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An overarching process to evaluate risks associated with infrastructure networks due to natural hazards.

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Extended Abstract

1. Introduction

Infrastructure networks are the backbone of modern society. If they do not work as intended, which can happen due to natural hazards, there is a high probability that there will be significant consequences (Bensi 2011). This can be predominantly attributed to system effects both during the hazard and following the hazard, and depends greatly on how all of the objects within the affected infrastructure networks behave, and how fast and how they will be restored so that they once again provide an adequate level of service. People who manage infrastructure, herein referred to as infrastructure managers, have to handle these risks. Each infrastructure manager relies on his own risk management processes. These processes are systematic, timely and structured processes that when followed will provide the infrastructure manager with a better understanding of what may go wrong with the system in which the infrastructure is embedded, the probability of this happening and the associated consequences. This risk assessment process is particularly challenging for managers of infrastructure networks, due to the large number of scenarios that need to be analysed in order to assess the risks appropriately, the spatial and temporal correlations between these events (MOVE 2011), and the correlation between event occurrences, or so called cascading events (Garcia-Aristizabal & Marzocchi 2011).

In addition to the challenges in the physical world, the process is made even more complex because the risk assessment process requires that persons work together from many different disciplines who each have their own discipline based approaches to risk assessment that are not always harmonious with those in other disciplines. This makes it so that independent risk assessments from different persons are not always easy to aggregate to a level that is useful for the infrastructure manager.

The overarching process presented in this article is meant to be helpful to infrastructure managers who want to assess the infrastructure related risks due to natural hazards. It is to be used to help bring together people from many different disciplines so that they can provide information in a way that will be useful to an infrastructure manager. It has been specifically developed to deal with road and rail infrastructure networks but it is believed to be generally applicable to all types of infrastructure networks. The proposed overarching process is meant to fit within the risk management process of any infrastructure owner. This process is developed so that it can be coupled with detailed sub-processes to achieve varying levels of detail in risk assessment. This flexibility ensures that the overarching process is applicable for different types of infrastructure, different types of hazards, different levels of detail in the assessment, different sizes of regions, different types of regions and different levels of abstraction. It is also developed to ensure that the temporal and spatial correlation of events can be considered.

The work was carried out in the scope of the European project INFRARISK, with the aim to develop reliable stress tests to establish the resilience of European road and rail network infrastructure to rare low frequency extreme events and to aid decision making in the long term regarding robust infrastructure development and protection of existing infrastructure. This article is a summary of Hackl et al. (2014). Additional information also can be found in the report Adey et al. (2014) which was submitted as a deliverable in the INFRARISK project. The work builds on that done for the Swiss Federal Roads Authority in 2005 (Adey et al. 2009; Adey et al. 2010).

2. Overarching Process

The overarching process is based on the ISO 31000 (2009), including different principle activities: communicating and consulting, establishing the context, and identifying, analysing, evaluating, treating, monitoring and reviewing risk. Beside the basic concepts of the ISO 31000, the proposed framework has been extended to allow explicit consideration of the spatial and temporal correlation between hazards as well as the modelling of the functional interdependencies between multiple elements in the infrastructure networks, including physical dependencies, cybernetic dependencies, geographical dependencies and the modelling of impacts. The process is described using generic definitions of sources, hazards, objects of the network and the network itself, which eases the application to different decision-making situations.

It is constructed keeping in mind that for many decision-making situations it will be desired to have the process be computer supported, for example to model specific parts of the system. It has also been constructed keeping in mind that different decision situations will require the use of different types of models and models that will provide different levels of detail.

In the following, a brief overview of the different subprocesses of the overarching risk assessment is given.

2.1 Problem Identification

The first step is to identify the question to be answered. This step includes the generation of preliminary thoughts on the area to be investigated. It is only once this question is identified that a meaningful risk assessment can be conducted.

2.2 System Definition

The system definition is a model of the relevant part of reality used for the evaluation and consists of all relevant realizations of stochastic processes within the investigated time period. It includes sufficiently good representations of the hazards, infrastructure, and consequences, as well as the interaction between them so that it can be reasonably certain that there is an appropriate understanding of the system and that the risks and the effectiveness of the strategies can be determined.

2.2.1 Boundaries

By establishing spatial boundaries, the part of the natural and man-made environment to be specifically modeled is determined. By establishing temporal boundaries, the time period over which risk is to be assessed is fixed, as well as how this time period is to be subdivided for analysis purposes.

2.2.2 Elements

It is proposed to group the system elements from initiating events to the events that are considered to be quantifiable and no further analysis is required. In the assessment of risk related to infrastructure due to natural hazards, one can label these further as "hazard elements" and "consequence elements". Although the number of element types to be considered vary depending on the type of problem and the desired level of detail.

Each element type is considered to correspond with events, which can be considered to have a probability of occurrence. Five basic element types, or event types, that should be regularly considered are:

Source events, or initiating events, are events, which occur regularly (rainfall, tectonic plates movements, ground movement etc.). The occurrence of such an event does not necessarily mean that a hazard will be triggered.

Hazard events, or loading events, are events related to any earlier event or that may lead to consequences. A hazard always has a source event. It may also trigger another one (e.g. earthquake triggers landslide). Most hazards evolve through space and time and interact with their environment. In defining the hazards to be considered it is important to define the intensities of the hazards to be considered.

Infrastructure events include all the objects and the condition states of these objects to be considered, e.g. a bridge collapse is an infrastructure event. How the infrastructure networks to be modelled are subdivided into infrastructure objects depends on the specific problem and the level of detail desired in the risk assessment. In the development of the system representation it is important to consider which infrastructure objects are affected by which hazard and how the states of these objects may change over time. An example of a value that could be assigned to this element type may be the cost of reconstruction of the infrastructure object if damaged. This value depends on the level of damage that might happen and how the infrastructure manager plans to intervene on the object if it is damaged.

Network use events include the states of use of the infrastructure network that might occur. The probabilities of these events occurring are particularly difficult to estimate as their occurrence depends on spatial and temporal correlation, and physical relationships between initiating events, hazards and infrastructure events. The latter, which can lead to cascading events. An example of a value that can be assigned to this element type is the cost of deviating traffic around a closed road. Another example is the value of lost travel time due to the closed link.

Societal events include the actions of persons or groups of persons. In order to model the actions of persons or groups of persons it is often beneficial to group them into categories based on their general behavior, which in turn is coupled with how their behavior is to be modelled. Societal events may lead to other societal events. If they, however, do not then a value needs to be assigned to the event. This value then enters the risk assessment as a consequence.

2.2.3 Relationships

In order to estimate the likelihood of each subsequent event in the causal chain of events appropriate models of the relationship between them are to be developed. The amount of effort to be invested in this depends on the exact problem and the level of detail desired. In general, extra effort should be spent to achieve more detail when it is suspected that the results will add additional clarity for decision-making. If possible the availability of data to be used to model the relationships should be taken into consideration in determining the level of detail to be used.

2.3 Risk Identification

In the previous step emphasis is made on identifying the correct system elements to be used in the risk assessment and how to model the relationships between these. In its most extensive form the definition of these elements and relationships will provide all possible scenarios, or risks. As it is unrealistic to attempt to quantify all of these it is necessary to identify the specific scenarios that are to be part of the risk assessment.

Comprehensive identification of relevant scenarios is critical, because scenarios excluded in this step will not be included in further analysis and may result in an underestimation of risk. To minimize the possibility of this happening it is important that experts in each area are involved.

2.4 Risk Analysis

The analysis of risk has to do with estimating the probability of occurrence of the scenarios and the value of the consequences of the scenario if it occurs. It is only through doing this that an infrastructure manager can decide if action needs to be taken and if multiple options are available, which one is the best. It can be done using a qualitative or a quantitative approach. In both cases, however, the goal is to gain a better understanding of the probability of occurrence of a scenario and the consequence of that scenario.

2.5 Risk Evaluation

Risk evaluation has to do with verifying the meaning of the estimated risk to persons that may be affected. This is true regardless if a qualitative or a quantitative approach is used. A large part of this evaluation is the consideration of how people perceive risks and the consideration of this over- or under-valuation with respect to the analyst’s point of view used in the risk analysis step of the risk assessment.

3. Modules

The proposed risk assessment process is constructed in a way so that computational support can be constructed in modules. Providing a platform in which the necessary modules can be integrated does this. A module is a self-contained set of (computational) instructions with unambiguously defined input and output interfaces. Inputs are either provided via external input (e.g. user input) or via internal input (i.e. by using outputs of other modules generating compatible datasets). Therefore, each module interacts with other modules by receiving and delivering information. The type of information to be exchanged between modules is to be constant. Modules can perform a function itself or can be composed of sub-modules that each performs functions. The modular construction was chosen to allow continual updating of models as new information becomes available or better or detailed models are developed. The content of the modules depends on the established context of the risk management process. Thereby, modules can be described in terms of the functions they perform (e.g. a specific quantitative model) and the data they exchange.

In order to provide an efficient and accurate risk analysis the structure of the models and the framework in which they are embedded have to be adapted for their specific needs. For example, a damage calculation module that evaluates damage curves for streets based on inundation values may only take one inundation file for execution. Therefore, this module needs to be executed for each time step separately. Other modules may in contrast need a time series as input and therefore only need to be executed once. Relationships between modules are defined through the order of execution (module 2 can only be executed after the data of module 1 is present) as well as the data to be exchanged. For example, a damage calculation module needs inundation depths stored in a file of type raster. This raster is provided by a flood calculation module which produces this kind of data.

Additionally, there might be implicit assumptions for certain datasets. For example, when analysing geodata, typically it is adopted that the datasets use the same Coordinate Reference System and lie within a similar extent. Infrastructure managers do not necessarily create modules themselves since it can be assumed that certain tasks, existing tools can be reused and assembled. Also, one module may be reused within several configurations.

The different modules need different information for the risk assessment. The type of input and output of each module has to be specified. In some cases this is done through the problem identification and the system definition steps of the process.

An information exchange structure has to be constructed together with the experts, stakeholders and infrastructure managers. For instance, for each module things such as the area of application, the type of model, or the kind of intensity measurement, have to be specified. Data compatibility between modules is ensured through the concepts of syntactic and semantic interoperability. According to IEEE (1990), interoperability is defined as "the ability of two or more systems or components to exchange data and use information". In the context of the overarching methodology, these systems or components are represented in the form of modules.

Once, the modules and data are assembled appropriately, the infrastructure manager may perform simulations based on this framework. Running a simulation when specific external inputs are provided does this. These inputs may be defined by the infrastructure manager or potentially automatically when performing multiple runs (e.g. by sampling a certain distribution using the Monte Carlo Method).

4. Example

In this section, the use of the overarching process is demonstrated by using it to evaluate infrastructure related risk due to natural hazards for an example region. For the sake of simplicity, the example is presented in a sequential manner, although the process itself is highly iterative. The results of this example should be treated with care since only very simple physical models are used to evaluate the risk.

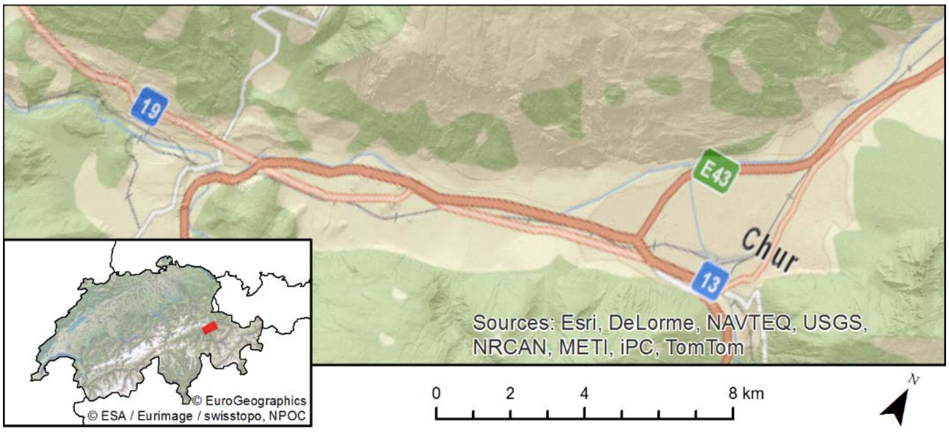

Figure 1: *Overview of the area of interest.*

4.1 Problem Identification

The target area is located around the city of Chur, the local capital of the easternmost Canton of Switzerland, Graubünden. The region is home to companies of different sectors such as finance, engineering and chemistry and its road network is part of one of two major transports links for goods from Italy to Northern Switzerland. Also, the main station of Chur is an important railway junction to other regions of Graubünden. Most of these objects are located in a valley between several mountains with many watercourses draining into the main river Rhine.

The addressee of this risk assessment is the city administration being interested in damage, cost and other consequences resulting from a low probability/high impact natural hazard scenario in the Chur region consisting of a coupled flood and landslide event.

4.2 System Definition

4.2.1 Boundaries

The spatial boundary of the system has been selected to be that shown in Figure 1. The system is spatially bordered by a bounding polygon which is aligned to the main valley of the region of interest and covers an area of approximately 150 km^2. Since the focus lies on the main watercourses, only those watercourses are taken into account.

The risk assessment is done for a flood hazard with a return period of 500 years. The occurrence of this hazard takes 3 days, i.e. water rises slowly and inundated the surrounding areas, and finally the flood water goes down. To compare the risk with other cities and regions, the losses resulting from this analysis are converted into an average annualized loss.

4.2.2 Elements

Source event precipitation: The model of precipitation was constructed using the precipitation data from a historical event which occurred from 07.08.2007 to 09.08.2007 and is scaled in such a way that it corresponds to a precipitation event resulting in a flood with a return period of 500 years.

Hazard event flood: The model of the amount of water on each land surface area and in the rivers was developed using a set of interrelated tools.

Hazard event landslide: In this scenario, the increase in soil saturation due to precipitation triggers one of the pre-modelled debris flows from the SilvaProtect project (Losey & Wehrli 2013) affecting the small town of Haldenstein.

Infrastructure event residential and industrial buildings: Information on buildings on the footprint level are taken from the swissBUILDINGS3D dataset (swisstopo).

Infrastructure event hospitals: In the area of interest, only one institution is present for ambulant care, the hospital of the Canton of Graubünden.

Infrastructure event road segments: Since road geometries for the target area can have lengths up to several hundred metres, these are partitioned in such a way that a spatial analysis can be undertaken on a feasible resolution. For this application, a segmentation interval of 4m was considered to give a reasonable trade-off between computational effort and accuracy.

Network events: The road network for the target area is extracted from the VECTOR25 dataset. Each road is represented by a linear geometry with assigned attributes on their type (swisstopo).

Societal events: Societal events are how the traffic behaves on the network when it is not fully operational. It is estimated using traffic simulations to estimate how much additional time is required to travel from anywhere in the hospital catchment area to the hospital.

4.2.3 Relationships

The interactions between infrastructure networks, elements and components of elements at the one hand side and between hazards, infrastructure and consequences on the other side, should be represented completely. This is necessary to determine dependencies in failure scenarios and evaluate common influencing factors.

Source-Hazard-Interaction: For reasons of simplicity and efficiency only a simple hydrological model for the runoff calculation is used. The ModClark model (Kull & Feldman 1998) is used to estimate the discharge during the precipitation event. This model accounts for retention by using a Linear Reservoir Model (LRM) and translation by taking account a grid-based travel-time model.

Hazard-Infrastructure-Interaction: To estimate damage resulting from inundation, simple damage curves are used. These take into account the inundation depth d, in the range of 0 to 5 m, associated with the infrastructure object and return a dimensionless damage factor $\alpha \in [0,1]$ where 0 represents no damage and 1 represents complete failure. The damage functions associated with the different categories are listed in Deckers, et al. (2010).

Infrastructure-Society-Interaction: It is assumed that if infrastructure is damaged that it would be restored to the condition it had prior to being damaged. These costs are estimated by multiplying the area of the affected object with the unit cost of constructing the object from scratch. For buildings, the area is directly derived from the geometry of the polygon. For roads, the area is calculated by multiplying the length of the linestring with the width associated with the corresponding road type. The unit values used are taken from Kutschera (2008).

Infrastructure-Network-Interaction: Since this connectivity changes during the scenario due to node failure, for each time step a distinct network needs to be created. Impassable road segments due to natural hazards are excluded from the network.

Network-Society-Interaction: The quantification of consequences related to travelling across the network resulting from the failure of infrastructure network nodes was undertaken in terms of the following non-exhaustive list of examples: travel time costs (e.g. man hours of work time lost), vehicle operating costs (e.g. increase of fuel needed), accident costs (e.g. number and type of injuries/deaths), environmental costs (amount of additional nose/pollution) (Adey et al. 2012).

4.3 Risk Identification

The target area has been historically prone to the mentioned natural hazards flooding and landslides. Information on past events are stored in the database "Unwetterschadens-Datenbank" (Hilker et al. 2009) for the period ranging from 1975 to 2007. In addition, two more recent projects, AquaProtect and SilvaProtect (Losey & Wehrli 2013) provide model based information on regions vulnerable to floods and landslides.

Based on the problem identification, the risk assessment was conducted on a medium scale area where buildings are taken into account on the footprint level and streets are represented by connected linear geometries.

For the sake of simplicity, only one scenario is considered. This scenario is comprised of the following events: Source event is rainfall, the hazard events are a flood, defined as being more severe as the largest volume of water expected in the main river expected in 500 years, and a landslide. The infrastructure events are derived from the buildings, road sections and hospitals being in specified damage states. The network events are derived from the different combinations of damage states of the different infrastructure objects. The societal events are derived from modelling the traffic flow results from the different network condition states.

4.4 Risk Analysis

For the risk analysis of the considered scenario a quantitative approach is used. This approach is based on historical information, expert knowledge as well as physical and mathematical models. Depending on the characteristics of the objects in question different approaches are used.

In order to aggregate risk that has been estimated based on the specific scenario, it is necessary to ensure that they are directly comparable and that they are not double counted. There is an especially high chance of this happening when cascading events are part of the scenarios.

The value associated directly to the condition of the infrastructure objects, i.e. the infrastructure events assuming that the objects will be restored to a like new condition at a later point in time, are added. It is assumed that the maximum damage predicted throughout the three-day period is the amount of damage that needs to be repaired. No consideration was made as to how the repair work would be executed or whether or not there would be reduction in costs because multiple objects would be repaired at the same time. Based on the cost associated with the single objects for each time step, the development of the total losses for the whole region of interest can be calculated.

The costs related to the disruption of traffic on the road network are estimated by counting the number of additional hours of travel time that is required on the network while the network is not fully operational. In this case study it is assumed that all road sections are restored to normal immediately following the three-day period.

Figure 2 exemplarily illustrates the results of this process. Here, for each event a pair of maps illustrates one stage of the overarching process in top-to-bottom order. To illustrate the change of the system, the left maps represent the state of the system for time step 20 and the right maps for time step 38.

The *source* maps show heavy rainfall over the region of interest, which decreases towards the end of the simulation period. The *hazard* maps show the maximum inundation depths of the resulting flood for each surface area until the respective time step. It becomes apparent that the maximum inundation depths increase with time, which therefore leads to increasing damages of affected infrastructure objects such as buildings and street segments. This causes rising reconstruction costs, which is shown in the *element* maps for the Haldenstein region. As indicated by the red rectangle in the *hazard* maps, this region is located in the northern part of the area of interest and is affected by flood as well as by the landslide. Because of the damage induced by these hazards, the road networks functionality is reduced as shown in the *network* maps. Here, red road segments indicate that they are isolated from the green main network. Impassable road segments are not shown. This reduced network state results for some regions, in particular in the northern and south-western parts, to be cut off from important infrastructure objects. For example, it is impossible for people in these areas to get to the hospital in Chur as indicated by the *society* maps.

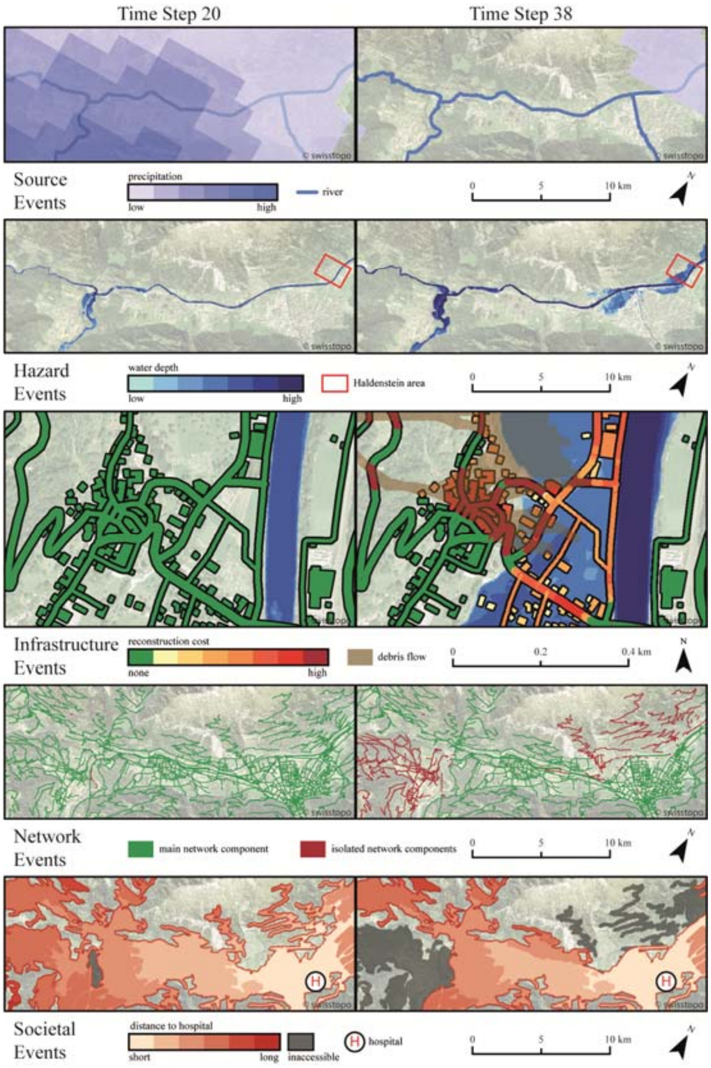

Figure 2: *Example results of the main processes of the overarching methodology for the time steps 20 and 38 for the area under investigation*

4.5 Risk Evaluation

In this paper, risk evaluation is not performed. If a complete risk management process is being conducted this work would need to be done in conjunction with the city administration of Chur. The results coming from the risk analysis would support this task in order to plan further analyses, safety measures or risk treatments.

5. Discussion

The example demonstrates that the proposed overarching risk assessment process is useful to assess infrastructure related risk due to natural hazards. Computer systems can highly accelerate its distinct steps so that the results can be delivered to infrastructure managers in a timely manner. However, in order to refine the results, the methodology needs to be applied to a greater number of scenarios.

The process can be used for a wide range of different problems at different levels of detail. In addition, the changes over time and interactions between different events can be modeled as shown in the example.

Although the proposed overarching risk assessment process can be used conceptionally for all kinds of different problems, its usefulness depends on the quality of available models and data. Often the physical models do not take into account interaction with their environment. For example, if a bridge collapses, the cross-section of the river will be changed, too.

In the presented example a deterministic point of view was chosen. In order to take the numerous uncertainties into account a probabilistic approach seems more suitable, especially when dealing with natural hazards. If one associates a probability of occurrence with the occurrence of the particular precipitation then one could quantify the risk. A more sophisticated example will require the consideration of the not only the probability of occurrence of different rain patterns, but also given the rain fall patterns, the probability of different water run-off events, different levels of water in different parts of the rivers, different behavior of the infrastructure objects in the network, and different behavior of the vehicles on the network. It would also require consideration of larger periods of time, in which multiple rain events occur and perhaps even different types of source events that may result in consequences.

In the expansion of the example to do this there are substantial hurdles with respect to the infinite number of scenarios possible, the uncertainties associated with many different models to be used to make approximations and the temporal changes in the probabilities of event occurrences.

6. Conclusions

This paper describes a generic overarching risk assessment process as well as an example of how it can be used and how it can be implemented using a GIS framework. Even in its current form it is believed that this process would be useful to infrastructure managers in the assessment of their infrastructure related risks due to natural hazards. It is applicable for different types of infrastructure, different types of hazards and different types of consequences and can take into consideration both simple and complex system representations.

The overarching risk assessment process will be further improved by taking into account multiple scenarios, including multiple initiating events, multiple hazards, multiple infrastructure events, multiple network events and multiple societal events. It will also be expanded to deal properly with the spatial and temporal consideration in the estimation of the probability of occurrence of scenarios and the establishment of the scenarios. More work is required to emphasis the human interaction in conducting the risk assessment.

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8. References

Adey B.T., T. Herrmann, K. Tsafatinos, J. Luking, N Schindele, and R. Hajdin., 2012, *Methodology and base cost models to determine the total benefits of preservation interventions on road sections in Switzerland*. Structure and Infrastructure Engineering. 8(7): 639–654.

Adey B.T., R. Hajdin, J. Birdsall, 2009, Methodology to determine optimal intervention strategies for structures adversely affected by latent processes, Transportation Association of Canada, Annual Conference, Vancouver, Canada, October 19-22.

Adey B.T., J. Birdsall, R. Hajdin, 2010, Methodology to estimate risk related to road links, due to latent processes, 5th International Conference on Bridge Maintenance, Safety and Management, IABMAS, Philadelphia, USA, July 11-15.

Adey, B.T., J. Hackl, M. Heitzler, and I. Iosifescu-Enescu, 2014, *Preliminary Model, Methodology and Information Exchange*. Eidgenössische Technische Hochschule Zürich, CH, INFRARISK Deliverable D4.1.

Bensi, M. T., A. Der Kiureghian, and D. Straub, 2011, *A Bayesian Network Methodology for Infrastructure Seismic Risk Assessment and Decision Support*. University of California, Berkeley; PEER Report 2011/02.

Deckers P., W. Kellens, J. Reyns, W Vanneuville, and P. Maeyer, 2010, *A GIS for Flood Risk Management in Flanders*. In: Showalter PS, Lu Y, editors. Geospatial Techniques in Urban Hazard and Disaster Analysis. vol. 2. Springer Netherlands; 51–69.

Garcia-Aristizabal, A., and W. Marzocchi, 2011, *Deliverable D3.1: Review of existing procedures for multi-hazard assessment*. New methodologies for multi-hazard and multi-risk assessment (MATRIX).

Hackl, J., B.T. Adey, M. Heitzler, I. Iosifescu-Enescu, 2014, *An overarching risk assessment process to evaluate the risks associated with infrastructure networks due to natural hazards*. International Journal of Performability Engineering (submitted).

Hilker N, A. Badoux, and C. Hegg, 2009, *The Swiss flood and landslide damage database 1972-2007*. Nat Hazards Earth Syst Sci. 9(3): 913–925.

IEEE, 1990, *IEEE Standard Glossary of Software Engineering Terminology*. IEEE Std 610.12-1990.

ISO 31000, 2009, *Risk management - Principles and guidelines*. International Organization for Standardization (ISO).

Kull D., and A. Feldman*, 1998, Evolution of Clark's unit graph method to spatially distributed runoff*. Journal of Hydrologic Engineering, 3(1): 9–19.

Kutschera G, 2008, *Analyse der Unsicherheiten bei der Ermittlung der Schadenspotentiale infolge Überschwemmung*. PhD Thesis, Technischen Hochschule Aachen.

Losey, S, and A. Wehrli*, 2013, Schutzwald in der Schweiz: Vom Projekt SilvaProtect-CH zum harmonisierten Schutzwald*. Bern, CH: Bundesamt für Umwelt (BAFU).

MOVE, 2011, *Assessing vulnerability to natural hazards in Europe: From Principles to Practice: A manual on concept, methodology and tools*. Methods for the Improvement of Vulnerability Assessment in Europe (MOVE).