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Stress tests for a road network using fragility functions and functional capacity loss functions

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ABSTRACT

A quantitative approach to conduct a specific type of stress test on road networks is presented in this article. The objective is to help network managers determine whether their networks would perform adequately during and after the occurrence of hazard events. Conducting a stress test requires (i) modifying an existing risk model (i.e., a model to estimate the probable consequences of hazard events) by representing at least one uncertainty in the model with values that are considerably worse than median or mean values, and (ii) developing criteria to conclude if the network has an adequate post-hazard performance. Specifically, the stress test conducted in this work is focused on the uncertain behavior of individual objects that are part of a network when these are subjected to hazard loads. Here, the relationships between object behavior and hazard load are modeled using fragility functions and functional capacity loss functions. To illustrate the quantitative approach, a stress test is conducted for an example road network in Switzerland, which is affected by floods and rainfall-triggered mudflows. Beyond the focus of the stress test, this work highlights the importance of using a probabilistic approach when conducting stress tests for temporal and spatially distributed networks.

1. Introduction

Managers of networks (often also referred to as infrastructure; e.g., road, drinking water distribution, or power transmission) rely on a variety of methods to estimate their network-related risk (i.e., probable consequences) due to the occurrence of (natural) hazard events (e.g., floods, landslides, and earthquakes). The estimation of risk is the initial step in determining if the network would have an adequate post-hazard (physical and functional) performance—assuming that such a performance is measured in terms of risk—and if risk-reducing interventions are necessary. Examples of risk include:

- those related to physical performance such as the probable cost of restoring individual structures, which are here referred to as objects (e.g., bridges, water pipes, or transmission towers), and
- those related to functional performance such as the probable cost absorbed by society because of changes in the network's level of service, which is here referred to as network functional capacity (e.g., connectivity between two points in the network).

Quantitative risk assessment methods offer an advantage over qualitative methods: the numerical characterization of the events and their relationships needed to estimate risk, which leads to a more refined estimation. As suggested by Hackl et al. [1], who built on the work of Adey et al. [2], these events can be classified as source, hazard, object, network and societal events. Table 1 describes these events, and provides examples.

Considering this classification and the use of a model to quantitatively estimate probable consequences (i.e., risk model), risk can be represented by the notation in Eq. (1). This notation designates the output (Out) of the model (Mod) to be the estimated risk ($Risk$). The risk model simulates the relationships (Rel) between all the observed in the scenarios of the system state space. The system state space can be constructed/enumerated by taking the (Cartesian) product of related temporally (t) and spatially (s) bounded source ($\overline{Scr_{t,s}}$), hazard ($\overline{Haz_{t,s}}$),

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Table 1
Classification of events and examples.

Event	Description	Example
Source	An event that may lead to a hazard event	• Fault rupture
Hazard	An event that may lead to an object event, and sometimes, to another (cascading) hazard event	• Strong ground-motion • Ground-motion-triggered landslides
Object	An event that represents a change in the object, which may lead to a change in network use and/or human behavior	• Bridge failure due to ground movement • Road damages due ground deformation
Network	An event that represents a change in how the network can be used, which may lead to a change in human behavior	• Loss of connectivity between two communities due to failed bridge and damaged roads
Societal	An event that represents a change in human behavior	• Restoration interventions • Re-routing of vehicles

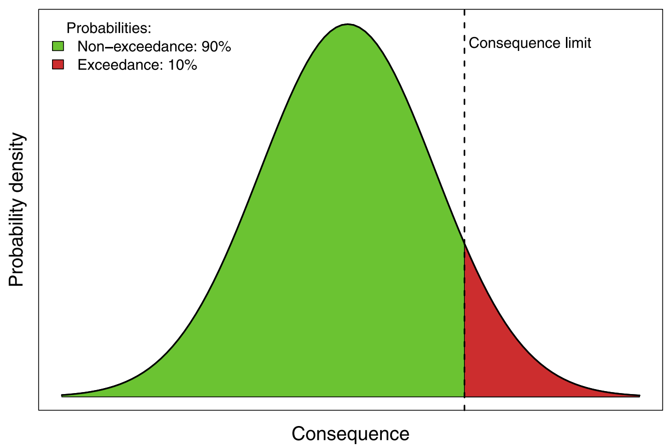

Fig. 1. Illustrative risk distribution described by adequate post-hazard performance.

object ($\overline{Obj_{t,s}}$), network ($\overline{Net_{t,s}}$) and societal ($\overline{Soc_{t,s}}$) events. Each of these—noted by an overbar—is a vector of events, or a vector of a Cartesian product of events when more than one event per category is of interest (e.g., earthquake hazard and earthquake-triggered landslide hazard). Events, and therefore scenarios, are linked to probabilities of occurrence. To accomplish this simulation, the risk model includes a number of sub-models that simulate individual events and their corresponding relationships.

$$Risk = Out\left(Mod\left(Rel\left(\overline{Scr_{t,s}} \times \overline{Haz_{t,s}} \times \overline{Obj_{t,s}} \times \overline{Net_{t,s}} \times \overline{Soc_{t,s}} \right) \right) \right) \quad (1)$$

When considering a large range of possible events along with their probabilities of occurrence given a desired set of scenarios, the output risk will be a distribution—for the purpose of the following illustration, it is here assumed that a risk model can estimate a distribution like the one presented in Fig. 1.

When a network manager can describe adequate post-hazard performance for the network in terms of risk, then this information can be used to interpret the resulting risk distribution. Adequate post-hazard performance can be evaluated against:

- a consequence indicator (i.e., the type of consequence that the network manager would use to measure performance; e.g., average additional travel time per vehicle immediately after the occurrence of a hazard event, cost of repairs),
- a consequence limit [i.e., the maximum consequence that the network manager would accept to observe if a hazard event occurs; e.g., a 10% increase in the average additional travel time per vehicle within the month following the occurrence of a hazard event, cost of repairs amounting to 0.1% of the regional Gross Domestic Product (GDP)], and
- the non-exceedance probability of that consequence limit (i.e., the probability that an observed consequence resulting from a hazard event will not exceed the consequence limit; e.g., a 90% probability that at most a 10% increase in the average additional travel time per vehicle in the month following the hazard event will be observed, a 95% probability that at most the cost of repairs will amount to 0.1% of the regional GDP).

To illustrate this, Fig. 1 shows: a consequence limit (vertical dotted line) and a calculated 90% non-exceedance probability (ratio between the green area under the curve and the entire area under the curve). Given this information, network managers would need to decide whether a 90% non-exceedance probability means that risk-reducing interventions should be executed, or not.

When the composition of the risk model changes, then the network manager can expect to obtain a different risk distribution, and therefore, observe a different consequence limit non-exceedance probability. Changes can occur when network managers are seeking to:

- reduce the uncertainty of the results due to improved knowledge, for example:
  - the execution of a traffic load analysis to determine the load carrying capacity of a bridge in the network after a simulated earthquake event rather than the use of a capacity heuristically approximated by experienced bridge engineers when computer support increases, or
  - the replacement of a macro traffic sub-model for a micro traffic sub-model when the resolution of the analysis is part of a city and more data are available, or
- better quantify the uncertainty, for example:
  - the consideration of a larger number of possible hazard events by extending the maximum considered return period,
  - the random application of interchangeable ground motion prediction equations (GMPEs) during the modeling of the earthquake event, or
  - the characterization of the number of available crews for post-hazard restoration interventions by a probability distribution instead of using an expected quantity.

In these cases, which this work refers to as model updating, the consequence limit should remain the same despite changes in the estimated risk. Fig. 2 shows the illustrative distribution with reduced uncertainty as well as the reevaluation of risk based on the same consequence limit. It is here observed that the new consequence limit non-exceedance probability is 97%. This means that network managers may be now more inclined to not execute interventions to reduce risk.

A network manager can also change a risk model by representing at least one uncertainty (i.e., an uncertain element of the risk model; i.e., events, relationships, parameters) with a subset of probable values (i.e.,