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Deterioration Modelling and Preventive Maintenance of Critical Torrential Protection Structures towards Improved Resilience – A Petri Net based Approach

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Abstract

Recently, understanding system's resilience and ensuring availability have become a priority particularly for those related to critical infrastructures, which serve the humanity and the society. Protection structures that reduce the risk caused by natural hazards are part of these critical infrastructures. In mountains, check dams are largely used. Their deterioration over time influences their level of performance and can lead to dramatic consequences. On the same hand, limited budgetary resources are provided for their maintenance. In the context of natural hazards, identifying and analysing dependencies between the structure and the environment, and supporting decision-making for choosing the best maintenance strategy remain challenging. It is therefore essential to go beyond traditional methods used in safety and reliability analysis and to develop a comprehensive approach that permits incorporating possible interactions when modelling system's deterioration and provides information for prioritizing maintenance actions. The approach presented in this study couples (1) a numerical model that analyses the dynamic deterioration of check dams based on civil and hydraulic engineering expertise, and (2) a decision-aiding model, based on stochastic Petri nets, that compares the evolution of the system deterioration and the associated incurred costs when subjected to maintenance operations.

Keywords: Dynamic deterioration; Transition times modelling; Maintenance decision-making; Maintenance for resilience ; Stochastic Petri nets; Protection structures; Check dams

1. Introduction

1.1 Context, motivations & background

Concerns about critical infrastructures (CIs) that provide vital resources necessary for a society's needs have increased among governments and citizens. Assessing the resilience of CIs and ensuring their availability and proper functioning have become an urgent priority [1]. Nevertheless, the ease or struggle in achieving such challenges is highly dependent on interdependencies involved within the same system, potential

uncertainties of collected data, and economic aspects [2-4]. The complexity of these systems, arising especially from the dependencies between components and subsystems failures, lead to several possible maintenance strategies, composed of different types of operations to be carried out in various order. Therefore, it is essential to develop maintenance models, which are the basis for improved decision-making and assessment of maintenance policies.

In mountains, protection structures are constructed in order to fulfil essential functions that provide protection to people, properties, and other infrastructures from the devastating consequences caused by natural hazards. These structures can be considered a sector of CIs since, as any other CI, their partial or total destruction, due to a triggering event, would pose threat to the safety, security, and economics of the society [5]. During their lifetime, protection structures are exposed to a large number of potential dangerous phenomena (e.g. torrential floods) and damaging events. If not regularly inspected and maintained, their deterioration over time leads to their complete failure, which in turns may increase the risk induced by the natural phenomena themselves. Even though non-preventable, the consequences of accumulated damages can be limited, if both direct and indirect failures that protection structures may be subjected to are identified and the interdependencies between failure modes are recognized. A comprehensive understanding of failure mechanisms allows choosing the appropriate preventive maintenance operations to be applied. A properly defined and implemented maintenance policy can thus improve the resilience of these critical protection structures as shown in several works, which have emphasized the link between maintenance and resilience [6 - 9]. However, maintenance operations have high costs and require complex preparations, especially on these remote structures. Consequently, instead of performing maintenance at pre-scheduled times (predetermined maintenance), it is more reasonable to adopt a condition-based maintenance strategy and to figure out the state of the structure at which applying maintenance increases the availability of the structure and saves money at the same time. Due to the crucial need of protection structures in mountain areas, researchers and risk managers, seek in predicting scenarios (failures, hazards, etc.), evaluating their consequences, and choosing between various available intervention strategies based on the technical and imposed budgetary constraints. However, existing approaches, especially those developed in the context of torrent protection structures, remain to be too static, in the sense that they do not take into account the time-dependent deterioration behaviour [10] and cannot compare strategies over protections' lifetime.

1.2 On the considered torrential protection structures: torrent check dams

The present study addresses check dams which are somehow one of the most dominating type of protection structures in French torrents. They are civil engineering structures, implemented in series in the flow channel (fig. 1), mainly in the most erodible zones of the torrent. Check dams act on the causes of production of solid materials due to erosion by water flows. They differ from classical hydraulic dams since they roughly have the same functions as retaining walls but with some additional specific functions: they retain materials, stabilize the torrent's bed, and reduce the bed's slope and incision but also they direct (center) the flow, preventing from lateral erosion of the banks. To protect people, infrastructures and socio-

economic stakes downstream, they are designed and constructed to resist to specific loads due to natural hazards (torrent flows, blocks impacts, landslides, and snow avalanches). In this context, these structures can often be severely damaged or may lose their functional efficacy if the central part of the dam is obstructed, the dam is laterally by-passed, etc. Several combinations of different situations can be observed. The objective in this study is to model the possible degradation scenarios of these check dams over time and then to test the different sequences of maintenance including inspection and repair.



Figure 1. Series of check dams. Saint Antoine torrent, Modane, France, 2014 (Source: INRAE, ETNA team).

1.3 Proposed general modelling approach: mixing physics-based and stochastic modelling

Stochastic Petri nets (SPNs) are able to represent the evolution of a system, subjected to (probabilistic) events, allowing its movement from one status to another. These techniques are applied in an innovative way in the context of these protection structures that are subjected to sequences of natural events.

A SPN model is developed to consider both functional and structural failures of a check dam (system), being itself part of a series of check dams (system of systems) of the Manival torrent in Saint-Ismier, France. The approach presented requires to be able to describe the way the system moves from one state (e.g. normal initial condition) to another (e.g. medium damage level) during its lifetime. These

transitions are represented by probability laws whose parameter identification remains one of the most essential and tricky step of the process.

The probability laws associated to the transitions are therefore one of the key feature of this SPN model, and are required to accurately model the involved deterioration processes. In industrial and technological systems, monitoring is common. In the case of protection structures in mountains, check dams are not instrumented and there is a lack of sufficient deterioration data to build these probability models. To compensate for this lack of data, it is proposed in this study to resort to simulations based on a numerical physics-based modelling of the evolution of the torrent's bed and the dam itself, in order to analyze the evolution of the degradation indicators of different failure modes triggered by torrential floods over time. This permits estimating the probability distribution of transition times to be used in the SPN model. This constitutes an indirect way to avoid part of the difficulty linked to the lack of degradation data. Finally, the results of the SPN model enable comparing different maintenance strategies in terms of efficiency and cost, hence contributing to better comparative and informed choices and to an improved resilience through the analysis of a large range of possible adverse scenarios. The main objective and interest of such a holistic approach, is to show how coupling both numerical physics-based and reliability-based models offers a more effective and realistic reliability analysis to be used for risk management decision-making.

The chapter is divided into two main sections. The first section introduces the context and the objectives. Section 2 first briefly reviews conventional methods used in both static and dynamic reliability analysis and decision-making approaches considering their associated limitations and challenges. It secondly describes the developed SPN model and the combination of numerical simulations and analytic models, which are used. A real case study on a torrent check dam is described and the corresponding results and discussions are presented in Section 3. Finally, the conclusion is given in section 4.

2. Proposed Modelling Methodology for Dynamic Performance Analysis of Maintained Torrent Protection Structures

2.1 Background: from static to dynamic modelling for dependability & performance assessment

Dependability analysis has become increasingly important as modern critical systems become more heterogeneous and complex [11]. It concerns the study of a system and its corresponding functions in order to distinguish between possible failures and consequences and finally to propose procedures for reducing the associated risk. It is an integrating concept that covers four different features: safety, reliability, availability, and maintainability. Indeed, the outcomes of such analysis are used to identify solutions that prolong the lifetime period of a system by controlling its possible means of failure. Researchers have focused on finding out techniques and methods to address such problems and challenges [12]. Reliability approaches can be classified into three different categories: basic, static, and dynamic. Basic models are

used to understand how the system operates, identify related risks, and perform the primary basic reliability analysis (e.g. functional analysis (FA), failure mode and effect analysis (FMEA), etc.). Static models are used to identify failure scenarios and their consequences on the functioning of the system by performing basic calculations (e.g. reliability block diagram (RBD), fault tree analysis (FTA), event tree analysis (ETA), etc.). Dynamic models are used to model the behaviour of a system when subjected to different conditions over its lifetime period (e.g. Markov chains, Petri nets (PNs), etc.). Moreover, classical decision-aid tools such as economic methods (e.g. cost benefit analysis CBA) and multi-criteria analysis (e.g. multi-criteria decision-making MCDM) allow comparing several alternatives through optimization. Yet, the existing complexities highlight the importance of dynamically modelling the degradation of the system over time to analyse the influence of maintenance actions on the evolution of the system's efficacy.

Besides, basic and static reliability models do not take into consideration dependencies between events, in which each failure is analysed separately. For supporting maintenance decision-making, especially towards an improved system resilience, it is expected to have tools and methods able to evaluate quantitatively the time evolution of the system's efficacy. Up to now, addressing the dynamic behaviour of systems remains to be quite challenging in practical cases especially when degradation states are partially documented. To cope with this issue, specific approaches should be designed in order to capture the integrated dynamic response of the system when subjected to different deterioration mechanisms (from continuous intrinsic deterioration to a sequence of external damaging events) or to maintenance operations [13].

In the context of protection structures subjected to natural hazards, a global approach integrating both the complex dynamic evolution (degradation process) and the maintenance decision problem is expected in order to obtain a complete representation and analysis of protection structures. SPNs comply with these objectives and allow representing the dynamic behaviour of the system using four basic elements: (1) circular-shaped places representing the defined states of the system, (2) rectangular transitions responsible for the evolution of the system from one state to another depending on transition firing times, (3) solid circular tokens revealing the state of the system when present in a specific place, and (4) arcs (arrows) connecting places to transitions and vice versa. SPNs have initially, been used in modelling automation systems and then developed and extended to be applied in a variety of areas including the domain of civil engineering and networked infrastructures (e.g. bridges, railway networks, etc.) [14, 15]. This development has been accomplished by using stochastic transitions and by moving from analytical calculations to Monte Carlo simulation [16], which is generally used for evaluating the reliability of a complex system [17]. Applying Monte Carlo method while using condition-based maintenance policy (CBM) enables SPNs to explore a wide range of possible scenarios over system's lifetime and therefore act as a decision support tool for infrastructure managers. Yet, a number of key barriers may pose difficulties in achieving a consistent and reliable dependability analysis. This includes difficulties in figuring out the probability laws of the stochastic transitions involved within the degradation process of the SPN model. For such reason and for the sake of simplicity, most researchers assume exponential distributions with constant deterioration rates, or

other often used probability laws (e.g. Weibull). However, seeking to find the actual transition laws allows better and more realistic understanding the performance of the structure.

2.2 General SPN model of a deteriorating system

The SPN model presented in this study can be considered as generic since it aims to describe the state evolution of any system when exposed to degradation mechanisms or to maintenance operations during its lifetime period. Its global framework integrates the three following processes: degradation, inspection, and maintenance. The developed SPN model has been implemented using the GRIF Workshop developed by TOTAL and SATODEV [18], which permits constructing and simulating the desired SPN model using the Petri module.

2.2.1 Degradation process

In the developed model, the system is considered to reside in one of four different states, each corresponding to a specific condition. Fig. 2 illustrates the degradation process in which four places P_1 - P_4 , reflecting the four conditions are present. P_1 corresponds to a good condition. After a period of time, the system degrades to P_2 , revealing a poor condition. Further degradation triggers the system to a very poor condition, represented by P_3 . The occurrence of a severe event or the accumulation of damage due to absence of maintenance drives the system to P_4 in which it totally fails. The presence of a token in P_1 means that, initially, at $t = 0$, the system is in a good condition. The conditional transitions between the four defined states are presented by the stochastic transitions T_1 - T_3 . The probability distributions of the transition time corresponding to each of the transitions are estimated based on modelling the deterioration of the system when exposed to hazardous events over a specified period of time. The numerical modelling of the system’s functional behaviour, applied on torrent check dams, is performed using a hydraulic software and presented in section 3.2.

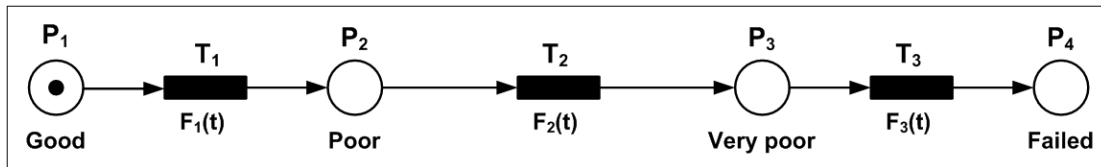


Figure 2. Degradation process involved within the SPN model.

2.2.2 Inspection process

Regular inspections can take place in order to detect the state of the system. The inspection process is incorporated in the SPN model by adding a periodic transition T_5 and the immediate transitions T_4 and T_6 - T_8 as shown in fig. 3. Inspections will take place at intervals of t_{insp} time units. At $t = 0$, a token is added to P_5 . Consequently, every t_{insp} time unit, transition T_5 fires, meaning that it is time for an inspection. P_6 is the place corresponding to the occurrence of inspection. Upon the firing to T_5 ,

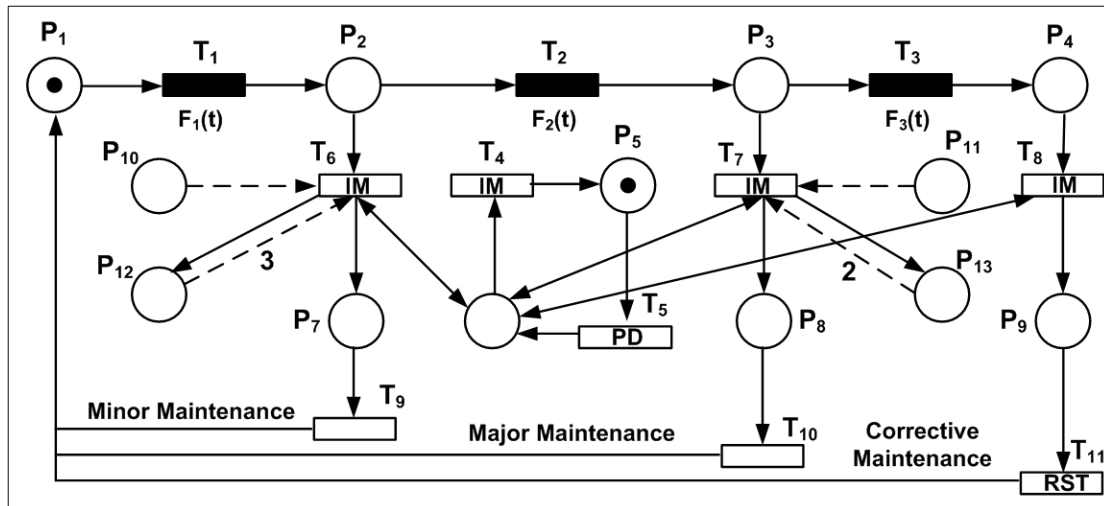


Figure 4. Complete SPN model of a torrent check dam involving the degradation, inspection, and maintenance processes [19, 20].

2.3 Dynamic deterioration of check dams when exposed to torrential floods

This section develops the proposed methodology to build the time probability laws of the transition events appearing in the SPN model from the physics-based modelling of the involved deterioration phenomena.

2.3.1 Description of the deterioration phenomena

Torrential floods are characterized by the gravitational and rapid movement of complex mixtures of fluids (e.g. water) and solids (e.g. fine sediments) [21]. While propagating from the upstream to the downstream of the watershed, water flows erode banks, incise the torrent's bed, transport sediments, and deposit materials on fans where people, houses and infrastructures are located. Check dams are civil engineering structures, implemented in series in the flow channel of the torrent (fig. 5), aiming to stabilize the longitudinal profile by limiting bed incision and banks erosion [22]. The design and monitoring of check dams require joint expertise in torrential hydraulics (including dynamics of solid transport), civil engineering (e.g. loading scenarios definition, failure analysis, reinforcement design), and geotechnics (e.g. soil characteristics, slope stability, etc.). Fig. 6 illustrates the primary components involved in the structural design of a check dam. The central hydraulic weir is responsible for directing the flow and the wings are extended to the torrent's banks in order to prevent lateral bypassing of the flow. Check dams may be subjected to two types of failures. Functional failures exist when the dam is no ore able to fulfil one of its functions. They are related to the dynamics of the flow and to the spacing between the dams. On the other hand, structural failures are those related to the internal (e.g. cracks, corrosion, etc.) and external (e.g. bearing capacity problem, overturning, sliding, etc.) stabilities of the dam.

Scouring is an unavoidable phenomenon, considered as one of the most common functional failures and the main cause of the total destruction of a structure. Scouring is accumulated by clear water floods (high energy without sediment supply) in which intense waterfalls passing through the central weir of the dam remove solid materials downstream the dam. The progression of the scour pit leads to local scouring upstream under the foundation of the dam, which in turns triggers structural failures from an external (global stability) and internal (material rupture) points of views.

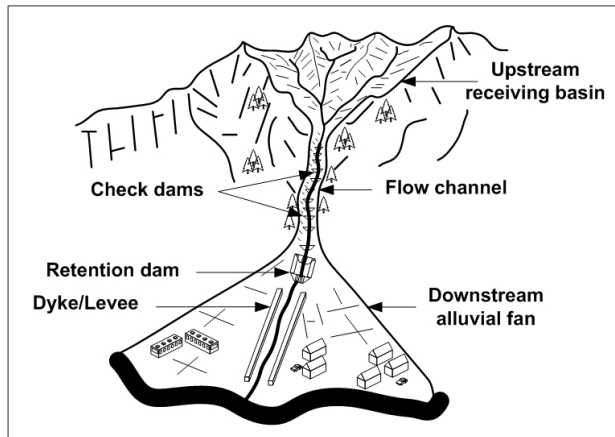


Figure 5. Protection structures in torrential watersheds.

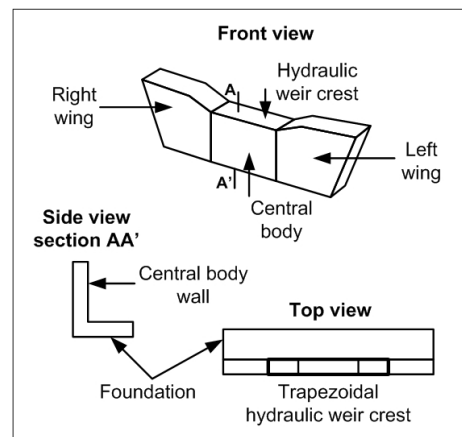


Figure 6. Components of check dam.

2.3.2 Numerical simulation

LOGICCHAR [23], developed by INRAE (ETNA research unit), is a hydraulic numerical tool that permits 1D simulation of torrential floods based on torrential hydraulics and sediment transport hypotheses. The input data required to launch simulations include the torrent characteristics (longitudinal and transverse profiles, grain size distribution, and thickness of erodible layer of torrent's bed), protection system (type of structures and their dimensions), and flood characteristics (hydrographs and sediment-graphs of flood events). In addition, some assumptions regarding the calculation principles are required (e.g. choice of sediment transport equation, shapes of hydrographs and sediment-graphs, etc.). Simulations via LOGICCHAR provides the water height (m), water velocity (m/s), slope (m/m), bed level (m), and solid discharge (m^3/s) along the whole torrent at different chosen temporal and spatial scan points.

These outputs are then used for computing the scour pit geometry [24], which in turns permits estimating the dimensions of local scouring [25]. The local scouring reduces the stiffness of the foundation and thus affect the external stability of the dam. Consequently, the dimensions of scouring are used in order to verify the different aspects considered when justifying the external stability of the dam (soil bearing capacity *SBC*, overturning *SOT*, and sliding *SSL*). The three stability indicators are then normalized and modelled over time. In order to estimate the global stability *S* of the dam, it is assumed that *S* is a combination of the three different stability indicators [26]. $S \in [0, 1]$ is a non-dimensional parameter where 1 corresponds to the perfect stability level (initial) and 0 corresponds to failure.

2.3.3 Building the probability estimates between deterioration states

The objective of such numerical computations is to model the evolution of the degradation indicator related to the global stability of the dam as a function of time. Such evolution enables identifying thresholds and thus defining the four states of the dam. Depending on these thresholds, the time spent in each state can be computed. Yet, in order to fit a probability distribution for the transition times (inputs to SPN model), as many as possible of scenarios must be simulated, in which each simulation results in an estimation of the time spent in each of the defined states. Different scenarios are obtained by introducing randomness into the physics-based numerical model. In torrential flood context, randomness can be generated on the peak discharges and the dates of the flood events involved within the series of events of each scenario. Fig. 7 illustrates all the steps required for fitting a probability distribution for the transition times involved in the degradation process of the SPN model, which can be described as follows:

1. Defining the torrent's geometry, its characteristics, and its protection system (series of check dams) and assuming a series of flood events with defined dates and peak discharges over a specified period of time.
2. Analysing the response of the global torrent's bed (numerical simulations via LOGICCHAR) and the check dams (scouring and external stability calculations) while being subjected to a series of flood events.
3. Identifying thresholds corresponding to different degradation states of the check dam based on the evolution of its stability indicator over time and estimating the transition times between these states in order to figure out their probability distributions depending on the considered flood scenarios.

3. Application, Results, and Discussions

The developed SPN model is applied on one of the check dams of the Manival torrent, located in Saint-Ismier, in the Chartreuse Mountains of the Northern French Prealps [27]. The entire torrent extends to more than 7km and contains about 180 check dams built since the 1890s and monitored by the French forest and torrent control service of the Isère department (ONF-RTM 38). The implementation of the 25000m³ sediment retention basin in 1926 followed by the construction of a retention dam in the 1992 aimed in protecting the urbanized alluvial fan against debris flows [28]. In the presented application, the reach, extending about 1km downstream the retention dam and containing 39 transverse check dams is modelled in LOGICCHAR. The data required as an input to LOGICCHAR such as the torrent's characteristics, torrential floods' intensities, and check dams' dimensions are extracted from the ONF-RTM database [29] and GIS surveys performed in 2009. All events are considered to be clear water floods assuming that sediments are trapped in the sediment retention basin before arriving to the reach under study. The hydrographs are assumed to have triangular shape with a peak discharge attained in the middle of the 1h flood event. In addition, only events with 10 years return period are considered. Over a period of 100 years, the peak discharges and the dates of the events are obtained by applying randomness assuming Gamma and Poisson laws

respectively. On this basis, 50 different scenarios, corresponding to 50 different event series, are obtained.

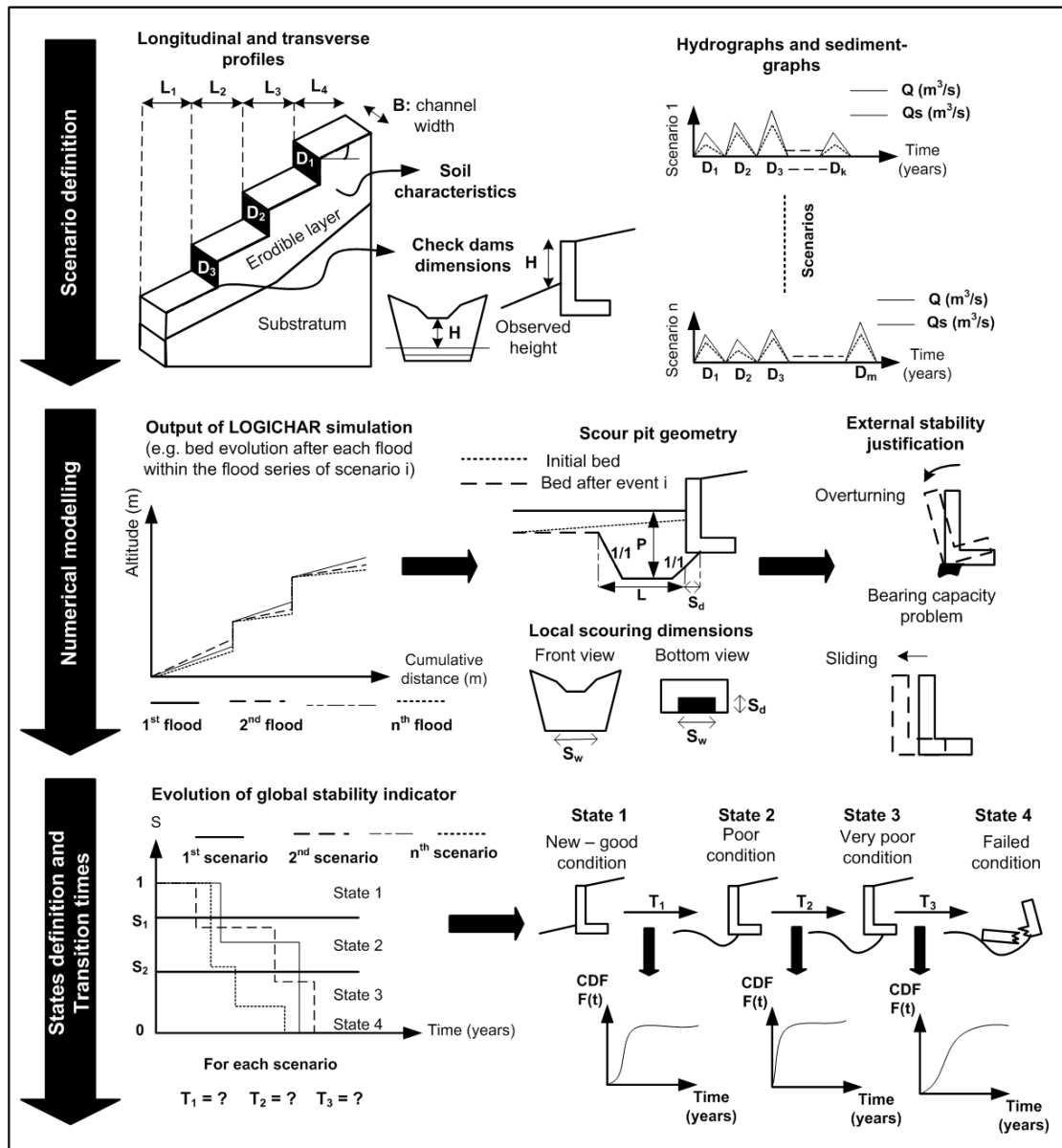


Figure 7. Numerical modelling framework - Steps required for identifying the probability distributions of the transition time involved in the degradation process of the SPN model.

The analysis against failure by external stability triggered by scouring phenomenon is performed on a reinforced concrete check dam (#54 in Manival), located about 70m downstream the retention dam. The results of the LOGICCHAR simulations are used as inputs for scouring and stability calculations of the selected dam. These outputs enable modelling the evolution of indicators corresponding to the external stability aspect *SBC*, *SOT*, and *SSL*, which in turn results in the evolution of the global stability indicator *S*. Fig. 8 represents the evolution of the global stability indicator of the check dam under study over time based on the results of the first 5 scenarios. In addition, the global states' thresholds are assumed as follows: $0.7 < S \leq 1$ for state 1;

$0.5 < S \leq 0.7$ for state 2; $0 < S \leq 0.5$ for state 3; and $S = 0$ for state 4. Besides, the 50 generated scenarios, permits estimating 50 times the time spent in each of the states resulting in the probability distribution of the transition times $T_1 - T_3$ involved in the degradation process of the SPN model. Fig. 9 provides the cumulative probability distribution of each transition to be used as an input in the SPN model presented previously in section 3.1.

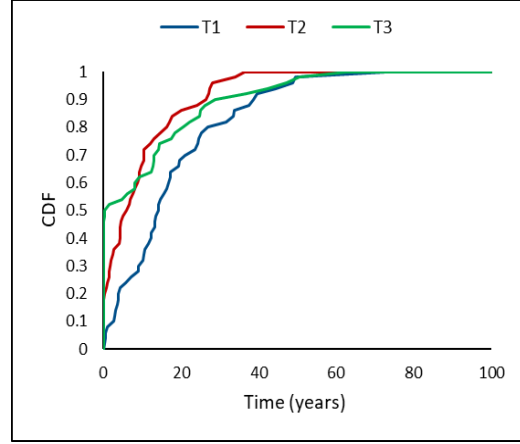
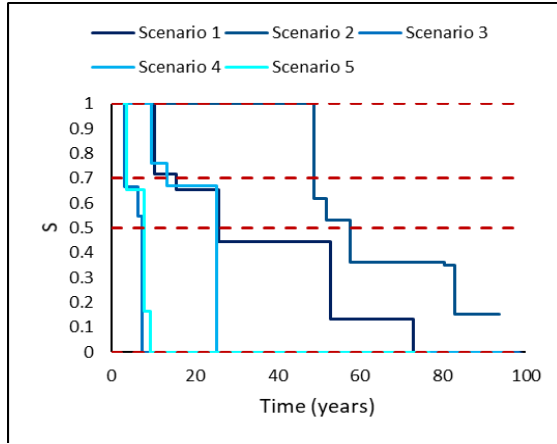


Figure 8. Evolution of the global state indicator over time. Red dashed lines correspond to the indicator thresholds ($S_1 = 1$, $S_2 = 0.7$, $S_3 = 0.5$, and $S_4 = 0$).

Figure 9. Cumulative distribution functions of the stochastic transitions involved in the degradation process of the SPN model.

Regarding the deterministic transitions corresponding to other processes in the SPN model, their constant firing times are assumed based on experts' knowledge. Inspection is assumed to be periodic occurring every year (T_5) and the constant firing times required for minor, maintenance, and corrective maintenance operation to be carried out are 5 days (T_9), 1 month (T_{10}), and 4 months (T_{11}) respectively. In the current application, convergence in results is reached after 200 Monte Carlo simulations for all of the defined maintenance strategies. The results achieved from the simulation of the SPN model for the four considered maintenance strategies are summarized in tables I and II.

Table I: Mean expected number of maintenance operations over a period of 100 years.

Strategy	Minor	Major	Corrective
1	3	1	1
2	0	2	2
3	3	0	1
4	0	0	2

Table II: Mean sojourn time (years) spent by the dam in each state over a period of 100 years.

Strategy	State 1	State 2	State 3	State 4
1	90.42	8.20	0.63	0.38
2	68.36	27.70	2.44	0.81
3	82.63	5.64	10.78	0.55
4	51.26	24.57	22.31	1.10

Assuming that reconstructing the dam costs 150000 € and major and minor operations cost 50% and 5%, respectively, of the reconstruction cost, the total cost of each

maintenance strategy can be computed (table III). The achieved results reveal that strategy 3, in which the dam is repaired upon its mild deterioration by minor operations that are the cheapest among the other operations, is the most effective in the long term. On the other hand, strategy 2 is the most expensive because maintenance is applied only when the dam reaches states 3 and 4 where expensive operations are required.

Knowing that some of the data involved in this study are assumed based on expert assessments (e.g. hydraulic data, maintenance costs), information quality (or imperfection) may of course have an influence on the results of the analysis. Different types of imperfection exist and can correspond either to uncertain, inconsistency, imprecise, or to incomplete data. Several methods and theories (e.g. probabilistic analysis, possibility theory, belief functions etc.) exist to cope with information imperfection traceability and decision-making processes [30 - 32]. Such approaches, developed to trace the propagation of this information imperfection throughout the analysis, would be useful in our context.

Table III: Total cost (k€) of each maintenance strategy.

Strategy	Minor operations cost	Major operations cost	Corrective operations cost	Total strategy Cost
1	22.5	75	150	247.5
2	0	150	300	450
3	22.5	0	150	172.5
4	0	0	300	300

4. Conclusion

Defining maintenance strategies of protection structures against natural hazards such as torrent check dams induces specific research issues due the combination of natural events and technological infrastructures and the dynamic behaviour of the interacting elements of those systems. In this chapter, the complexities in analysing the dynamic behaviour of CIs and supporting their maintenance decision making are addressed by going beyond traditional reliability techniques and decision-aid approaches. The new developed SPN model integrates stochastic process, Monte Carlo simulation, and condition-based maintenance and proposes an innovative way to overcome lack of knowledge and monitoring data related to system elements' degradation status. Its application on torrent check dams when exposed to natural risks has proven its abilities in analysing the state evolution of the dams during their lifetime period. The core contribution of the presented approach lies in the use of physics-based numerical computations in order to figure out the stochastic transition times between the different states of the dam and their incorporation in the SPN model. This approach opens the way to a better coupling between physics-based modelling of the deterioration behaviour (whenever available) and the stochastic modelling for dependability and maintenance assessment. Designing an effective protection is of course a basic objective of risk managers but considering the evolution of the efficacy of these structures during their lifetime is also essential and less classically addressed. The adaptation of reliability approaches combined with decision-aiding methods is

quite innovative and contributes to assessing the protection devices' resilience: it is indeed necessary to accept and consider that these structures will deteriorate. Approaches we work on are not too common. Performing scenario analysis permits us to imagine or predict what can happen over protection works' lifetime. It provides an innovative dynamic vision of the behaviour of protection structures thus making risk managers and local authorities better prepared to unavoidable evolutions of protection structures. This in turn supports risk managers to better anticipate and take the best decisions. Consequently, the developed approach contributes to a better and more resilient management. Yet, further developments, such as analysing more failure modes (e.g. dam's internal stability) and including information imperfection (e.g. uncertainties) can improve the model by driving it closer to reality.

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