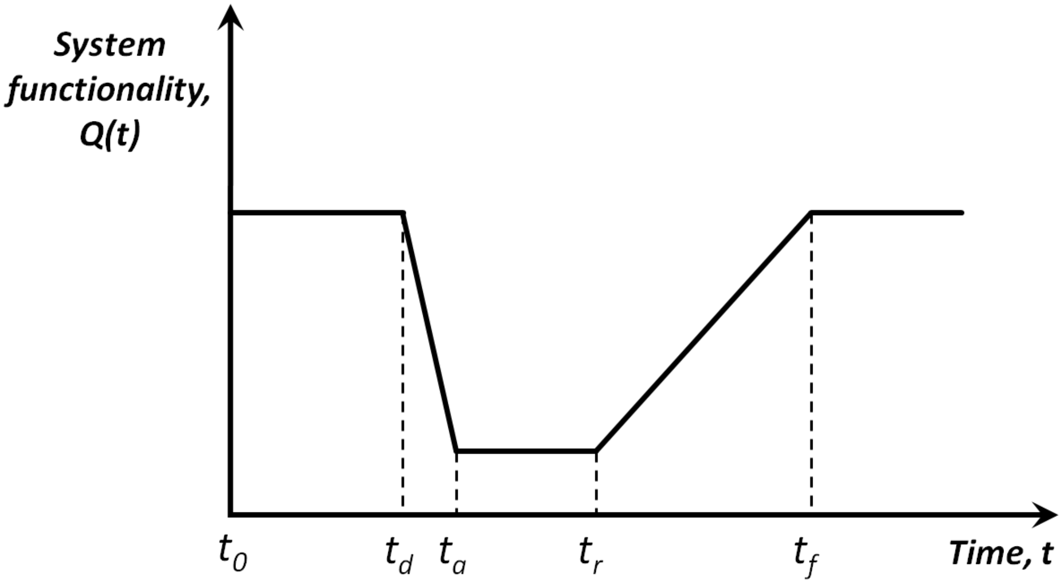

Figure 2. Typical loss of resilience over time

Resilience can be further described by four properties: robustness, rapidity, resourcefulness, and redundancy (Bruneau et al., 2003). Robustness refers to the strength of systems to withstand a given level of stress or demand without suffering a loss of functionality. Robustness is reflected in the absorption stage, where absorptive capacity matters. The higher the robustness of the system, the lower the likelihood that the damage propagates and consequences occur (Figure 3). Rapidity is the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption. Rapidity can contribute in the recovery stage by increasing efficiency in the performance recovery (Figure 4). Resourcefulness is the capacity to identify problems, establish priorities, and mobilize resources (i.e., monetary, physical, technological, and informational resources). During the assessment stage t_a to t_r, resourcefulness can contribute in lessening the time of assessment. In addition, resourcefulness can contribute in developing mitigation measures for disaster prevention and contribute in the recovery process (Figure 5). For example, sufficient monetary and informational resources reduce the time in identifying damages or vulnerability of the system. Redundancy indicates the extent to which existing elements or systems are substitutable. Redundancy can reduce the consequences from failures because failure of redundant system or units will not significantly affect the overall performance of the system (Figure 3).

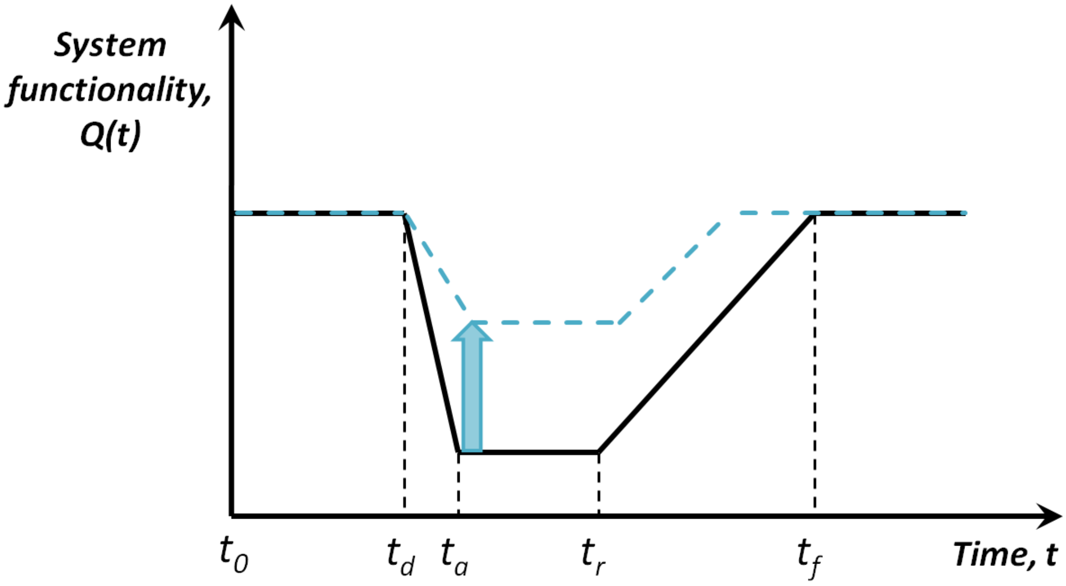

Figure 3. System with high robustness and redundancy

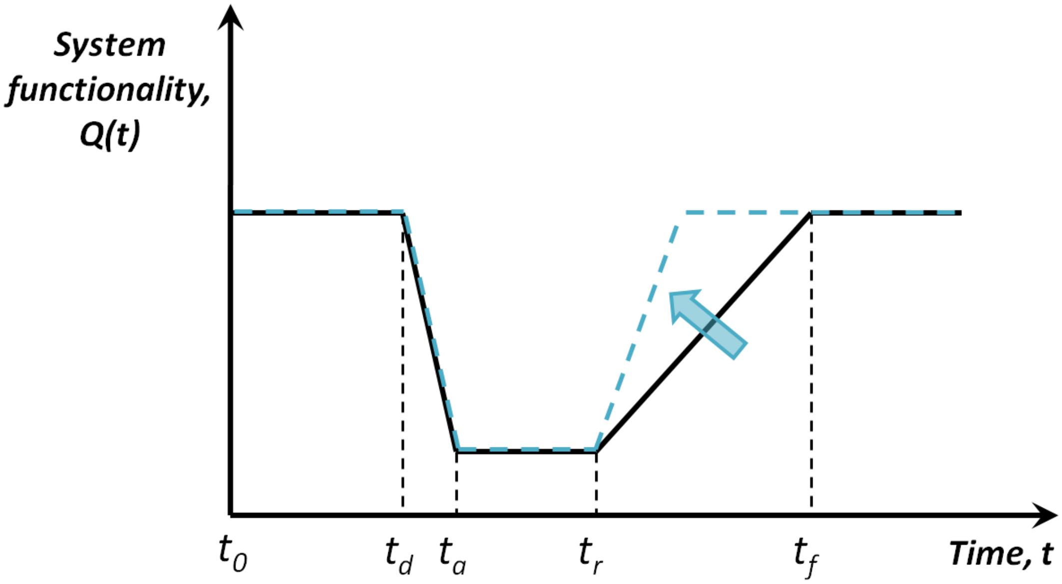

Figure 4. System with high rapidity

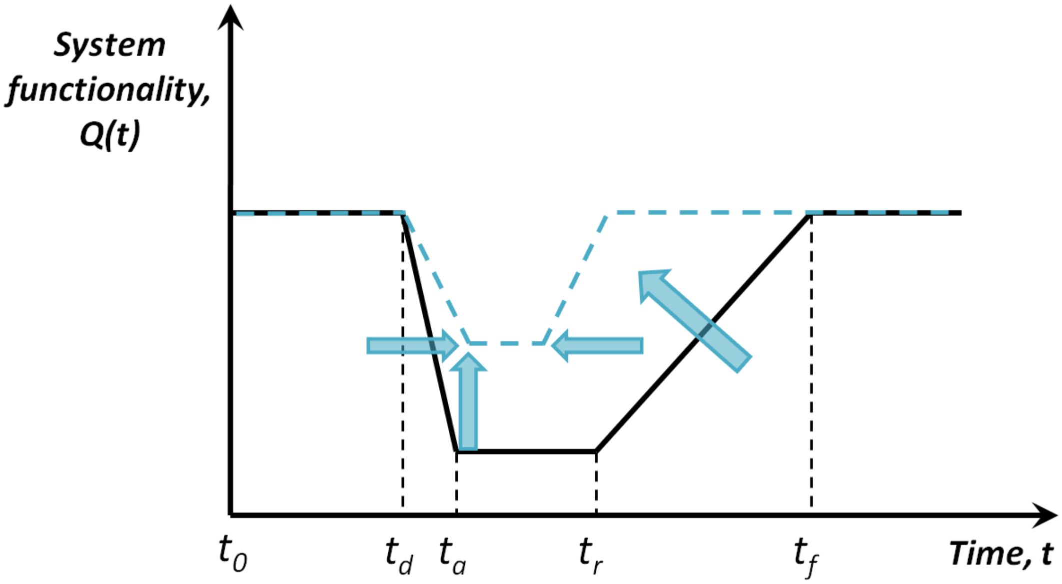

Figure 5. System with high resourcefulness

Bruneau et al. (2003) further categorized resilience within the engineering discipline into different dimensions — technical, organizational, social, and economic. Technical dimension refers to the physical response of the infrastructure after disruption; organization dimension indicates the capacity of organizations for disaster management and decision-making; social dimension considers the impacts of failure of infrastructure system to social groups; and economic dimension refers to the economic losses, both direct and indirect, because of the occurrence of the disaster. O'Rourke (2007) provided examples of technical, organizational, social, and economic activities that support the properties of a resilient community (Table 1).

Table 1. Qualities of resilient community

Property/Dimension	Technical	Organizational	Social	Economic
Robustness	Building codes and construction procedures for new and retrofitted structures	Emergency operations planning	Social vulnerability and degree of community preparedness	Extent of regional economic diversification
Redundancy	Capacity for technical substitutions	Alternate sites for managing disaster operations	Availability of housing options for disaster victims	Ability to substitute and conserve needed inputs
Resourcefulness	Availability of equipment and materials for restoration and repair	Capacity to improvise, innovate, and expand operations	Capacity to address human needs	Business and industry capacity to improvise
Rapidity	System downtime, restoration time	Time between impact and early recovery	Time to restore lifeline services	Time to regain capacity and lost revenue

Retrieved from O’Rourke (2007)

Consideration of multiple dimensions of resilience is necessary to enable a holistic conceptualization of resilience from an interdisciplinary perspective (Rogers et al., 2012). The

Royal Academy of Engineering (2011) outlined the need for conducting a holistic approach: to ensure (i) integration and linkages to break down boundaries, (ii) joined up management and thus a new form of administration, (iii) a realistic understanding of the costs involved and a dialogue between government and the public regarding the extent and level of resilience acceptable, (iv) the knowledge of the limitations of what can be achieved in terms of finance, engineering, and planning, (v) the removal or change in regulations prohibiting processes and systems of management to enable resilience to take place, and (vi) flexible engineering.

2.2 Qualitative frameworks to evaluate resilience

Qualitative methodologies are useful for screening or preliminary evaluation and comparison of complex systems that cannot be represented by a single metric. They are also useful for providing an overview of complex systems in a way that is easy to share among professionals, stakeholders, and any other decision-makers.

Uda and Kennedy (2015) developed a framework that qualitatively analyzes the resilience of communities or cities at a neighbourhood scale. A neighbourhood is defined as a system of built form, natural environment, and community. The following steps are carried out to conduct resilience assessment of a neighbourhood system using the framework proposed by the study: (i) identify the essential needs of a neighbourhood system (i.e., human needs) that are required for it to continue function, (ii) identify the future risks (e.g., social, economic, technological, political, and environmental risks) to which the neighbourhood may be subject to, (iii) determine how the future risks would impact the neighbourhood system and identify actions to prevent or minimize the impacts at the neighbourhood scale, and (iv) determine the actions to deal with the impacts if not prevented.

Longstaff et al. (2010) developed a qualitative framework for the assessment of community resilience. The framework requires answering questions to evaluate the resource robustness and adaptive capacity of communities (see Table 2 for details).

Table 2. Resilience assessment framework by Longstaff et al. (2010)

Attribute of resilience	Question
General	Which functions are vital to our community within this subsystem?
Resource robustness	What resources are available to perform this function? How well does this resource perform a particular function? How well would it perform in a disruption? How much of this resource do we have? Are there other resources available that could perform this function?
Adaptive capacity	To what extent do organizations and informal social groups within this subsystem instill and maintain a common memory? To what extent do organizations and informal social groups within this subsystem foster a culture of continuous learning and innovation? To what extent are organizations and informal social groups within this subsystem internally and externally connected? Are they loosely connected or tightly connected? How will a disturbance that affects one organization or social group impact others?

Berte and Panagopoulos (2014) utilized a decision support model called SWOT (strengths, weaknesses, opportunities, and threats) to generate urban planning strategies and to provide evidence for the enhancement of the resilience of cities. SWOT analysis was conducted on a city in Portugal to identify which ecosystem services needed to be improved through urban green infrastructure. Some examples of SWOT analysis outcomes on the city are provided in Table 3.

Table 3. Example of SWOT analysis

SWOT	Description
Strengths	Increasing tourism causes less degradation in areas of the city centre and more investment in urban green facilities The presence of wetlands helps regulation of the urban microclimate
Weaknesses	The majority of streets, buildings, and open areas do not benefit from green facilities The city suffers low connectivity with the hinterland green areas
Opportunities	Urban rehabilitation policy emphasizes the importance of sustainability and the use of green walls and green roofs The regulation services provided by urban green areas can help to mitigate flooding and heatwaves and enhance water quality and supply Urban agriculture improves resilient urban food systems
Threats	Flooding in urban areas Heatwaves Water scarcity and droughts Coastal erosion

Retrieved from Berte and Panagopoulos (2014)

Montgomery et al. (2012) utilized causal loop diagrams to comprehensively understand the network of interactions within complex adaptive systems. Many engineered systems are considered as complex adaptive systems because they include nested and interacting social, environmental, and technical components. Causal loop diagrams illustrate the cause and effect of hazards, interventions, and regulations; therefore, they are useful for planning, designing, and maintaining infrastructure. For example, Montgomery et al. (2012) used causal loop diagrams to identify the physical causes of flooding, effects of actions to prevent flooding, and effects of introduction of national standards and regulations on road transportation under extreme weather events and natural disasters. It is qualitatively evaluated if the effects of actions eventually lead to positive or negative adaptive capacity and resilience through multiple interactions identified in the causal loop diagrams.

Resilience of a system can also be assessed using the matrix approach which allows inclusion of both quantitative and qualitative data in the resilience evaluation process. It simultaneously considers multiple properties and dimensions of resilience. Fox-Lent et al. (2015) constructed a 4 by 4 matrix in which the rows represent general management domains (i.e., physical, information, cognitive, and social domain) and the columns represent the stages of disaster management (i.e., preparation, absorption, recovery, and adaptation) as shown in Table 4. Each cell (box) in Table 4 represents a specific aspect of resilience. For example, the cell for information-recovery refers to the ability of a system to collect, monitor, and analyze data that is helpful in the recovery stage. The cell for social-adaptation refers to the capacity of users to modify behaviour and sustain changes beyond the immediate incident response. The matrix was used to quantify the community resilience of a residential area prone to flooding, hurricanes, and coastal storms. Indicators that represent each cell were selected, and scores ranging from 0 to 1 were assigned to each indicator by normalizing indicator values with respect to the upper bound. If quantification is not possible, expert judgment can be used to assign a value ranging from 0 to 1 corresponding to none, low, medium, and high range. The matrix can be aggregated by averaging all scores to compare with other communities.

Table 4. Resilience 4 by 4 matrix

	Preparation	Absorption	Recovery	Adaptation
Physical				
Information				
Cognitive				
Social				

Shah et al. (2014) developed a decision support framework which examines the resilience of geotechnical design solutions to improve socio-economic, technological, environmental, and political conditions in the future. The framework is in a multi-criteria matrix form and qualitatively analyzes if the effects of geotechnical solutions in terms of their geotechnical performance, serviceability, and stability requirements change towards desirable future conditions. The scores were qualitatively assigned, ranging from -3 (least resilience potential) to 3 (most resilience potential) in regards to the potential of the solutions to improve or degrade resilience (Table 5).

Table 5. Score assignment for Shah et al. (2014) matrix approach

Score	Description
+3	Existing solution works with no change in design
+2	Existing solution works with minor amendments and marginal cost and time implications
+1	Existing solution with room for improvement to design with reasonable time and cost implications
0	Neutral or not applicable
-1	Existing solution requires design changes with additional time and cost implications
-2	Existing solution requires substantial design amendments to its original form and surrounding area with substantial time and cost implications
-3	Existing solution does not work and requires replacement with re-engineered solution have major time and cost implications

2.3 Resilience quantification methodologies in engineering

The concept of resilience embraces several complex aspects, and the most important aspects in a study depend on the discipline in question. In engineering, resilience should be measured in terms of both spatial and temporal scales to reflect the system's progress of degradation and development after disruption occurs. Figure 2 is frequently referred to as a guideline to understand the typical response of a system to disruptions, and it is related to mathematical formulations presented in this section. Resilience of a system can be quantified in terms of the change in the system performance over time as expressed in Equation [1] (Bruneau et al., 2003; Bocchini and Frangopol, 2011).

$$R = \frac{1}{t_h} \int_{t_d}^{t_d + t_h} Q(t)\, \mathrm{d}t \qquad [1]$$

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. Therefore, resilience can be simply computed as the integration of a known performance function with respect to time. The boundary conditions are the time at which disruption occurs and a given inspection time. The time, at which full recovery or acceptable recovery of the system is achieved, is not used as the upper boundary to ensure that a higher resilience value is assigned to the system that recovers at a faster rate and reaches the target recovery over a shorter period of time.

The integration of the performance function $Q(t)$ with respect to time, as described in Equation [1], is utilized as the fundamental basis for measuring the engineering resilience of a system, and it is widely used in several studies with different definitions of $Q(t)$ (Omer, 2013; Comes and Van de Walle, 2014; Cimerallo et al., 2010; Tokgoz and Gheorghe, 2013). For resilience quantification, two approaches, deterministic and probabilistic, have been considered in engineering as described next.

2.3.1 Deterministic resilience quantification

Deterministic approaches usually involve assuming the performance function $Q(t)$ based on a known trajectory or as a ratio of performance levels at two different stages of system performance.

Omer (2013) measured resilience as the integration of performance functions (using Equation [1]) with respect to a given time for a transportation network connecting Boston and New York City. Three performance functions were defined in terms of travel time, environmental impact, and cost. The performance functions were computed as the ratio of the performance level prior to the disruption to the performance level after the disruption:

$$Q(t) = \frac{Q(t_0)}{Q(t_a)} \tag{2}$$

where $Q(t_0)$ is the performance level at t_0 (prior to disruption) and $Q(t_a)$ is the performance level at t_a (post-disruption). For example, the travel time performance function was defined as the ratio of travel time from Boston to New York City before the traffic disruption to the delayed travel time after the disruption. A similar approach was taken for the other two performance functions. The environmental impact was estimated by the increased carbon dioxide (CO_2) emissions because of the prolonged time travel after the disruption. The cost was estimated by the financial costs caused by users' extra time, fuel, and mitigation of the environmental impacts. The disruption in the road network between Boston and New York City was simulated by adjusting the traffic demand and capacity of the roads within the network.

Comes and Van de Walle (2014) also measured resilience using Equation [1] and defined the performance function for electric power infrastructure as:

$$Q(t) = 1 - \frac{Q(t_f) - Q(t_0)}{Q^*(t)} e^{-bt} \tag{3}$$

where $Q(t_f)$ is the capacity for a fully functioning physical system, $Q(t_0)$ is the performance level prior to disruption, $Q^*(t)$ is the target performance level after recovery, b is a fitted parameter to model the speed of the recovery processes. In Equation [3], robustness is represented by the ratio $\left\{Q(t_f)-Q(t_0)\right\}/Q^*(t)$, and rapidity is represented by the exponential term. Equation [3] assumes that recovery follows an exponential trajectory, and it depends on the rapidity parameter b. Comes and Van de Walle (2014) demonstrated the use of Equation [3] for the outage of electric power grid affected by Hurricane Sandy and for the outage of power delivery system affected by Hurricane Katrina. The robustness and rapidity in Equation [3] were empirically estimated using the outage information (i.e., the number of customers affected by the power outage).

Several authors defined engineering resilience without using Equation [1]. For example, Sandoval-Solis et al. (2011) defined resilience in the context of water management as:

$$R_i = \frac{\text{No. of times } \mathrm{D}_t^i = 0 \text{ follows } D_t^i > 0}{\text{No. of times } \mathrm{D}_t^i > 0 \text{ occured}} \tag{4}$$

$$D_t^i = \begin{Bmatrix} X^t_{\text{target,t}} - X^i_{\text{supplied,t}} & \text{if } X^i_{\text{target,t}} > X^i_{\text{supplied,t}} \\ 0 & \text{if } X^i_{\text{target,t}} = X^i_{\text{supplied,t}} \end{Bmatrix} \tag{5}$$

where D_t^i is the water deficit for time period t and for i$^{\text{th}}$ user, $X^i_{\text{target,t}}$ is the water demand, and $X^i_{\text{supplied,t}}$ is the supplied water. They conducted a simulation study for a complex basin where both Mexico and United States hold water rights, there exists extended periods of droughts, and there is low efficiency in irrigation systems. The effectiveness of various policies on water management for the complex basin was evaluated in terms of resilience. The water demand was varied from 20% to 100% to observe the change in resilience.

Henry and Ramirez-Marquez (2011) estimated the resilience of a tram network in a park in terms of stage-specific performance levels given by

$$R = \frac{Q(t^*) - Q(t_a)}{Q(t_0) - Q(t_a)} \qquad [6]$$

where $Q(t^*)$ is the performance level at the time of interest (i.e., typically after recovery), $Q(t_0)$ is the performance level prior to disruption, $Q(t_a)$ is the performance level after the disruption. In simple terms, resilience is measured as the ratio of recovery $\left\{Q(t^*) - Q(t_a)\right\}$ to the loss of system functionality $\left\{Q(t_0) - Q(t_a)\right\}$. If a full recovery is attained from its loss, then the resilience is equal to 1 which indicates fully resilient system. If the system reaches a stable state at a lower functionality than the original state, then the system is considered less resilient. The metric expressed in Equation [6] was demonstrated for a tram network in a park. The tram network was expressed as a directed network with nodes indicating the entrance of the park, intermediate stops, and final destination. The lengths and capacities (i.e. maximum number of trips) were defined for each road. Three different resilience measures were defined in terms of (i) the shortest path from the origin to the destination, (ii) number of trips per day to represent the flow from the origin to the destination, and (iii) the ratio of length of usable roads to the total length of roads to represent the overall health of the network. Two disruption scenarios (i.e., rock slide and river floods) were applied to a set of roads, and two restoration strategies were examined. The affected roads were restored sequentially one by one at a particular order.

Rochas et al. (2015) also utilized Equation [6] to quantify the resilience of a water pipeline network used as a heating system for a village. Resilience measures were defined in terms of three performance functions: total heated area, number of inhabitants of the heated dwelling, and total length of functioning pipelines to represent the overall quality of the network.

Zobel and Khansa (2011) developed a resilience metric assuming that the performance was degraded and recovered linearly:

$$R = 1 - \frac{XT_R}{2T^*} \qquad [7]$$

where X is the loss of performance level ranging from 0 to 1, T_R is the time needed for recovery to normal operations, and T^* is some long time interval. Equation [7] was further developed so that it is applicable for multi-events as:

$$R_i = 1 - \frac{(X_i + X_i^{'})T_R}{2T^*} \qquad [8]$$

where R_i is the partial resilience for event *i*, X_i is the lost performance level after *i*th event (i.e., first shock at t_i), $X_i^{'}$ is the lost performance level before (*i*+1)th event (i.e., before the second shock at t_{i+1}). Equation [8] computes the area that corresponds to the loss of performance level by *i*th event as shown in Figure 6. For multi-events, the total resilience can be computed as the summation of partial resilience R_i as given by

$$R = 1 - \sum_i (1 - R_i) \qquad [9]$$

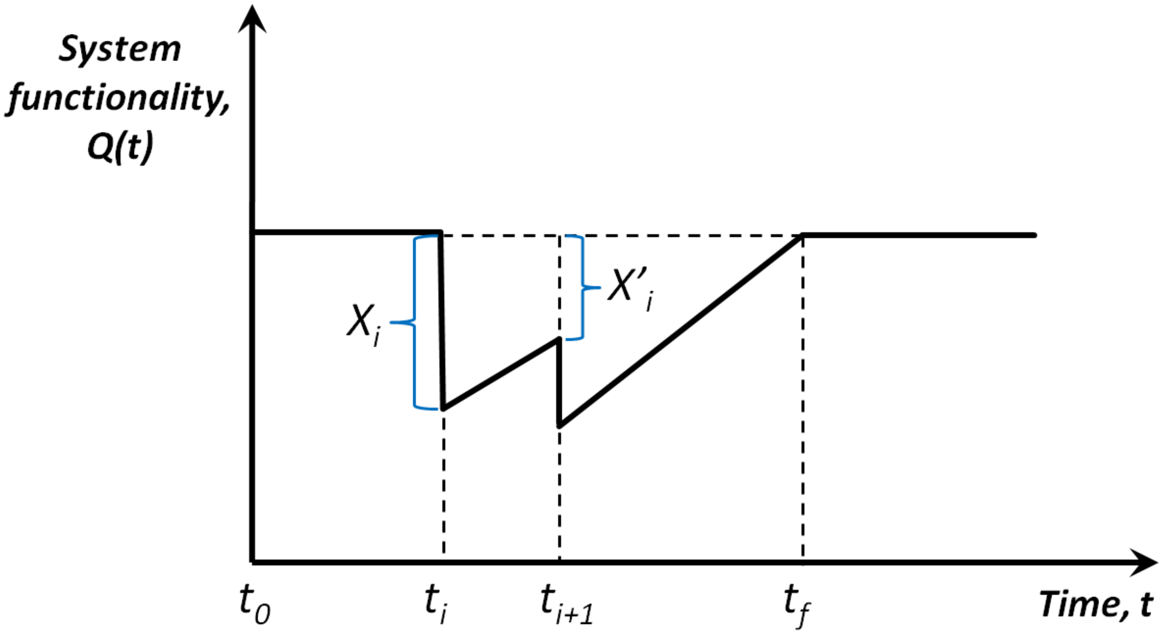

Figure 6. System functionality for multi-events

The resilience metrics given in Equations [7]-[9] were used for an earthquake-prone residential area. It was assumed that an earthquake will occur followed by a landslide. Five disaster scenarios with different impacts of earthquake and landslide were qualitatively described, and the expected resilience profiles for the five disaster scenarios were estimated.

2.3.2 Probabilistic resilience quantification

The probabilistic approaches measure resilience by probabilistically assuming the loss of performance levels. For example, fragility functions, which describe the vulnerability of a system to a given disaster, are incorporated in defining performance loss functions (Francis and Bekera, 2014). The probability of disaster occurrence or probability of being in a specific damage state is also incorporated as a weight factor to account for its uncertainty. Recovery functions are defined either probabilistically or deterministically by assuming simple mathematical functions.

Bocchini et al. (2014) compared resilience of two types of overpass bridges: girder and frame bridges. Seismic fragility of the bridges was analyzed based on the location of the bridges, soil conditions, and structural characteristics. For each bridge, the probabilities of no damage, slight damage, moderate damage, extensive damage, and total collapse were computed for an earthquake with 2,475-year return period. The seismic resilience of the bridges was computed in terms of the expected direct and indirect impacts, measured in monetary units, for a given seismic event (Equations [10] and [11]). Three functions were used to quantify resilience as described in Equations [10]-[12].

$$C_{dir}^{s} = P^{s} \times C^{c} \times \sum_{d=1}^{5} P_{d} D_{d} \qquad [10]$$

where C_{dir}^{s} is the expected direct cost associated with the investigated seismic event, P^{s} is the probability of occurrence of the investigated seismic event over the life cycle of the bridge, C^{c} is the construction cost of the bridge, P_{d} is the probability of being in damage state, d , as computed by the fragility analysis, and D_{d} is the damage ratio associated with a damage state d (d = 1, …, 5 representing the states of no damage, slight damage, moderate damage, extensive damage, and total collapse).

$$C_{ind}^{s} = P^{s} \int_{t=0}^{t_{f}} [1 - f_{rec}(t)] \times c_{ind} \, \mathrm{d}t \qquad [11]$$

where C_{ind}^{s} is the total expected indirect costs of the seismic event, t_{f} is the time at which full recovery is achieved, $f_{rec}(t)$ is the expected recovery function, and c_{ind} is the indirect daily cost of structural failure considering costs associated with vehicles on detour. The expected recovery path of the bridges affected by the seimic event can be computed as:

$$f_{rec}(t) = \sum_{d=1}^{5} P_d \cdot Q_d(t) \qquad [12]$$

where $Q_d(t)$ is the traffic flow functionality recovery function obtained from surveys on traffic flow capacity.

Francis and Bekera (2014) formulated a resilience metric for infrastructure systems vulnerable to natural disasters. The metric is expressed as the ratios of performance levels at different stages, and it also includes a parameter that represents the speed of recovery:

$$R = S_p \left(\frac{Q(t_f)}{Q(t_0)} \right) \left(\frac{Q(t_a)}{Q(t_0)} \right) \qquad [13]$$

where

$$S_p = \begin{Bmatrix} \frac{T_\delta}{T_R{}^*} \exp\left[-a(T_R - T_R{}^*) \right] & \text{for } T_R \ge T_R{}^* \\ \frac{T_\delta}{T_R{}^*} & \text{otherwise} \end{Bmatrix} \qquad [14]$$

in which S_p is the speed recovery, $Q(t_f)$ is the performance level at full recovery, $Q(t_0)$ is the performance level prior to disruption, $Q(t_a)$ is the performance level after disruption, T_R is the time needed for recovery to normal operations, T_δ is the maximum amount of time at the post-disaster stage that is acceptable before recovery ensures, T_R^* is the time to complete initial recovery actions to reach an intermediate state, and a is the parameter to account for increases in the time it takes to reach the final post-disruption state. Francis and Bekera (2014) developed the weighted resilience metric to account for the uncertainty in disaster occurrence and vulnerability of infrastructure systems to the disaster, as given below:

$$R_w = \sum_i \Pr\left[D_i\right] \times f\left(\mu \mid Z_i\right) \times R \tag{15}$$

where $\Pr[D_i]$ is the probability occurrence for disaster D_i and $f(\mu, Z_i)$ is the probability density function with a system failure mean of μ and conditional on event *i* occurring. The resilience metrics shown in Equations [13]-[15] were demonstrated on an electric power network exposed to hurricanes. The probability of hurricane occurrence was estimated using a Poisson distribution depending on the El-Nino Southern Oscillation, sea level pressure anomaly, and temperature. Three strategies were proposed as solutions to avoid the impacts of hurricanes for the electric power network: (i) place all overhead structures to underground, (ii) place overhead structures in the commercial area only to underground, and (iii) do nothing.

Cimerallo et al. (2010) developed analytical formulations to measure the resilience of physical facilities in a community subjected to earthquakes. Equation [1] was used as the resilience metric, and the performance function $Q(t)$ was formulated as a piecewise continuous function in terms of loss and recovery functions as:

$$Q(t) = (1 - L)[H(t - t_d) - H(t - (t_d + T_R))] \times f_{rec} \tag{16}$$

where L is the loss function, H is the Heaviside step function, f_{rec} is the expected recovery function, t is the time of interest, T_R is the time needed for recovery to normal operations, and t_d is the time at which disruption occurs. Two aspects of resilience, namely robustness and rapidity, were quantified as:

$$Robustness = 1 - \tilde{L}(m_L, \beta\sigma_L) \tag{17}$$

$$Rapidity = \frac{\mathrm{d}Q(t)}{\mathrm{d}t} \text{ for } \mathrm{t}_d \leq t \leq t_d + T_R \quad [18]$$

where $\tilde{L}$ is a loss random variable expressed as a function of the mean m_L and the standard deviation σ_L, and β is a multiplier of the standard deviation to decrease uncertainty. The loss function was estimated by the expected economic and causality losses. Direct economic losses occur instantaneously during the occurrence of disaster, and are given by

$$L_{DE}(I) = \sum_{j=1}^{n} \left[\frac{C_{s,j}}{I_s} \prod_{i=1}^{T_i} \frac{(1+\delta_i)}{(1+r_i)} \right] P_j \left\{ \bigcup_{i=1}^{n} \frac{(R_i \geq r_{\lim,i})}{I} \right\} \quad [19]$$

where $L_{DE}(I)$ is the direct economic losses for an earthquake with intensity I, $C_{s,j}$ is the building repair costs associate with a j damage state, I_s is the replacement building costs, r_i is the annual discount rate, T_i is the time range in years between the initial investments and the occurrence time of the extreme event, δ_i is the annual depreciation rate, P_j is the probability of exceeding a performance limit state j conditional an extreme event of intensity I occurs, R_i is the response parameter related to a certain measure (e.g., deformation, force, velocity, etc.), and $r_{\lim,i}$ is the response threshold parameter correlated with the performance level. Indirect economic losses are caused by business interruption which is difficult to quantify. Direct causality losses and indirect causalities were quantified as below:

$$L_{DC}(I) = \frac{N_{in}}{N_{tot}} \quad [20]$$

where $L_{DC}(I)$ is the direct causality losses for an earthquake with intensity I, N_{in} is the number of injured or dead people caused by the disaster, and N_{tot} is the number of occupants in the building.

$$L_{IC}(I) = \frac{N'_{in}}{N_{tot}} \qquad [21]$$

where $L_{IC}(I)$ is the indirect causality losses for an earthquake with intensity I and N'_{in} is the number of injured persons because of dysfunction. The direct and indirect losses can be combined to obtain the total losses as:

$$L = L_D(I) + \alpha_I L_I \qquad [22]$$

$$L_D = \left(L_{DE}\right)^{\alpha_{DE}} (1 + \alpha_{DC} L_{DC}) \qquad [23]$$

$$L_I = \left(L_{IE}\right)^{\alpha_{IE}} (1 + \alpha_{IC} L_{IC}) \qquad [24]$$

where L_D is the direct losses, L_{DE} is the direct economic losses, L_{DC} is the direct causality losses, L_I is the indirect losses, L_{IE} is the indirect economic losses, L_{IC} is the indirect causality losses, α_I is the weighting factor related to indirect losses based on the importance of the facilities for the community, α_{DE} is a weighting factor related to construction losses in economic terms, α_{IE} is a weighting factor related to business interruption, relocation expenses, and rental income losses, α_{DC} and α_{IC} are the weighting factors related to the nature of occupancy (i.e., schools, critical facilities, and density of population). Weighting factors were determined based on social-political criteria using cost-benefit analysis, emergency functions, and social factors.

The recovery function f_{rec} in Equation [16] was estimated based on simple mathematical functions, e.g., linear (Equation [25]), exponential (Equation [26]), and trigonometric (Equation [27]) functions:

$$f_{rec,linear} = a\left(\frac{t-t_d}{T_R}\right)+b \qquad [25]$$

$$f_{rec,\exp} = a\exp\left[\frac{-b(t-t_d)}{T_R}\right] \qquad [26]$$

$$f_{rec,trig} = \frac{a}{2}\left\{1+\cos\left[\frac{\pi b(t-t_d)}{T_R}\right]\right\} \qquad [27]$$

where a and b are constant values that are calculated using curve fitting to available data sources, T_R is the time needed for recovery to normal operations, t_d is the time at which disruption occurs, and t is the time of interest. Each function characterizes different preparedness and response of communities to disasters. For example, the linear recovery function is assumed when there is no information on the preparedness, resources available, and societal response. The exponential recovery function is suitable for communities that have high resources and have the capability for rapid recovery in the early stage. The trigonometric recovery function is used when there is limited organization and/or resources. The Equations [16]-[27] were used to estimate the resilience of a specific hospital building and the resilience of a city based on a network of hospital buildings in the city.

Venkittaraman (2013) quantified the seismic resilience of a highway bridge which was severely damaged during the Northridge earthquake in 1994. Equations [1] and [16] were used to compute the seismic resilience and performanc function of the highway bridge, respectively. In order to model the performance function $Q(t)$, defined in Equation [16], the loss and recovery functions of the highway bridge also need to be defined. To estimate the loss functions, the vulnerability of the bridge against seismic events are determined. The fragility curves of the bridge describe the probability of bridge failure in a damage state under a certain ground motion intensity such as peak ground acceleration (PGA) (Banerjee and Shinozuka, 2008), and are represented by the following equation:

$$F(PGA_j, c_k, \zeta_k) = \Phi\left[\frac{\ln(PGA_j / c_k)}{\zeta_k}\right] \qquad [28]$$

where PGA_j is the peak ground acceleration of a ground motion *j*, k is the damage states of the bridge (*k*=1, …, 4 representing the minor, moderate, major damage and collapse states), and c_k and ζ_k are fragility parameters for a damage state *k* which can be estimated by maximing the likelihood function *L* given as:

$$L = \prod F(PGA_j, c_k, \zeta_k)^{r_j}\left[1 - F(PGA_j, c_k, \zeta_k)\right]^{1-r_j} \qquad [29]$$

where r_j = 0 or 1 depending on whether or not the bridge sustains the damage state *k* against j^{th} ground motion. The loss functions were computed in terms of direct and indirect losses. The direct losses are the costs associated with repair and rehabilitation of damaged structural components which occur immediately after the seismic event, as given below:

$$L_D = \sum_{k=1}^{n} P_E(DS = k) \cdot C \cdot r_k \qquad [30]$$

where C is the replacement cost estimated by multiplying bridge deck area with the unit area replacement cost, r_k is the damage ratio corresponding to damage state k as obtained from HAZUS, and $P_E(DS = k)$ is the probabillity that the bridge can sustain a damage state *k* during the seismic event *E* obtained from the bridge fragility curves. The indirect losses include rental, income losses, relocation, business interuptions, traffic delay, losses in revenue from traffic to businesses. To account for the indirect losses, the direct losses calculated from Equation [30] were multiplied by 13, an average of the range 5-20, as suggested by Dennemann (2009). The recovery functions were modeled using Equations [25]-[27]. Venkittaraman (2013) proposed three retrofit strategies to reduce the shear demand from bridge piers: (i) application of steel jackets around bridge piers, (ii) assigning seat-type abutment, and (iii) assigning shear keys in addition to the seat-type abutment. The seismic resilience of the bridge, after the three retrofit strategies were applied, was calculated and compared with the seismic resilience of the bridge prior to the seismic event in order to understand the effectiveness of the different retrofit strategies.

Tokgoz and Gheorghe (2013) developed a resilience metric for residential buildings subjected to hurricane winds by combining Equation [1] and the probability of windspeed as:

$$R = 100 \int_{w_1}^{w_2} \frac{1}{T_R} \left[\int_0^{T_R} Q(t,w)\,\mathrm{d}t \right] P(w)\,\mathrm{d}w \bigg/ \int_{w_1}^{w_2} P(w)\,\mathrm{d}w \qquad [31]$$

where w is the wind speed, w_1 and w_2 are minimum and maximum wind speeds for the hurricane category considered according to the Saffir-Simpson hurricane damage potential scale, $P(w)$ is the distribution for probability of having winds with a speed of w, T_R is the time needed for recovery to normal operations, and $Q(t,w)$ is the performance function of residential buildings. The performance function was expressed in terms of loss and recovery functions as:

$$Q(t,w) = 1 - \sum_{j=1}^{N_{ds}} L_j \times f_{rec}^{j} \qquad [32]$$

where N_{ds} is number of damage states, L_j is structural losses for damage state j, and f_{rec}^{j} is recovery function for damage state j. The five damage states, j, for external components of residential buildings were obtained from HAZUS software program. The wind speed probability can be estimated using Weibull distribution as:

$$P(w) = \frac{1}{\alpha}\exp\left(-\frac{w}{\alpha}\right) \quad [33]$$

where α is a Weibull distribution parameter and w is the wind speed. The structural losses for damage state j can be estimated as:

$$L_j = \frac{1}{I_t}\sum_{i=1}^{N_m} I_{i,j} D_{i,j} P_i\left(j \mid w\right) \quad [34]$$

$$D_{i,j} = \frac{C_{i,j}}{I_{i,j}} \quad [35]$$

$$I_t = \sum_{i=1}^{N_m} I_{i,j} \quad [36]$$

where I_t is total replacement cost for all building types, N_m is number of different building types, $I_{i,j}$ is replacement cost for building type, i, in damage state j, $D_{i,j}$ is loss ratio corresponding to the ratio of building repair costs to building replacement costs for building type, i, in damage state j, $P_i(j \mid w)$ is probability to be in damage state, j, at a given wind speed , w, for building type i, and $C_{i,j}$ is the repair cost for building type i in damage state j. The recovery functions were expressed in simple mathematical functions including linear, exponential, normal, and sinusoidal functions to characterize different response scenarios.

Shinozuka et al. (2004) quantified the seismic resilience of communities in Los Angeles dependent on electric power supply systems. The seismic resilience was computed in terms of robustness and rapidity (i.e., average recovery rate) of electric power supply systems, as given by

$$Robustness = Q(t_a) \qquad [37]$$

$$Rapidity = \frac{Q(t_f) - Q(t_a)}{t_f - t_a} \qquad [38]$$

where $Q(t_a)$ is the performance level immediately after disruption, $Q(t_f)$ is the performance level after recovery, t_f is the time at which power supply is restored to 100% performance level, and t_a is the time at which earthquake occurs. The study considered 47 scenario earthquake events and determined fragility curves for electric/mechanical components in receiving stations of transmission systems such as transformers, circuit breakers, and disconnects switches and buses. The fragility curves describe the probability of failure of the components at given PGA and were empirically obtained from damage data of the Northridge earthquake. The power output for each service area in Los Angeles was obtained for the different earthquake scenarios using the IPFLOW computer code and Monte Carlo simulations. The seismic performance of the power supply system was represented by the ratio of the average power supply of the damaged network to that associated with the intact network. The losses from the earthquakes were quantified in terms of technical (e.g., reduction in power supply), societal (e.g., rate of households without power supply), and economic (e.g., regional economic loss or employment loss). The reduction in power supply was estimated as:

$$P_{wo} = 100\% - P_w \qquad [39]$$

in which

$$P_w = \frac{\sum_{m=1}^{M} \frac{1}{N} \sum_{n=1}^{N} P_d(m,n)}{\sum_{m=1}^{M} P(m)} \times 100\% \qquad [40]$$

where P_w is the percentage of power supply, *m* is the service area number (1, …, *M*), *n* is the simulation number (1, …, *N*), $P_d(m,n)$ is the power output in service area *m* under n^{th} simulation, and *P*(*m*) is the power output in service area under normal conditions. The percentage of households without power (i.e., societal loss) was computed as:

$$H_{wo} = 100\% - H_w \qquad [41]$$

in which

$$H_w = \frac{\sum_{m=1}^{M} \frac{1}{N} \sum_{n=1}^{N} R_d(m,n) \times Hshld(m)}{\sum_{m=1}^{M} Hshld(m)} \times 100\% \qquad [42]$$

where H_w is percentage of households with power, $R_d(m,n)$ is the power output ratio in service area *m* under n^{th} simulation, and $Hshld(m)$ is the number of households in service area *m*. The economic loss can be quantified as:

$$L = \sum_{s} \sum_{j} l_j \cdot d_s \cdot e_{s,j} \qquad [43]$$

where l_j is a loss factor for industry *j* that ranges from 0 to 1, d_s is a disruption indicator for service area *s* (*d* = 1 in case of power outage and *d* = 0 in case of no outage), and $e_{s,j}$ is daily industry *j* economic activity in service area *s* in dollars. The study expressed the economic loss as the percent of gross regional product (GRP) that would be lost during the power outage caused by earthquakes. Using the fragility curves and loss calculations, the expected annual probabilities as a function of (i) loss of power supply, (ii) percentage of households without power, and (iii) reduction in GRP after an earthquake were computed. The recovery of the power supply system was modeled by assuming hypothetical repair and replacement curves for the electrical/mechanical components. The seismic resilience of communities was evaluated based on system performance criteria defined in terms of robustness, rapidity, and reliability. For example, the robustness and reliability of seismic resilience in the technical dimension need to have at least 80% of power supply after an earthquake with high level of reliability (i.e., 99% of annual probability). The rapidity criterion in the technical dimension is to have at least 95% of power supply as rapidly as possible within 3 days with at least 90% of earthquake events. System performance criteria in societal and economic dimension can also be considered.

CHAPTER 3. RESILIENCE ASSESSMENT FRAMEWORK

3.1 Objectives of the proposed framework

The concept of resilience in different disciplines emphasizes different characteristics or properties of resilience, as summarized in Table 6. Different terminologies are used to represent similar properties of resilience. For example, persistence, resistance, and robustness are similar to each other. Adaptive capacity, creativity, and reorganization signify similar properties. Resource robustness and resourcefulness are similar to each other except that resource robustness in community resilience also mentions redundancy in resources which is similar to the idea of having redundancy in engineered systems. Renewal, transformability, and regeneration are also equivalent properties.

It is evident that the recovery aspect of a system is important while defining resilience. However, recovery is characterized differently across disciplines. For example, ecological resilience (with engineering perspective) and engineering resilience emphasize the speed of recovery. Ecological (with biological perspective), social-ecological, and disaster resilience describe recovery in terms of transformability. Social-ecological, social, and disaster resilience consider adaptability as a mean of recovery.

The key aspects of resilience should include (i) resistance, (ii) recovery in terms of speed, adaptability, and transformability, (iii) resourcefulness, and (iv) redundancy. It is important that the proposed resilience assessment framework quantifies these key aspects of resilience for geotechnical infrastructure and estimates the change in them before and after disruptions.

Table 6. Concepts of resilience in different disciplines

Resilience in different disciplines	Properties
Ecological resilience (engineering perspective)	Speed of recovery Efficiency, constancy, and predictability
Ecological resilience (biological perspective)	Persistence, change, and unpredictability Renewal of system (i.e., regime shift)
Social-ecological resilience	Adaptive capacity and transformability Self-organization Learning aspect of system
Social resilience	Resistance, recovery, and creativity Resource robustness and adaptive capacity
Disaster resilience	Resistance, regeneration, and reorganization
Engineering resilience	Robustness, rapidity, resourcefulness, and redundancy

The objectives of the proposed resilience assessment framework for geotechnical engineering include the followings: (i) to simulate hazard scenarios and quantify the response of geotechnical assets in terms of their limit states, (ii) to capture the impacts of damaged geotechnical assets to critical infrastructure systems and societies, (iii) to quantitatively assess the resilience of geotechnical assets considering the key aspects of resilience (i.e., robustness, rapidity, resourcefulness, redundancy, adaptability, and transformability), and (iv) to evaluate the effectiveness of response strategies implemented for improving the resilience of geotechnical assets.

3.2 DPSIR framework

The structural thinking of the Driver-Pressure-State-Impact-Response (DPSIR) framework, developed by the European Environment Agency, is adopted in this study. Although the DPSIR framework is widely used as a tool for the reporting and analysis of environmental problems, it is reinterpreted so that the proposed resilience assessment framework is applicable to geotechnical infrastructures in this study. The DPSIR framework addresses five aspects of a given problem: drivers, pressures, states, impacts, and responses (Figure 7).

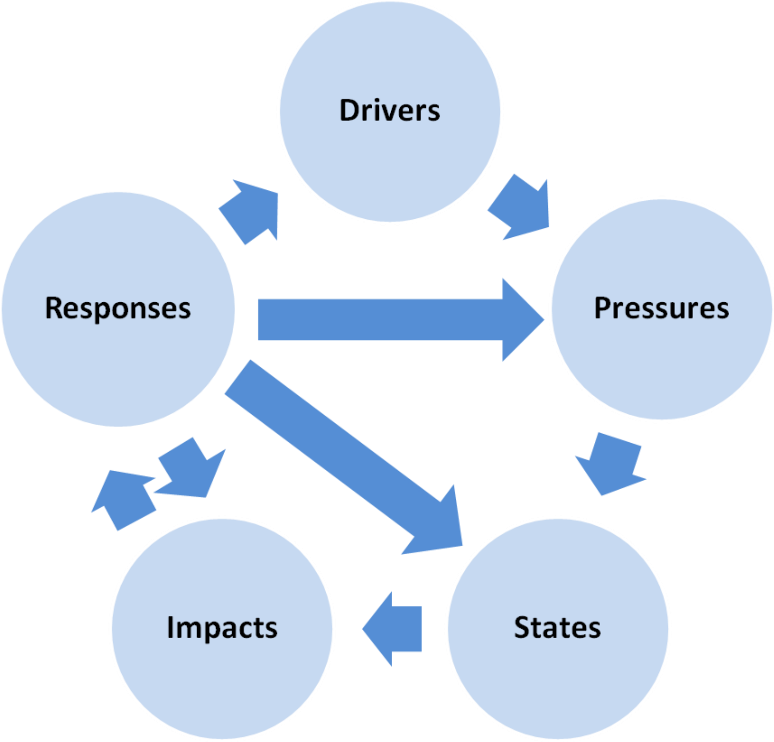

Figure 7. DPSIR framework

Drivers or driving forces are the fundamental factors that influence the human activities to fulfill basic human needs. Pressures are the specific human activities that result from the driving forces which impact the system or environment. States refer to the conditions of the natural and built environment, and human systems. Impacts are the ways in which changes in the states influence the welfare of humans. Responses refer to institutional efforts to prevent, compensate, ameliorate, or adapt to changes in the states (Bradley and Yee, 2015; Carr et al., 2007; Gabrielsen and Bosch, 2003). The DPSIR framework is a comprehensive framework that fulfills the objectives of the proposed resilience assessment framework outlined in section 3.1. ‘Drivers’ and ‘pressures’ in the DPSIR framework can describe and simulate the hazard scenarios applied to a geotechnical infrastructure; the robustness, rapidity, resourcefulness, and redundancy of the geotechnical infrastructure can represent the ‘states’; the technical, economic, environmental, and social impacts of the damaged geotechnical infrastructure can be described and quantified in the ‘impacts’; strategies in response to the hazard scenarios can be planned in the ‘responses’; and effectiveness of the response strategies to improve the resilience of geotechnical infrastructure can be evaluated considering the ‘states’ and ‘impacts’ in the DPSIR framework. The reinterpretation of the five components of DPSIR framework for the proposed resilience assessment framework is discussed in the following sections.

3.2.1 Drivers: identification of driving forces

The drivers can be understood as the fundamental causes that change the pressures to the geotechnical infrastructure. Indicators for drivers should describe the social, demographic, and economic developments in societies (Grabrielsen and Bosch, 2003). For example, there are economic driving forces which fulfill human needs for food and raw materials, water, shelter, health, security, infrastructure, and culture. Social driving forces fulfill human needs for social relations, equity, governance, and cultural identity (Bradley and Yee, 2015). Table 7 and Table 8 provide examples of driving forces which influence different human needs that can be used as a guideline to identify the driving forces for a given geotechnical infrastructure.

Table 7. Examples of economic driving forces

Human need	Sector
Food and raw materials	Agriculture Aquaculture Oil and gas extraction Fishing Forestry Mining and quarrying
Water	Drinking water supply Irrigation
Shelter	Housing Textiles and apparel
Health	Medical care Pharmaceuticals Social assistance (e.g., child care centres) Waste management (e.g., sewage treatment facilities and landfills)
Culture	Tourism and recreation Education Information (e.g., telecommunications and scientific research) Social organizations
Security	National defense Public administration
Infrastructure	Manufacturing and trade Transportation Construction and civil engineering Utilities

After Bradley and Yee (2015)

Table 8. Examples of social driving forces

Human need	Sector
Social relations	Family dynamics Religious affiliations Social groups
Equity	Access to education Access to healthcare Access to jobs
Governance	Roles of decision-makers Types of government
Cultural identity	Urban, rural, tribal, or coastal communities

After Bradley and Yee (2015)

The relevant driving forces are identified according to the factors that can affect the primary functions of a given geotechnical infrastructure or its associated infrastructure system. For example, dams and levees are critical geo-structures for the management of water levels and prevention of floods; hence, the drivers are the fundamental causes that affect the water level of the regions and the frequency of floods. The local sea level can be affected depending on the type of communities; for instance, coastal communities are at higher risk for storm surges and floods, and urban communities may affect the water levels because of large areas of impervious surfaces. Agriculture, irrigation, drinking water, and fish production (i.e., aquaculture) can be factors that influence the amount of water storage that is required (Shultz, 2002). Oil and gas extraction can cause land subsidence and subsequently change the regional water level (Church et al., 2013). Embankments, slopes, tunnels, retaining structures, and bridge foundations are important components in transportation networks (Basu et al., 2014). These geo-structures provide access and support to road and rail transportation infrastructures for mobility of passengers and goods. Therefore, the drivers can be identified primarily focusing on the factors that affect the users' travel behaviour (e.g., travel distance and frequency, and mode of transportation) and business logistics. Oil and gas extraction affect the energy or fuel availability for vehicle use. Tourism, recreation, and leisure activities affect users' travel frequency. Manufacturing and trade influence business logistics and the supply of goods through freight transportation. Pipeline systems are responsible for the transportation of water, energy (i.e., oil and gas), and other fluids through steel or plastic pipes buried underground. Considering the fact that transportation and construction sectors are in high demand of petroleum products, and residential homes are heated by natural gas, oil and gas extraction affect the volume of energy transportation through the pipes. Drinking water and irrigation influence the volume of water to be transported. Agriculture affects the need for transporting fertilizers and fuels. Some other examples on the primary functions of geotechnical infrastructure to consider are (i) structural support of foundations to telecommunication towers, power plants, medical care, and other critical facilities and (ii) waste containment in landfill systems using geotechnical clay liners or other geotechnical solutions.

3.2.2 Pressures: hazard scenarios

The driving forces result in pressures which are hazards or threats to the selected geotechnical infrastructure over its lifespan. The pressures can be identified according to the eight categories of possible threats that physical civil infrastructure may encounter: (i) gradual deterioration from ageing, (ii) damage from surface loading or stress relief, (iii) severely increased demand and ever-changing demands, (iv) the effects of climate change, (v) the effects of population increase, (vi) funding constraints, (vii) severe natural hazards, and (viii) terrorism (Rogers et al., 2012). For example, dams and levees can continuously experience gradual deterioration because they have relatively low importance than other locations and have minor risks to the population, ecosystems, and other critical infrastructures. Increased demands of water storage can be caused by drivers related to agriculture, irrigation, and drinking water. Dams and levees can be at high risk of floods because of their geographical location (e.g., coastal communities). Excessive settlement to road embankments can occur because of loadings from heavy or commercial trucks. High traffic demand and congestion can be the effects of population increase which is caused by the area being urban and prominent. Embankments in rural areas may experience funding constraints in construction and maintenance. Climate change can be caused by the emissions of greenhouse gases (GHGs) because of oil and gas extraction necessary for pipeline transportation. Pipeline systems that transport flammable fluids and gas (e.g., crude oil and natural gas) can be a target of terrorism to cause devastating consequences. Different hazard scenarios based on the identified pressures can be generated for a comprehensive analysis.

3.2.3 States: geotechnical engineering analysis and characteristics of resilience

In the proposed framework, the states indicate metrics that represent the resilience of geotechnical infrastructure which can be represented by robustness, rapidity, redundancy, and resourcefulness aspects of resilience. Robustness of geotechnical infrastructure can be represented by the ultimate limit state (ULS) and serviceability limit state (SLS) of the geotechnical infrastructure affected by the hazard scenarios. For example, the limit states of a foundation are its bearing capacity, which correspond to a ULS, and its allowable settlement, which represent a SLS. Geotechnical analyses are performed to calculate the changes in ULS and SLS caused by the hazard scenarios generated in section 3.2.2. Rapidity is characterized by the recovery in the limit states of geotechnical infrastructure with respect to time. Redundancy can be quantified by the number of substitutable or redundant components within the network of geotechnical infrastructure. Resourcefulness can be represented by the costs required for construction, maintenance, mitigation, and repair of the geotechnical infrastructure compared to an available budget.

3.2.4 Impacts: impacts on the infrastructure systems and societies

The impacts are interpreted as the effects of damaged geotechnical components to the associated infrastructure systems and societies. Many civil infrastructure systems, especially transportation networks, are highly dependent on the geotechnical components (e.g., embankments, slopes, foundations, and retaining structures). Therefore, the states of the geotechnical components, which are disrupted by the hazard scenarios, directly affect the functionality of the associated infrastructure system and eventually affect the communities. The impacts can be measured from technical, economic, social, and environmental points of view. The technical impact refers to the loss of functionality of the infrastructure system measured according to their primary functions defined in section 3.2.1. For example, the loss of functionality of dams and levees can be represented by the loss of capacity to retain water. The primary function of embankments and other geo-structures in transportation network is the mobility of passengers and goods. Therefore, the technical impact can be quantified in terms of the increased traffic volumes and travel times. Volume of fuel, water, or other fluids and gas can be an indicator to measure the technical impact of pipeline systems. Economic, environmental, and social impacts can be measured using relevant sustainability indicators. For example, the economic losses can be measured by the cost of property damage and cost of repair. The environmental impacts are the pollution to the air, water, and land. The social impacts can be measured by human health impact, life quality index (Pandey and Nathwani, 2004), public safety (e.g., fatalities, injuries, and evacuations), and equity (Ministry of Community Safety and Correctional Services, 2012).

3.2.5 Responses: mitigation and rehabilitation scenarios

Mitigation and rehabilitation actions are institutional efforts to cope with the hazards and disrupted geotechnical infrastructure. Mitigation measures aim for the prevention and reduction of the impacts of hazards whereas rehabilitation actions target for recovery of the disrupted infrastructure in a timely manner. The rehabilitation actions can be implemented to either improve the adaptability or transformability of the disrupted geotechnical infrastructure. If complete failure of geotechnical components has not reached, retrofitting or reinforcement of geotechnical infrastructure can be undertaken to partially repair the damage and improve their adaptability. However, if partial repair is no longer possible because the damage is severe, the damaged geotechnical components can be completely rebuilt to transform into a new system. Several mitigation and rehabilitation strategies can be planned and combined to generate different response scenarios. Improvement of infrastructure functionality, recovery time, redundancy, and reduction of impacts can differ depending on which response scenario is undertaken. The effectiveness of the response scenarios can be evaluated based on the metrics and the impacts determined in sections 3.2.3 and 3.2.4, respectively.

4.1 Problem definition

The proposed resilience assessment framework is demonstrated using an example of a transportation network consisting of road embankments in Ontario, Canada. The relationship between the road embankment and transportation networks is investigated to systematically quantify the resilience of the embankment network. The chosen transportation network connects two major cities, London and Toronto, in the province of Ontario. In this study, London is considered as the departure location and Toronto as the destination point. The transportation network consists of provincial highways (i.e., Highway 401, 403, 427, Queen Elizabeth Way), a municipal expressway (i.e., the Gardiner Expressway), a privately owned tolled highway (i.e., Highway 407), and arterials (i.e., Highway 4, 5, 6, 7, 8, 24, and 59). The schematic for the selected transportation network is shown in Figure 8.

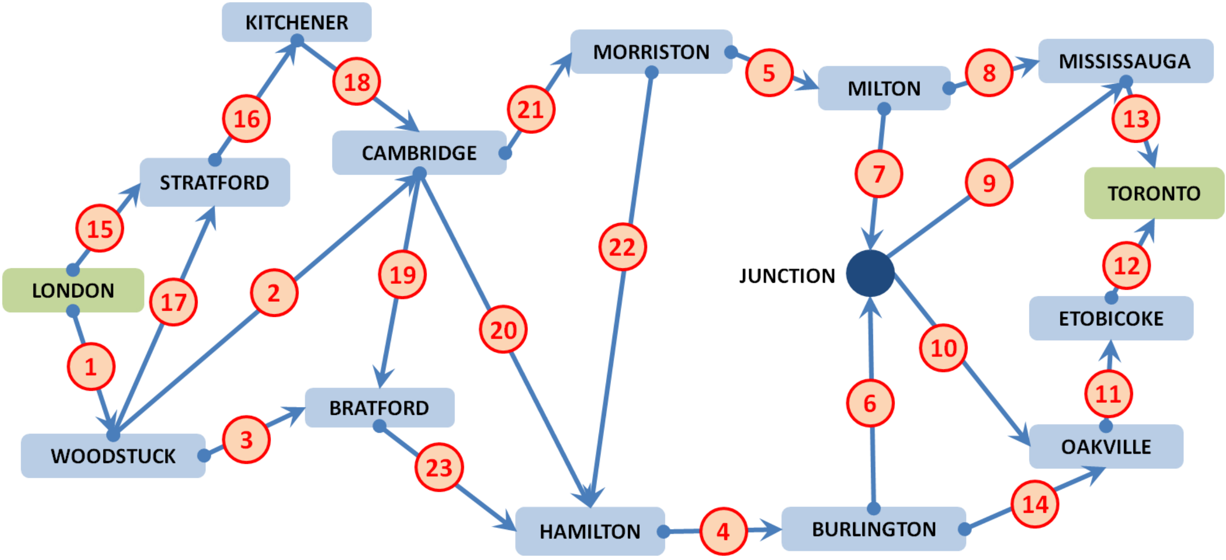

Figure 8. London-Toronto transportation network

The geometric sections of road embankments considered in this study are simplified as trapezoids. Table 9 summarizes the top width, height, and slope of seven different embankment sections considered to represent the transportation network for this study. The different embankment sections are assigned to different sets of network links as summarized in Table 10. The network link No. indicates the numbers shown in Figure 8.

Table 9. Dimensions of embankment sections

Embankment section No.	Top width (m)	Height (m)	Slope (Vertical:Horizontal)
1	54	5	1:3
2	60	7	1:2
3	40	5	1:4
4	43	5	1:5
5	36	5	1:4
6	50	5	1:3
7	12	3	1:3

Table 10. Embankment sections for network links

Embankment section No.	Highway/Arterial No.	Network link No.
1	Highway 407	6, 7
2	Queen Elizabeth Way and Gardiner Expressway	11, 12
3	Highway 403	3, 4, 14, 23
4	Highway 401	1, 2, 21
5	Highway 401 and 427	5, 8, 13
6	Highway 403	9, 10
7	Arterials 4,5,6,7,8,24,59	15, 16, 17, 18, 19, 20, 22

4.2 Drivers: importance of the problem

The primary function of the transportation network and road embankments is to provide mobility to the public so that accesses to food and clothing, work, medical care, education, and social activities are gained (Wang, 2015). Therefore, the driving forces are the factors that motivate human activities to fulfill maximum mobility of passengers and goods to the destination point. Transportation mobility can be affected by various drivers including demographics, economic and social change, technology, energy, and policy (Akhyani, 2015). Demographics such as the population age and gender, household structure, urbanization, and immigration affect transportation patterns by causing variation in individual’s travel distance, frequency of trips, and car ownership. Human needs for better living and increased personal income tend to result in increased possibilities for optimized residential location, purchasing transport, and making longer and more frequent trips. Production and trade of goods influence the traffic density of freight transportation. Leisure activities and tourism affect travel demand as these activities mostly take place outside of private homes (Peterson et al., 2009). Development and application of technologies can also influence the transportation patterns. For example, satellite tracking of traffic conditions and online ticketing services for public transportation can influence the users’ behaviour and the choice of transportation mode. Price and availability of energy can influence car ownership, car running costs, passenger costs, and trip density and frequency. Policy making, either for short-term or long-term, can potentially affect energy prices, passenger traffic, logistics, trade and security policies, migration, tourism, and social aspects of living (Akhyani, 2015).

In this case study, the identified drivers do not directly affect the calculations for evaluating the resilience of the transportation network. However, identification of drivers is necessary and useful for comparative assessment of similar infrastructure systems. For example, multiple transportation networks at different locations may need to be compared. Since drivers are often site-specific, the drivers for the different transportation networks will be different. Depending on the importance and value of the identified drivers, the transportation network that is the most in need of building resilience can be determined.

4.3 Pressures: flood scenarios

The traffic demands and patterns caused by the aforementioned driving forces create stresses to the road embankments which can affect their stability and serviceability. In addition, the atmospheric discharges, like greenhouse gases (GHGs), from the operation of vehicles contribute to global warming, climate change, and increased risk of natural hazards. Climate change can influence the frequency and intensity of natural hazards. For example, climate change can intensify precipitation which causes loss of soil quality, change in water table, change in pore water pressure inside the soil, rapid soil wetting, and collapse of fill materials (Vardon, 2015). Increased storm water run-off from the impervious surface of pavements can also occur. Potential failure modes from increased precipitation include slope failure, erosion (either internally or externally), piping, and excessive settlement (Vardon, 2015).

In this study, the generation of hazard scenarios is focused on the natural hazards in Ontario. According to the statistics of disaster types in Ontario from 1900 to 2013 provided by Nirupama et al. (2014), the most frequently occurred hazards which directly affect the performance of road embankments are floods, storms, tornadoes, and winter storms. The case study focuses on floods mainly because it is the most frequent natural hazard in Ontario, and hydraulic inputs and outputs to soil and water system are directly significant to geotechnical failures (Vardon, 2015). Floods in Canada can be caused by many factors such as excess rainfall, storm water run-off over impervious surfaces, drainage problems, snowmelt during spring seasons, ice jams, rain on snow, riverine flooding, and failure of natural dams or flood management structures (Dotto et al. 2010; Shrubsole et al. 2003). Four natural hazard scenarios on floods are generated with different rainfall intensities – scenarios (1) with 100 mm/hr, (2) 50 mm/hr, (3) 25 mm/hr, and (4) 10 mm/hr rainfall intensities. All hazard scenarios are assumed to have the same rainfall duration and flood return period which are 6 hours and 100 years, respectively. For demonstration purpose, only the results obtained from hazard scenario 1 are presented in this thesis. It is unlikely that flood occurs simultaneously at all locations throughout the entire network; thus, a set of road links in a certain area is selected for the investigation. In this case study, five network links are assumed to be affected by the hazard scenarios: highway 401 between Woodstuck and Cambridge (link No. 2 in Figure 8), highway 403 between the junction and Oakville (link No. 10), highway 401 between Cambridge and Morriston (link No. 21), arterial 59 between Woodstuck and Stratford (link No. 17), and arterial 5 between Cambridge and Hamilton (link No. 20), as indicated in Figure 9. It is assumed that only 1/3 of the embankments in the entire link will be affected.

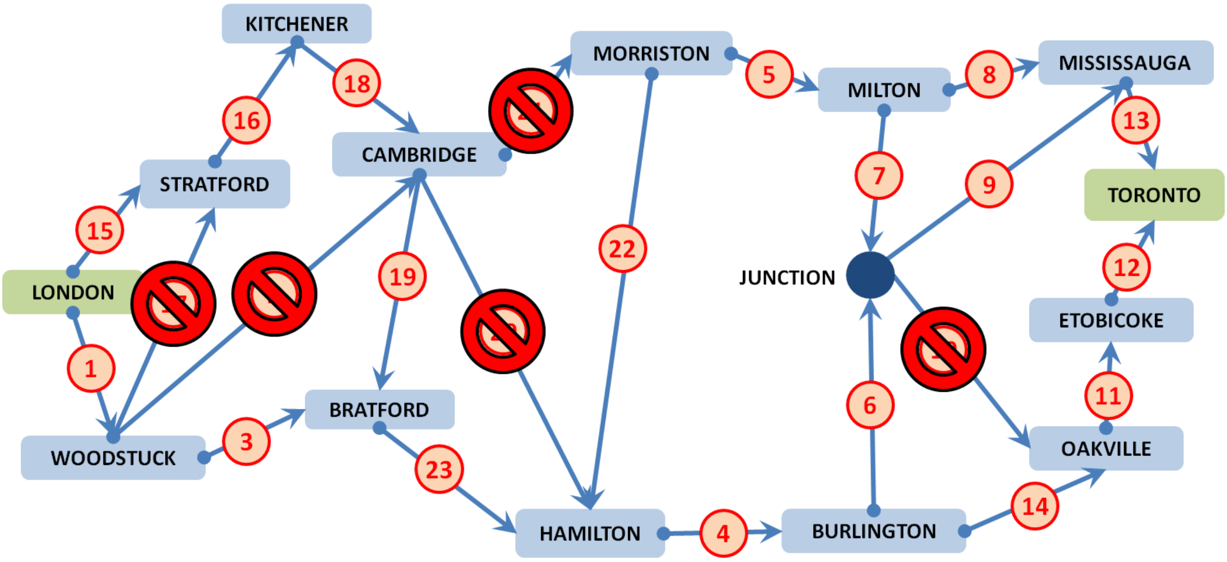

Figure 9. Affected road links by the hazard scenarios

4.4 States: characteristics of resilience

Resilience of the transportation network consisting of road embankments can be calculated using Equation [1] with respect to appropriate multiple performance functions like the factor of safety (FoS) and settlement. On the other hand, 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 ULS and SLS of embankments, which are represented by the slope stability and settlement, respectively, as given below:

$$\mathit{Robustness}\ (\mathrm{ULS}) = U(t_a) - U(t_0) \qquad [44]$$

$$\mathit{Robustness}\ (\mathrm{SLS}) = S(t_a) - S(t_0) \qquad [45]$$

where $U(t_0)$ is the initial ULS (factor of safety in this case study) before the occurrence of disruption, $U(t_a)$ is the ULS after the occurrence of disruption, $S(t_0)$ is the initial SLS (settlement in this case study) before disruption occurs, and $S(t_a)$ is the SLS after disruption occurs. Thus, $U(t)$ and $S(t)$ are the performance functions, and Equation [1] can be used to calculate the resilience in terms of both ULS and SLS. The lower the value obtained from Equations [44] and [45], the more robust the embankments are against the hazards.

The rapidity aspect of resilience for the road embankments can be measured by the recovery of FoS and settlement with respect to time as:

$$Rapidity\ (\mathrm{ULS}) = \frac{dU(t)}{dt} \text{ for } t_a \leq t \leq t_f \qquad [46]$$

$$Rapidity\ (\mathrm{SLS}) = \frac{dS(t)}{dt} \text{ for } t_a \leq t \leq t_f \qquad [47]$$

where t_a is the time after the disruption (see Figure 2) and t_f is the time at which the system reaches full or an acceptable level of recovery. The faster embankments recover, the higher the rapidity.

Resourcefulness can be quantified by the ratio of construction costs required for implementing a response strategy to the government budget on highway management, as given by

$$Resourcefulness = \frac{C_{actual}}{C_{budget}} \qquad [48]$$

where C_{actual} is the costs for carrying out a response strategy and C_{budget} is a given budget.

The redundancy aspect of resilience can be represented by how ‘distributed’ the highway network is, and can be measured by its 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. The network entropy is calculated using the Shannon entropy as:

$$H = -\sum_{i}^{n} p_i \log_2 p_i \qquad [49]$$

where H is the Shannon entropy or network entropy, n is the total number of network links, and p_i is the proportion of traffic flow at i^{th} link with respect to the total traffic flow over the entire network (i.e., traffic demand).

4.5 Impacts: impacts on the transportation network and communities

The impacts of damaged embankments can be measured with respect to technical, economic, environmental, and social impacts. The technical impact of damaged embankments to the transportation network is estimated by the change in mobility which is represented by the change in traffic volumes over the entire transportation network. It is assumed that the capacities of network links to carry a number of vehicles per time are directly affected by the slope stability or serviceability of the supporting embankments. The traffic capacities of the network links are assumed to be affected proportionately by the change in FoS and settlement of embankments, as summarized in Table 11. The lower of the capacities calculated based on FoS and settlement is used in further calculations. For example, if the FoS of an embankment is below 1.0, then it is expected that slip surface failure occurs and the corresponding network link becomes inoperable; thus, a capacity of 0% for the affected network link is assumed. If the FoS of the embankment is above or equal to 1.5, then it is likely that the road will not be severely affected; thus, a capacity of 100% is assumed for such scenarios. For FoS between 1.0 and 1.5, the capacity is estimated by linear interpolation. A capacity of 0% is assumed for settlement equal to and over 50 mm. A linear interpolation is used for estimating the capacity of network links for settlements ranging between the initial settlement and 50 mm settlement.

As mentioned earlier, the lowest capacity obtained according to FoS and settlement calculations is assigned to the respective network link.

Table 11. Capacity of links based on slope stability and serviceability of embankments

Slope stability (factor of safety)	Serviceability (settlement)
Capacity = 100% if FoS ≥ 1.5	Capacity = 100 % if settlement = initial settlement
Capacity = 0% if FoS < 1.0	Capacity = 0% if settlement ≥ 50 mm
0 < Capacity < 100% if 1.0 ≤ FoS <1.5	0 < Capacity < 100% if 0 < settlement < 50 mm

An optimization study is conducted on the transportation network with the degraded capacities (under a hazard scenario) to estimate the change in traffic volumes for all network links. The objective of the optimization problem is to minimize the traffic volume over the transportation network while meeting the traffic demands from London to Toronto. The transportation network is perceived as a directed graph with the cities representing the nodes and the highway/arterial links representing the arcs. The optimization is conducted by linear programming and solved using the software MATLAB. The algorithm for the optimization problem is given below.

Minimize $[x]$

Subject to the constraints:

$$A_{eq}x = b_{eq} \tag{50}$$

$$A_{eq} = \left\{ \begin{array}{l} -1 \text{ for inflow} \\ 1 \text{ for outflow} \\ 0 \text{ otherwise} \end{array} \right\} \tag{51}$$

$$b_{eq} = \begin{Bmatrix} D \text{ for } i = 1 \\ -D \text{ for } i = m \\ 0 \text{ otherwise} \end{Bmatrix} \quad [52]$$

$$Ax \leq b \quad [53]$$

$$A = \begin{Bmatrix} 1 \text{ for } i \in e \\ -1 \text{ for } i \in n - \{e\} \\ 0 \text{ otherwise} \end{Bmatrix} \quad [54]$$

$$b = 0 \quad [55]$$

$$0 \leq x_i \leq C_i \text{ for } i \in n \quad [56]$$

where x_i is the traffic volume in annual average daily traffic (AADT) for the i^{th} link, A_{eq} is an arc-node incidence matrix in size (m, n), m is the number of nodes (cities), n is the number of arcs (network links), D is the traffic demand in AADT, A is an arc-node incidence matrix in size (e, n) , e is the number of arcs corresponding to toll routes and arterials, and C is the degraded capacity of arcs (network links).

After determining the traffic volume x_i, the travel time along any link or route can be calculated. The travel time from one point to another depends on the number of vehicles or traffic volumes. It is determined that there are 43 possible routes between London and Toronto based on the network considered in this study (Figure 8). Using the degraded traffic capacities and the corresponding traffic volumes obtained from the optimization, the travel time in each route can be calculated as (Omer, 2013):

$$t_k = \sum_i^n \frac{l_i}{88.5}\left[1 + 0.15\left(\frac{x_i}{C_i}\right)^4\right] \quad [57]$$

where t_k is the travel time of route k, n is the total number of arcs in the route k, and l_i is the distance of the i^{th} network link.

Equations [50]-[52] indicate the equality constraints which describe (i) the outflow from the starting point (London) is equal to the traffic demand, (ii) the inflow to the destination point (Toronto) is equal to the traffic demand, and (iii) the inflow and outflow at all other cities (nodes) are equal. Equations [53]-[55] define the inequality constraints that describe the fact that commuters have less preference of taking toll routes (i.e., Highway 407) and arterials. Equation [56] defines the lower bound (i.e., non-negativity) and upper bound (i.e., capacity of network links) of the traffic volumes. The optimization program was verified by solving two similar network flow example problems by Henry and Ramirez-Marquez (2012) on a tram network of a park and by Fourer et al. (2003) on a transshipment network.

The economic impacts are quantified by the construction costs for implementing response strategies. The environmental impacts of failed road embankments can be estimated by the pollution to air caused by construction activities required for implementing response strategies. The social impacts are quantified by the damage to human health because of toxic emissions generated during any construction activities and by the loss of leisure time during traffic congestion.

4.6 Responses: mitigation and rehabilitation scenarios

In order to prepare for floods and repair geotechnical infrastructure from failures, mitigation and rehabilitation strategies have to be made. The mitigation technique for embankments considered in this study is construction of toe berms to improve their stability. Three types of response actions are considered in this case study: no action, proactive repair to improve adaptability, and retroactive repair to improve transformability. The proactive repair refers to retrofitting the embankments before they reach complete failures, and retroactive repair indicates reconstruction of the entire embankments because they can no longer be partially repaired. Five combinations of the possible mitigation and rehabilitation strategies are selected for the response scenarios, as summarized in Table 12.

Table 12. 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

The retrofitting action in response scenarios 1 and 4 is completed if only it is applicable. If an embankment exceeds a certain threshold for slope stability and settlement after the flood occurs, it is assumed that retrofitting can no longer be completed; therefore, the failed embankment is reconstructed instead. For example, if the FoS of an affected embankment is less than 1.0 after the flood, it is assumed that retrofitting is not possible and reconstruction of the embankment needs to be completed. If its settlement exceeds 50 mm, the embankment is reconstructed instead of retrofitting. For response scenarios 1 and 4, the aim is to retrofit the embankments as much as possible. Therefore, depending on the threshold explained above, several embankments may be retrofitted while the rest may need to be reconstructed at the same time.

4.7 Results

The details of the ULS and SLS calculations for the different embankments of the transportation network are demonstrated next. The slope stability of the embankments subjected to different rainfall intensities was modeled using RocScience Slide 6.0, and the FoS were obtained using the Bishop simplified method. A distributed load of 20 kN/m was axially applied at the top horizontal surface of the embankments to represent the traffic loads. For arterials, a distributed load of 15 kN/m was applied to simulate relatively lower traffic loads. The initial water table was assumed to be located 1 m below the base of all embankments. The boundary conditions on the exposed surfaces of the embankments were set to the respective rainfall intensity. The settlement of embankments was estimated from finite element modelling using the software RocScience RS2. The same conditions and assumptions defined as used in Slide 6.0 were used in the software RS2. The results of slope stability and settlement analyses of the embankments subject to hazard scenario 1 (i.e., 100 mm/hr of rainfall intensity) are summarized in Table 13.

Table 13. Results of slope stability and settlement analysis for hazard scenario 1

Embankment section No.	Initial FoS	FoS after 6 hours	Initial settlement (mm)	Settlement after 6 hours (mm)
1	1.902	0.846	33.9	36.6
2	1.832	0.77	14.1	100.4
3	1.897	0.946	4.1	4.7
4	1.894	0.841	28.6	30
5	1.901	0.928	15.9	22.3
6	1.885	0.843	10.7	10.8
7	3.485	2.395	14.9	15.3

The geometric sections of toe berms is assumed to be parallelograms, and berms are constructed at both sides of toes of the existing embankments. Table 14 provides the top width, height, and slope of toe berms for the 7 different existing embankments. Construction of toe berms changes the overall geometry of the embankments; therefore, the FoS and settlement change accordingly as shown in Table 15. The traffic capacities of affected network links are also degraded accordingly; therefore, optimization was conducted using the new traffic capacities to examine the effect of implementing the mitigation measure.

Table 14. Dimensions of toe berm sections

Toe berm for embankment section No.	Top width (m)	Height (m)	Slope (Vertical:Horizontal)
1	8	2	1:3
2	13.5	2.5	1:3.75
3	15	2	1:3
4	9	2	1:3
5	17	2	1:3
6	20	2	1:3
7	7	1	1:3

Table 15. FoS and settlement of embankments with toe berms for hazard scenario 1

Embankment section No.	Initial FoS	FoS after 6 hours	Initial settlement (mm)	Settlement after 6 hours (mm)
1a	1.904	0.929	29.0	31.3
2a	1.357	0.669	11.5	11.7
3a	1.897	0.941	3.81	3.88
4a	1.894	1.30	22.7	22.7
5a	1.901	0.942	11.7	15.4
6a	1.885	0.977	4.2	4.2
7a	2.52	1.50	12.8	13.3

In this case study, embankments with three different geometric sections were considered affected: section No. 4, 6, and 7 or embankments with toe berms section No. 4a, 6a, and 7a. The possibility of retrofitting was determined based on the FoSs because the settlements of the affected embankments do not exceed the threshold 50 mm. In response scenario 1, in which toe berms were not constructed, embankments in link No. 2, 10, and 21 (see Figure 8) that have section No. 4 and 6 cannot be retrofitted because their FoSs are less than 1.0 after the flood (see Table 13). Therefore, reconstruction is completed for those embankments instead. In response scenario 4, in which toe berms were constructed prior to the flood as a mitigation measure, embankments in link No. 10 that have section No. 6 are reconstructed instead of being retrofitted because their FoSs are less than 1.0 (see Table 15). Hypothetical construction times were assumed depending on the type of rehabilitation action and the presence of toe berms prior to the flood. For example, retrofitting generally takes less time to complete compared to reconstruction. Toe berms lessen the damage of flood; therefore, shorter construction time for rehabilitation was assumed in response scenarios 1 and 4. The assessment period was assumed to be 15 days for all response scenarios.

The effectiveness of different response scenarios (Table 12) was evaluated based on (i) the improvement of the highway embankments using the resilience metrics which reflect the four aspects of resilience — robustness, rapidity, resourcefulness, and redundancy, and (ii) the technical, economic, environmental, and social impacts that have resulted from implementing the mitigation and rehabilitation strategies. The robustness aspect of resilience was estimated using Equations [34]-[35] for every affected embankment. It was assumed that embankments eventually reach at least FoS of 2 and their initial settlement after rehabilitation is completed.

Since it was assumed that five different links in the transportation network are affected by the hazard scenarios, the average change in FoSs and settlements were computed. Figure 10 and Figure 11 show the average change in FoSs and settlements of the affected embankments normalized with respect to the initial FoS and settlement, respectively. Table 16 shows the average robustness of affected embankments in terms of slope stability (FoS) and settlement for all response scenarios.

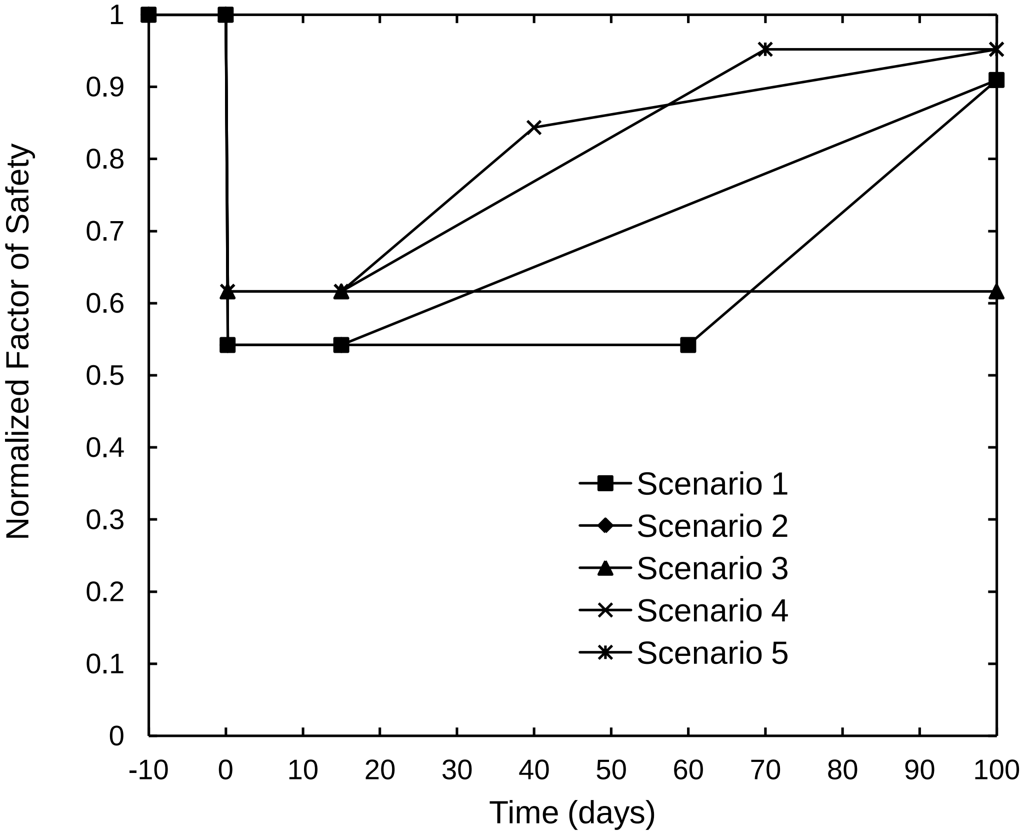

Figure 10. Change in FoS for hazard scenario 1

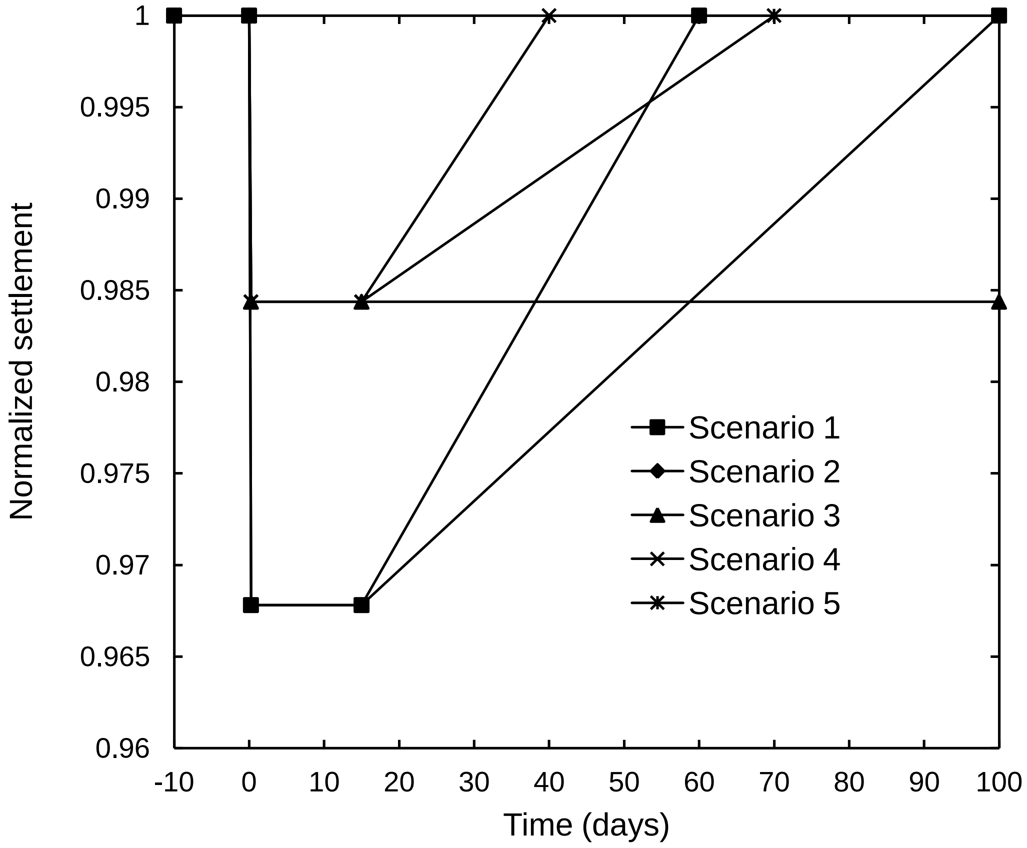

Figure 11. Change in settlement for hazard scenario 1

Table 16. Robustness of road embankments in hazard scenario 1

Response scenario	Robustness (FoS)	Robustness (settlement, mm)
1	1.41	0.74
2	1.07	0.74
3	0.83	0.2
4	0.83	0.2
5	0.83	0.2

Rapidity corresponds to the speed of recovery to reach the full level recovery as shown in Equations [36]-[37]. Table 17 summarizes the average rapidity of recovery in absolute values for the five response scenarios based on Figure 10 and Figure 11.

Table 17. Rapidity of embankments recovery in hazard scenario 1

Response scenario	FoS/day	Settlement/day
1	0.00368	0.203
2	0.00697	0.203
3	0	0
4	0.00686	0.383
5	0.00982	0.218

Resilience in terms of FoS and settlement can be computed using Equation [1] by considering the change in FoS and settlement, shown in Figure 10 and Figure 11, as performance functions, $Q(t)$. Table 18 summarizes the resilience in terms of FoS and settlement for the response scenarios — resilience was calculated by integrating the area under the curves in Figure 10 and Figure 11 following Equation [1]. In this case study, 100 days of inspection time t_h were assumed.

Table 18. Resilience in terms of FoS and settlement

Response scenario	Resilience (Equation [1])	
	FoS	Settlement
1	0.690	0.904
2	0.699	0.908
3	0.617	0.949
4	0.814	0.963
5	0.810	0.978

To calculate the redundancy aspect of resilience, entropy of the transportation network considered in this study was computed using Equation [47]. The entropies for the different response scenarios were computed based on the change in traffic volumes after rehabilitation actions were completed. The traffic volumes used in the computation were obtained from the optimization and are given in Table 19. The change in network entropy over time, shown in Figure 12, is expressed in a normalized measurement with respect to the entropy at normal condition of the transportation network.

Table 19. Traffic volumes in AADT

Network link No.	Normal condition	Response scenario				
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
1	461858	397239	461858	459603	462667	461858
2	223651	0	223651	217391	220539	223651
3	235381	388821	235381	240404	237628	235381
4	298530	439832	298530	300403	298537	298530
5	201470	80147	201470	199597	201463	201470
6	119580	134895	119580	99281	98175	119580
7	31894	23194	31894	20177	20792	31894
8	169575	97026	169575	179420	180671	169575
9	88590	118015	88590	119459	118967	88590
10	62884	0	62884	0	0	62884
11	241834	306831	241834	201121	200363	241834
12	241834	306831	241834	201121	200363	241834
13	258166	193169	258166	298879	299637	258166
14	178950	306831	178950	201121	200363	178950
15	38142	102761	38142	40397	37333	38142
16	40968	111179	40968	42205	41833	40968
17	2826	42468	2826	1808	4500	2826
18	40968	111179	40968	42205	41833	40968
19	28007	73237	28007	28762	28746	28007
20	14432	67539	14432	12010	12528	14432
21	222180	0	222180	218824	221098	222180
22	20710	0	20710	19227	19636	20710
23	263388	432461	263388	269166	266374	263388

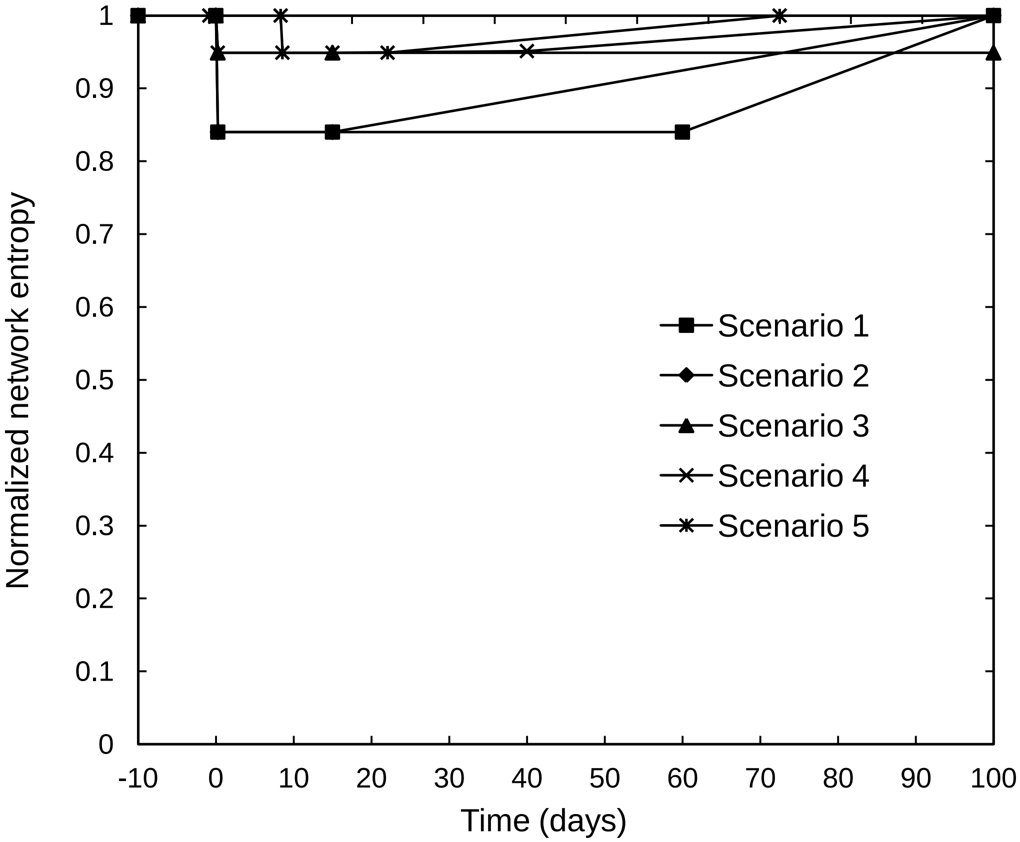

Figure 12. Change in network entropy for hazard scenario 1

Resilience in terms of network entropy was computed by considering the change in network entropy, shown in Figure 12, as a performance function in Equation [1]. Table 20 provides resilience calculated using Equation [1] in terms of network entropy for the response scenarios.

Table 20. Resilience in terms of network entropy

Response scenario	Resilience (network entropy)
1	0.904
2	0.908
3	0.949
4	0.963
5	0.978

Because of the delayed traffic and increased travel time, leisure time of individuals is expected to decrease throughout the flood event and rehabilitation period. According to Statistics Canada (2005) the average leisure time of an individual who resides in Ontario is 324 minutes per day. The decrease in leisure time was estimated by the average delay duration of all 43 possible routes to travel from London to Toronto. The delays in travel time can be calculated by comparing the travel times under post-disaster conditions to the travel times under normal-operation condition. Figure 13 shows the change in leisure time, normalized with respect to the standard leisure time (324 minutes), as embankments undergo different response scenarios.

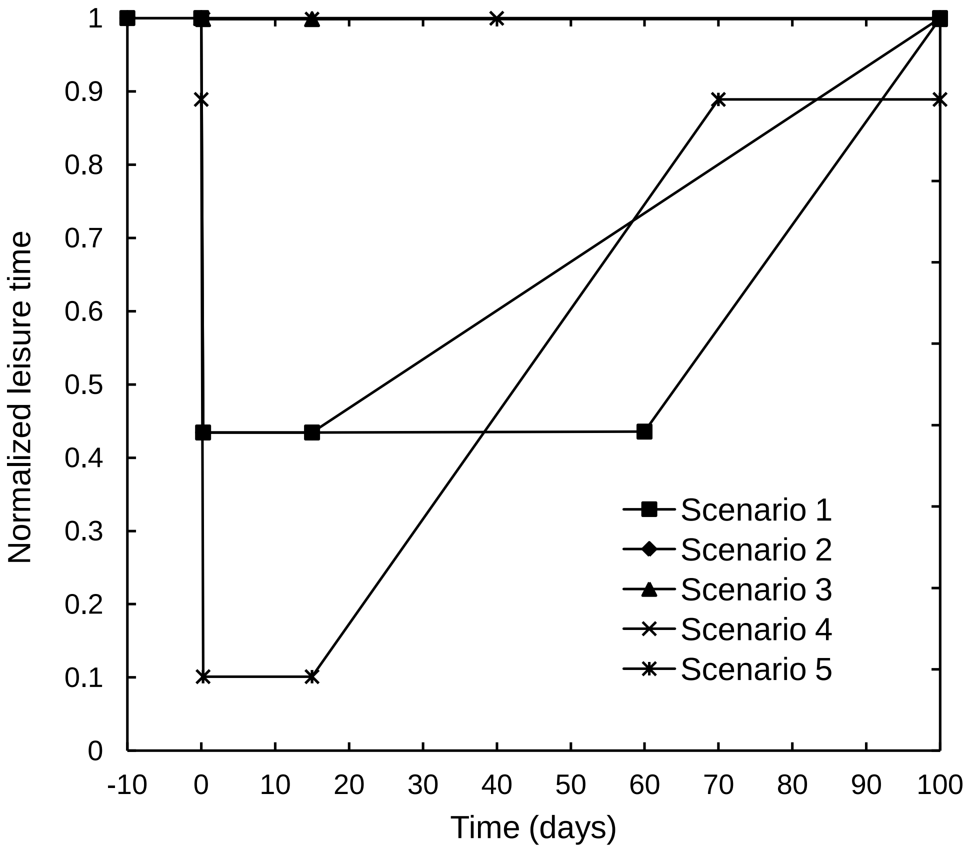

Figure 13. Change in leisure time for hazard scenario 1

The change in leisure time over time can also represent a performance function; therefore, resilience in terms of leisure time was calculated (using Equation [1]) and provided in Table 21.

Table 21. Resilience in terms of leisure time

Response scenario	Resilience (leisure time)
1	0.436
2	0.675
3	0.150
4	0.999
5	0.999

The construction cost data by RSMeans (2014) was referred to here for estimating the construction costs incurred for the mitigation measure, retrofitting, and complete reconstruction of embankments (Figure 14 and Table 22). The types of construction activities considered in the cost estimation were installation of barricades, clearing debris, spreading new embankment fills, compacting fills, and installation of new sodding.

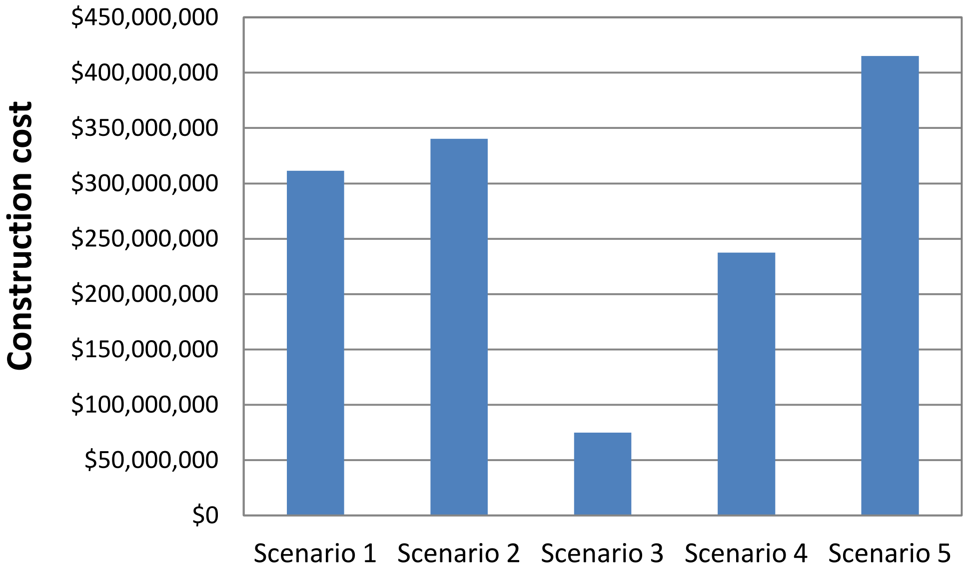

Figure 14. Construction costs in hazard scenario 1

Table 22. Construction costs for mitigation and rehabilitation in hazard scenario 1

Construction activity	Woodstuck-Cambridge	Junction-Oakville	Woodstuck-Stratford	Cambridge-Hamilton	Cambridge-Morriston
Complete reconstruction	$ 212 334 748	$ 28 592 606	$ 48 363 629	$ 51 090 258	$ 116 875 068
Berm installation	$ 34 718 182	$ 6 673 118	$ 16 359 318	$ 17 080 236	$ 20 978 798
Retrofitting (no berms)	$ 96 875 728	$ 11 977 675	$ 34 379 217	$ 36 229 442	$ 54 538 036
Retrofitting (berms)	$ 90 529 543	$ 7 419 149	$ 21 257 809	$ 22 285 713	$ 51 111 692

Using Equation [38], the resourcefulness aspect of resilience was calculated as the relative cost of mitigation and rehabilitation constructions (Table 12) to the operation expense budget of Ministry of Transportation Ontario (MTO) on provincial highway management ($ 363 944 485) obtained from expense estimates report by Ministry of Finance (2015). The resourcefulness of embankments for the five response scenarios are provided in Table 23.

Table 23. Resourcefulness of recovery in hazard scenario 1

Response scenario	Resourcefulness
1	0.29
2	0.31
3	0.07
4	0.22
5	0.38

Life cycle assessment (LCA) was conducted to quantify environmental impacts such as global warming, terrestrial acidification, freshwater ecotoxicity, terrestrial ecotoxicity, photochemical oxidant formation, and human toxicity. Figure 15 shows the normalized environmental impacts with respect to the maximum value obtained in the respective impact category as summarized in Table 24. For example, global warming potentials (GWP) for the five response scenarios were normalized with respect to their maximum value, 1.70×10^{14} kg of CO_2. All impact categories are greatly influenced by the hauling of embankment fills and have the same normalized values as shown in Figure 15. The social impacts were estimated by the damage to human health measured in disability-adjusted loss of life years (DALY). Damage to human health was also estimated using LCA and is caused by airborne chemicals toxic to human, infra-red radiation, and concentrated photochemical ozone (Goedkoop et al., 2013). The human health impacts were normalized by the same methodology performed for the environmental impact analysis, and the values and trends are the same as shown in Figure 15. The human health impacts are also greatly influenced by hauling embankment fills while the impacts from operation of machineries and hauling machineries are negligible. Therefore, Table 25 summarizes the both actual and normalized human health impacts caused by hauling embankments only.

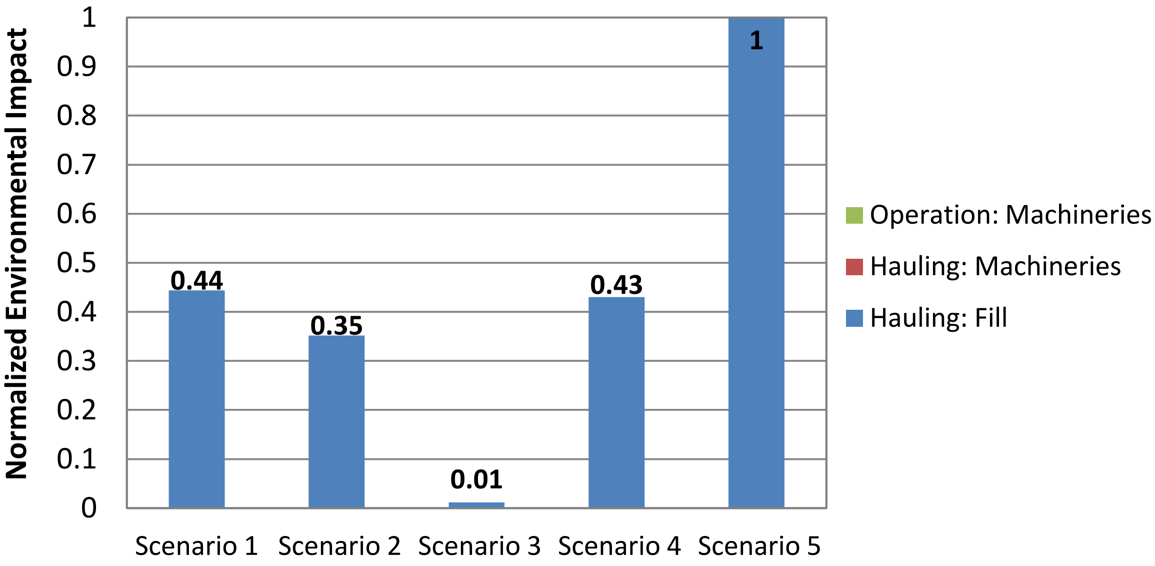

Figure 15. Normalized environmental impacts for hazard scenario 1

Table 24. Maximum values used for normalizing environmental impacts

Environmental impact	Maximum value	Unit
Global warming	1.70×10^{14}	Kg of CO_2
Terrestrial acidification	1.05×10^{12}	Kg of SO_2
Photochemical oxidant formation	1.09×10^{12}	Kg of NMVOC[1]
Freshwater ecotoxicity	3401647	Kg of 1,4-DB[2]
Terrestrial ecotoxicity	3373681	Kg of 1,4-DB
Human toxicity	959526353	Kg of 1,4-DB

[1] NMVOC = Non-methane volatile organic carbon compound

[2] 1,4-DB = 1,4 dichlorobenzene

Table 25. Human health impacts in DALY

Response scenario	Infra-red radiation	Photochemical ozone	Human toxic emission	Normalized Human health impact
1	105503533	18886	298	0.44
2	83526238	14952	236	0.35
3	2827564	506	8	0.01
4	102185699	18292	289	0.43
5	237644768	42540	672	1

Considering all aspects of sustainability and resilience, it is apparent that response scenarios 4 and 5 are the most resilient options. However, considering the sustainability aspects, i.e., environmental impacts and human health impacts, scenario 4 seems to be the best option.

CHAPTER 5. CONCLUSIONS

Resilience is generally considered as the ability of a system to bounce back following a failure. This concept brings a different perspective on how systems should be designed and maintained in order to mitigate and prepare for external shocks. Systems designed with conventional risk-based methods may be robust against known or expected disturbances; however, they remain vulnerable against unexpected shocks especially those with low probability and high consequences. Therefore, it is necessary that design and management of critical civil infrastructures incorporate resilience thinking so that these infrastructures are prepared to withstand disturbances such as climate change, natural and man-made disasters. Resilience in infrastructure systems is not just about protecting and recovering the technical aspects, but also improving the resilience in local communities, local economy, associated environmental systems, and any other systems that may be affected by the functionality of the infrastructure systems. In order to understand resilience from multiple points of view, the concept was studied across different disciplines like ecology, social science, economy, and engineering. From the literature review, the key aspects of resilience were identified which include, robustness, rapidity, resourcefulness, redundancy, adaptability, and transformability.

A quantitative framework for assessing the resilience of geotechnical infrastructure against various hazard scenarios was presented in this thesis. The DPSIR framework was utilized and reinterpreted for the development of the proposed framework so that it is applicable to geotechnical infrastructure systems. In this study, the proposed framework was demonstrated using a case study of road embankments in a transportation network in the province of Ontario subjected to floods. Hazard scenarios on floods were generated with varying rainfall intensities. Metrics which reflect the robustness, rapidity, resourcefulness, and redundancy aspects of resilience were developed to evaluate multiple aspects of resilience in the network of road embankments. The robustness aspect of resilience was computed based on the change in factor of safety and settlement of road embankments during the floods. The rapidity was calculated by the speed of recovery in terms of factor of safety and settlement. The resourcefulness was expressed in terms of proportional cost of repair and construction with respect to the available provincial budget. The redundancy aspect was calculated in terms of network entropy that indicated how distributed the network is after disruptions caused by flood. The social aspect of resilience was captured by calculating the loss of leisure time for commuters because of traffic delay.

Life cycle assessment was utilized to measure the environmental impacts of the damaged road embankment network; economic losses were quantified by estimating construction costs for mitigation and restoration actions, social impacts were measured in terms of human health damage; and technical impacts were quantified by the change in traffic volumes and travel times after the disruptions. The change in factor of safety, settlement, network entropy, and leisure time were considered as performance functions to compute the resilience of the transportation network consisting of road embankments. Five response strategies that have different combinations of mitigation and rehabilitation actions were generated and evaluated based on the calculations using all relevant metrics that consider the resilience and impacts explained above. Construction of toe berms was considered as a mitigation measure to improve the slope stability of embankments and lessen the damage of floods. The response strategies incorporate approaches to improve adaptability and transformability of the embankments. Retrofitting and reconstruction of damaged embankments by the floods were considered as methods to improve the adaptability and transformability, respectively.

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