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Cascade Effect Analysis in Torrential Context for Prioritizing Check Dams Maintenance strategies

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Key Words: cascading events, check dams' series, degradation modeling, maintenance strategies, natural hazards

SUMMARY & CONCLUSIONS

Natural hazards in mountains pose threat to people, properties, and infrastructures. Several mitigation strategies aim to reduce the induced risk and to protect vulnerable issues exposed to such dangerous phenomena. Check dams are one type of structural protection measures constructed in series along mountain streams. They constitute a critical interdependent multi-component system that deteriorates over time and requires regular inspection and maintenance. The propagation of damage is influenced by failure dependencies existing within a single dam and/or between multiple dams. Such cascading events reduce the efficacy of the overall system in providing protection. Due to limited budgetary resources, it is essential to identify the most critical structures involved within the system and to capture the state of degradation at which preventive maintenance should be carried out. Consequently, performing a dependability analysis of such systems is highly important. This requires analyzing the dynamic deterioration of each dam and the local or distant effects of its partial or total unavailability on other consecutive dams. The present study integrates physical numerical models analyzing the dynamic state evolution of check dams while being subjected to a series of torrential flood events over a specified period of time with stochastic Petri nets modeling the maintenance processes. The developed models are applied on a simple protection system composed of two check dams. The results achieved permit analyzing the behavior of one dam in the presence or the absence of the other dam and prioritizing several proposed maintenance strategies taking into consideration economic constraints.

1 INTRODUCTION

Natural phenomena that occur in mountain streams 'torrents' induce risk in downstream areas triggering casualties, injuries, and destructions. Consequently, different types of protection structures are constructed in mountains aiming to provide protection and to reduce the risk level either by acting on the causes of the hazards or on their consequences. Generally, in France, a series of check dams (fig. 1) is implemented in the flow channel of the torrent, aiming to participate collaboratively in stabilizing the torrent's bed and

preventing longitudinal and lateral erosions thus reducing the intensity of the hazard. However, as any other civil engineering structure, check dams are subjected to several types of failures that can be either functional (e.g. scouring, lateral bypass, etc.) or structural (e.g. overturning, corrosion, etc.). Due to possible endangers encountered while accessing mountain sites and also budgetary constraints, the frequency of inspection and the level of maintenance strategies to be applied must be carefully identified. In the domain of maintenance management, several decision-aiding tools that aim in enhancing maintenance budgets are developed (cost benefit analysis - CBA, multi-criteria decision-making - MCDM).

These tools have been used for assessing the efficacy of protection works considering both technical (structural and functional) and economic components of efficacy [1]. However, they remain static in which they do not consider the evolution of the structure's efficacy over time. Therefore, there is a strong direction nowadays towards the use of tools (stochastic Petri nets) and policies (condition-based maintenance) developed in the field of reliability engineering for addressing such problems and challenges. Such techniques consider the dynamic response of the system while dealing with the maintenance decision problem. Yet, they require prior numerical models that capture the physical behavior of the system and its evolution over time while being subjected to continuous deterioration.

In recent studies [2], hydraulics and stability calculations were performed in order to assess the functional and structural efficacy of check dams when subjected to a series of flood events over a specified period of time. Then stochastic Petri nets (SPN) were used for supporting check dams' maintenance decision-making based on a condition-based maintenance policy. This integrated approach was applied on a single check dam and not on a global scale, which covers the whole system of dams. Therefore, it involved analyzing one-direction dependencies occurring between failures modes that a check dam may be subjected to but did not consider the effect of the presence of consecutive dams on the evolution of the dam under study. In fact, there exist bi-directional interactions between the dams located in series in which the presence of a dam can affect positively on the evolution of the other dam. On the



Figure 1 – Series of check dams located in the Saint Antoine torrent in France. Source: ©INRAE/ETNA, 2014.

other hand, the failure (partial or complete destruction) of one dam can have a negative influence on other dams involved in the multi-component system, which in turn increases the risk induced.

Until now, no study has been performed in the context of protection structure for tackling this issue and hence no clear vision regarding these cascading effects is yet provided. However, due to the criticality of protection structures and their important role on protecting people and the society as a whole, the approach developed in this article aims in assessing the evolution of a multi-component system (composed of two check dams) while being exposed to a series of threatening events (natural hazards, failures). The main objective is to address: Which dam fails before the other? To what extent does the presence or absence of one dam affects the evolution of the others? Which dam should be maintained first? In addition, a SPN model is also developed for choosing between several proposed maintenance strategies to be applied on the failed dam. Both, the answers to the previous questions and the results of the SPN model participate in the maintenance management process by optimizing maintenance strategies and respecting available budgets.

This section explains the global context, the problems to be tackled, and the objectives of this study. Section 2 describes tools that are used and the methodology followed for achieving the desired objectives. Section 3 presents the application and the achieved results and provides a brief discussion. Conclusions and perspectives are given in section 4.

2 METHODOLOGY

In the context of natural risk assessment, a risk scenario is identified by reviewing possible potential events that may occur within a specified work-scope and then developing paths leading to possible negative outcomes and consequences. Scenario building is mainly based on experience from the past. However, like any other simplification of reality, the definition of a scenario involves a set of logical, reasonable, and consistent subjective assumptions. Furthermore, expert opinions are

important throughout scenario analysis. Consequently, this process is always influenced by the amount of available data, the reliability of sources, and the thoroughness of the suggested assumptions. The modelling approach presented in this section is divided into two main parts: (1) Defining risk scenarios by coupling multiscale analytical and numerical hydraulic models with the structural behavior of a multi-component system composed of several check dams; and (2) supporting maintenance decision-making of the system with the help of condition-based maintenance policy and SPN models.

2.1 Risk Scenario Definition: Hydraulic & Stability Analysis

In order to analyze the time-dependent efficacy of check dams from functional and structural points of view, a risk scenario following the three steps below should be defined (fig. 2):

- *Identify multi-hazard scenarios*: create fictive series of flood events occurring over a considered lifetime period;
- *Identify possible consequences*: analyze the behavior of the torrent's bed (erosion, deposition) and its influence on the stability level of the implemented structures taking into consideration cascading effects (dependencies between failures within the same structure or separate structures);
- *Identify software (tools) to be used for running the scenarios*: model the information to visualize and facilitate decision-making process.

The main features of torrential phenomena (e.g. velocity, flow rate, volume of transported materials) are linked to the particular topographical and morphological features characterizing the torrent such as steep slopes, grain size distribution, channel width, and the distance separating check dams (fig. 2, a). While propagating from upstream to downstream, clear water flows pass through the central bodies of check dams causing local scouring downstream under their foundations (fig. 2, b). The phenomenon of scouring, considered as a functional failure, is characterized by the removal of soil under the foundation of a structure due to continuous water jets. This will in turn lead to a loss in external stability of the structure triggering a structural failure such as soil rupture due to exceedance of soil bearing capacity on the remaining part of the foundation or overturning of the structure (fig. 2, c). The alterations (in the bed, banks, topography) that occur due to the malfunctioning or the destruction of one dam has the potential to propagate downstream or upstream influencing the behavior of other dams (fig. 2, d).

LOGICCHAR [3] is a simplified 1D numerical model, which allows simulating the evolution of the torrent's bed during flood events considering torrential hydraulics hypotheses and sediment transport laws. Specific data such as the torrent's geometry, location of protection structures, torrent's bed characteristics, and water hydrographs corresponding to the flood events are necessary for launching simulations via LOGICCHAR. In order to obtain the time-dependent evolution of check dams, degradation indicators should be identified. The main interest in this study is to capture the change in the external stability state of the check dams due to the phenomenon of local scouring. Hence, a global

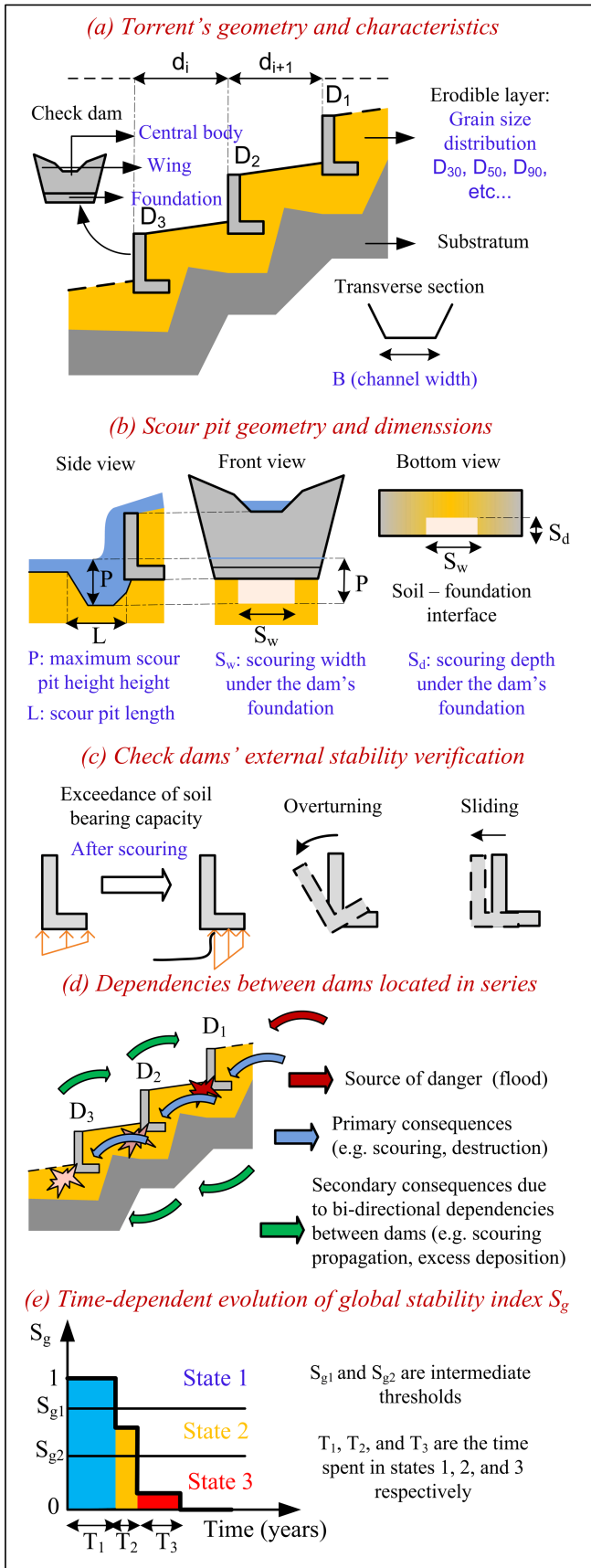


Figure 2 – Steps involved in the physical modeling of a system of check dams.

stability index S_g , given by Eq. 1, is determined based on the scour pit dimensions and civil engineering external stability calculation.

$$S_g = (S_{BC}^\alpha * S_{OT}^\beta * S_{SL}^\gamma)^{1/(\alpha+\beta+\gamma)} \quad (1)$$

S_{BC} is the soil bearing capacity (BC) stability ratio, S_{OT} is the overturning (OT) stability ratio, and S_{SL} is the sliding (SL) stability ratio. The three components (BC , OT , and SL) are used for the justification of the external stability of any civil engineering structure. The coefficients α , β , and γ are given as powers to these stability components depending on the extent of their dependency with scouring phenomenon. Note that, S_g is a non-dimensional parameter that belongs to the interval $[0, 1]$ where 1 corresponds to a maximum stability level of the structure and 0 corresponds to failure by external stability. In the present study, four states corresponding to different stability levels of check dams are defined as follows:

- State 1: initial or good level with $0.7 < S_g \leq 1$;
- State 2: poor level with $0.5 < S_g \leq 0.7$;
- State 3: very poor level with $0 < S_g \leq 0.5$;
- State 4: failed level with $S_g = 0$.

The intermediate chosen thresholds can be modified and discussed based on expert assessment. Hence, the results provided after the simulation of the generated series of flood events via LOGICAR are used to estimate the dimensions of the scour pit under the foundation of each dam, and then to model the evolution of S_g as a function of time. The end-purpose objective of such a model is to compute the time spent by a check dam in each of the defined states (fig. 2, e) and to compare these times when (1) the dam is constructed alone; (2) when other dams also exist; and (3) when other dams exist but structurally failed at a specific time.

2.2 Maintenance Decision-Making: SPN model

Depending on its functional and structural efficacies, a system of check dams either can provide high level of protection or can aggravate the danger on downstream vulnerable issues (releasing high volume of material after collapse). This highlights the importance of monitoring and repairing these dams so that they always reside in a good state that enables them to perform effectively. As mentioned before, specific economic constraints are imposed on the budget provided for the maintenance of protection structures. This necessitates developing a maintenance management approach that facilitates choosing the most convenient maintenance strategy in terms of cost and efficiency. Using the physical model, it is possible to identify which dam, (involved in the system of dams) fails first and to check whether its failure increases the risk by negatively affecting other dams or not. Such results reveal the dam that has the priority to be repaired. Yet, how often should this dam be inspected and repaired? At which state should it be repaired? Will it be economically more effective to repair it prior to its complete failure (preventive maintenance) or to wait until it collapses and reconstruct a new one (corrective maintenance)? Developing a SPN model based on condition-based maintenance policy and simulated

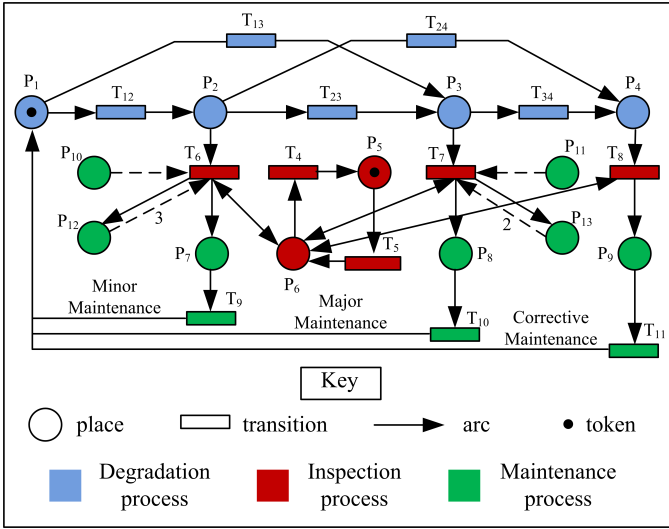


Figure 3 – SPN model involving the degradation, inspection, and maintenance processes.

according to Monte-Carlo principle provides answers to these questions. The SPN approach aims to describe the change of state of the structure when exposed to degradation mechanisms and to inspection and maintenance operations. Indeed, it permits comparing between several maintenance strategies and help decision-makers to choose the best strategy based on multi-criteria.

The developed SPN model is constructed using GRIF Workshop [4]. The model is dedicated to a single dam. It involves degradation, inspection, and maintenance processes as represented in fig. 3. In the degradation process, places $P_1 - P_4$ corresponds respectively to the good, poor, very poor, and failed state. At $t = 0$, a token is added to P_1 meaning that initially, the structure was in a new-good condition. The stochastic transitions T_{ij} link between the state i and state j . Their firing delay times should follow a probability distribution. Therefore, it is necessary to simulate as many as scenarios (e.g. n different flood series) using the physical model. The n flood series can be generated by choosing the average peak discharge and event's dates as random variables following a specific probability law [2]. The n resulted estimations of the times spent in each state allow fitting a probability distribution for these stochastic transitions. In order to detect the condition of the structure, inspection should be carried out. The inspection cycle is represented by places P_5 and P_6 and transitions T_4 and T_5 . At $t = 0$, a token is added to P_5 . In this study, it is assumed that inspection takes place periodically each t_{insp} years. Hence, after t_{insp} , the periodic transition T_5 fires and the token in P_5 moves to P_6 so that inspection takes place. Depending on the condition of the structure revealed by inspection, one of the immediate transitions T_6 , T_7 or T_8 will fire. T_4 , an immediate transition, will then fire immediately after the firing of T_5 so that the token in P_6 returns to P_5 to wait for another inspection. Regarding the maintenance process, $P_7 - P_9$ correspond respectively to the necessity of performing minor, major, and corrective maintenance operations. Transitions $T_9 - T_{11}$ are associated with constant firing times corresponding to the time

needed to accomplish each of the maintenance operations. After maintenance, the structure returns back to its initial state assuming that the operations are perfect. Yet, it is important to note that in the developed model, only three minor and two major operations are allowed prior to a corrective maintenance. This constraint is incorporated into the SPN model by the addition of P_{12} and P_{13} . P_{12} welcomes a maximum of three tokens whereas P_{13} welcomes a maximum of two tokens.

In order to compare the cost and efficiency of different maintenance strategies, four different maintenance strategies are proposed:

- Strategy 1: all maintenance operations are allowed;
- Strategy 2: minor operations are inhibited;
- Strategy 3: major operations are inhibited;
- Strategy 4: only corrective operations are allowed.

Places P_{10} and P_{11} are added to the SPN model in order to select the maintenance strategy to be simulated. Both places are attached to inhibitor arcs in which if a token is present in these places, the transition attached to them will be inhibited from firing. After Monte-Carlo simulation, the model provides for each strategy: (1) the time spent by the structure in each of the defined states and (2) the number of maintenance operations carried out over the specified duration of simulation.

3 APPLICATION, RESULTS & DISCUSSIONS

As a first trial, a simple application on a system composed of two identical check dams is carried out. The reach under study is 80 m in length. The dams are separated by a distance of 40 m. All other data regarding the longitudinal and transverse profiles, grain size distribution, and the dimensions of the dam are given in table 1 and illustrated in fig. 4.

Table 1 – Principle data of the torrential system under study.

Longitudinal profile	Length (m)	80
	Slope S (%)	6
Transverse profile (Trapezoidal cross-section)	Width (m)	6
	Slope (°)	45
	Height h (m)	5.5
Grain size distribution of the torrent's bed	D ₃₀ (cm)	2.6
	D ₅₀ (cm)	3.7
	D ₉₀ (cm)	9
Check dam's dimensions	H _{TOT} (m)	4.5
	H _{weir} (m)	3
	b (m)	4.2
	L _F (m)	6
	L _{TOT} (m)	9
	B _{TAL} (m)	1.9
	B _{SUP} (m)	0.4
E (m)	0.4	

Initially, the foundation is totally covered by earth materials (sand and gravel). Consequently, the initial downstream bed level (Z_{FI}) is 0.4 m and the initial observed height under the weir of the dam (H) is 2.6 m. Moreover, it is assumed that 2 m of the torrent's bed materials can be eroded.

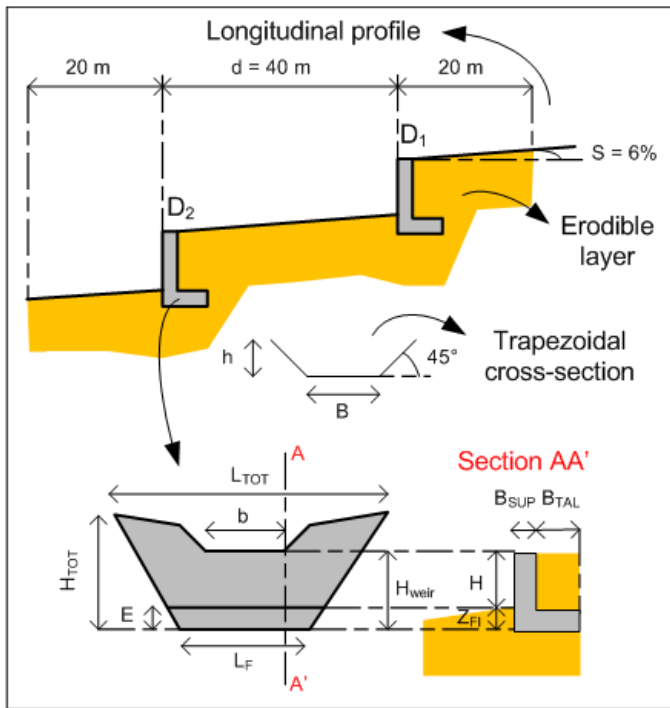


Figure 5 – Description of the check dam's system under study.

Concerning the clear water flood events, the average peak discharge corresponding to 10 years return period is $Q_{10} = 5 \text{ m}^3/\text{s}$. Gamma (for peak discharge) and Poisson (for event dates) laws are considered for generating 50 flood series scenarios over a period of 50 years. Each flood event has a triangular shaped hydrograph and lasts for 1 hour. The peak discharge is attained at the middle of the event. Note that this application does not correspond to a real case study and all the data are assumed and assessed by experts. Moreover, the number of scenarios to be considered (50 scenarios) has been chosen on the basis of (i) observing convergence in the estimated empirical distribution law of the stochastic transitions and (ii) keeping a reasonable size of data.

3.1 Physical Modeling: Check Dam's Stability Evolution

In order to analyze the dependencies that exist between the two dams and to assess the influence of the presence or absence of one dam on the behavior of the other, three cases, presented in fig. 5, are to be considered in the modeling:

- *Case a:* two systems with single dams are modeled in which the behavior of each dam in the absence of the other is analyzed;
- *Case b:* the system of two dams is modeled and the behavior of each dam in the “permanent” presence of the other is analyzed;

Case c: the system of two dams is modeled and the behavior of each dam in the “temporary” presence of the other dam is analyzed. In other words, if one of the dam fails during the duration of simulation, the surviving dam will continue to be modeled in the absence of the failed dam starting from the instant of its failure.

After the simulation of the 50 generated flood series

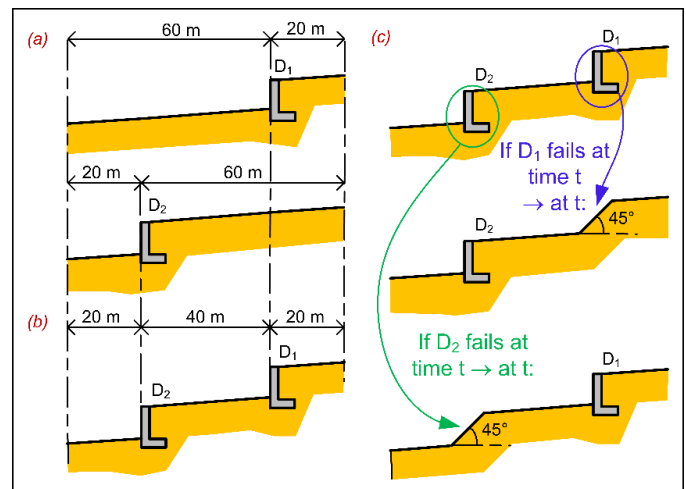


Figure 4 – The three different cases to be analyzed.

scenarios for each of the three considered cases, several conclusions are to be discussed. Regarding case a, in the absence of D_2 , it is noticed that D_1 evolves gradually from a good state (state 1) to a failed state (state 4) in most of the scenarios. Yet, in some scenarios, the deterioration is rapid in which D_1 directly moves from a new state (state 1) to a very poor state (state 3) or from a poor state (state 2) to a failed state (state 4). This is the case when there exist events with high peak discharges ($> 10 \text{ m}^3/\text{s}$) in the beginning or the end of the flood series or when two or more consecutive events involved within the series attain a peak discharge greater than the average one ($\sim 7 - 9 \text{ m}^3/\text{s}$). On the other hand, in the absence of D_1 , D_2 never fails over the duration of simulation. It slightly deteriorates and evolves maximum to a poor state (state 2). This can be interpreted by the fact that the distance between the start of the reach (upstream) and D_2 is quite long (60 m). The absence of a fixed point in between leads to extreme erosion in the upstream. Consequently, when events with high peak discharge occur, the eroded materials will be transported downstream D_2 . Downstream deposition supports the dam by lifting the bed level thus limiting local scouring and loss in stability. Concerning case b, although D_1 deteriorates and reaches a failed state in most scenarios, it shows a lower deterioration rate than that attained in the absence of D_2 (fig. 6). On the other hand, D_2 shows quite the same response (slight deterioration) as that attained in the absence of D_1 . However, in the presence of D_1 , there is no problem of excessive erosion upstream and thus no deposition occurs downstream D_2 . To sum up, the behavior of D_1 is dependent on the presence or absence of D_2 . In the contrary, in the absence or presence of D_1 , the global bed evolution is affected but not the behavior of D_2 . In case c, upon the failure of D_1 , D_2 continues to be modeled in the absence of D_1 . In reality, the collapsed dam will trigger the bed's materials that were initially supported by the dam to fall with a specific slope. Hence, in order to consider the effect of the failed dam D_1 on the behavior of the surviving dam D_2 , D_1 is replaced by a 45° slope. After simulations, it is revealed that the stability of D_2 continues to evolve until D_1 fails. The reason behind this is that the materials in the slope replacing D_1 , will be eroded and

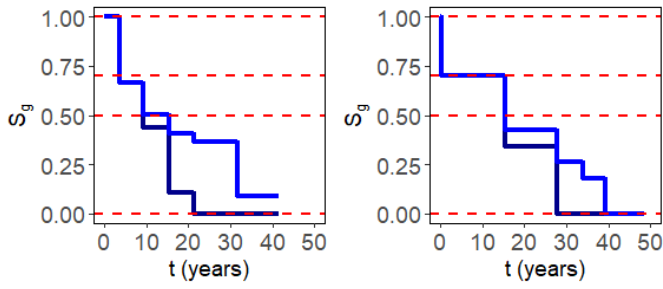


Figure 7 – Evolution of the global stability index S_g of dam D_1 corresponding to two different scenarios (as an example). Dark blue: absence of D_2 ; blue: presence of D_2 ; red dashed lines: S_g thresholds ($S_{g1} = 1$, $S_{g2} = 0.7$, $S_{g3} = 0.5$ and $S_{g4} = 0$).

deposited downstream D_2 thus acting as a stability support. Over the duration of simulation, the stability level of D_2 remains constant after the failure of D_1 . However, if simulations have been performed for a longer period of time, D_2 will continue to deteriorate when the upstream slope again reaches equilibrium where no more materials are deposited downstream.

3.2 SPN Modeling: Maintenance Decision-Making

Since D_1 is the dam that deteriorates faster and reaches eventually a failed state, only the maintenance of D_1 will be modeled using the SPN model. As previously mentioned, the simulation of the generated flood scenarios results in assigning a probability distribution for each of the stochastic transitions involved within the degradation process of the SPN model. However, few scenarios provide results for transitions T_{13} and T_{24} respectively. Hence, it is assumed that T_{13} and T_{24} follow an exponential distribution with a constant firing rate λ equals to the inverse of the average of their obtained values. The cumulative distribution functions of T_{12} , T_{23} and T_{34} are presented in fig. 7. Regarding deterministic transitions, inspection (T_5) is scheduled every year. Minor (T_9), major (T_{10}), and corrective (T_{11}) maintenance operations requires respectively 5 days, 1 month, and 4 months to be carried out. The simulation of the SPN model revealed that the behavior of D_1 in the presence or the absence of D_2 is more-less the same. In other words, the applied maintenance strategies have the same efficacy in both situations. The average sojourn times of D_1 in the different states show a very slight difference ($\sim 7\%$)

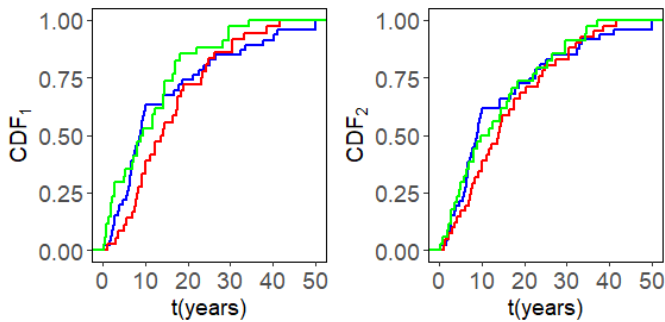


Figure 8 – Cumulative distribution functions of the stochastic transitions involved in the SPN model. CDF_1 : absence of D_2 ; CDF_2 : presence of D_2 ; blue: T_{12} ; red: T_{23} ; green: T_{34} .

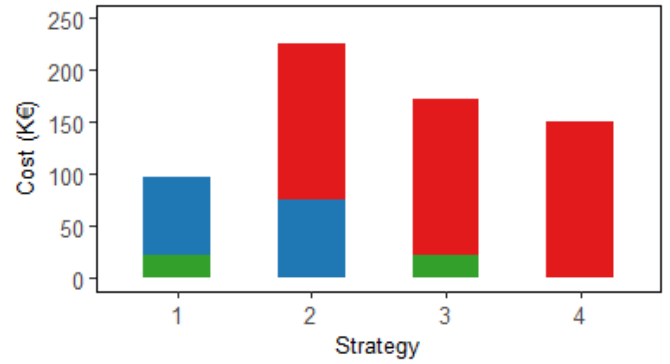


Figure 6 – Total cost of maintenance strategies. Green: minor; blue: major; red: corrective operations.

in both cases. However, the same number of interventions (maintenance operations) is applied to D_1 .

The information provided after the simulation of SPN model permit to sort, compare, and to choose the best maintenance strategy considering economic constraints given an assumed cost of each maintenance strategy. Fig. 8 reveals that strategy 1 is the cheapest among the other. In strategy 1, the dam is not allowed to deteriorate to states where expensive operations are to be carried out. Strategy 2 is the most expensive since maintenance is applied only when the dam reaches critical states requiring expensive operations.

4 CONCLUSION

In this article, physical and reliability analyses of a system of check dams are presented. In particular, the proposed approach aims in modeling quantitatively the bi-directional dependencies between check dams located in series. Of course, at this stage, the achieved results are not generic and correspond to the proposed case study. Several features (e.g. longitudinal slope, distance separating the dams, etc.) could have resulted in different types of dependencies. All the used data were assumed and assessed by experts. Consequently, imperfection resulting from uncertain, inconsistency, imprecise, or incomplete data propagates within the model and of course may have an influence on the results of the analysis. Hence, the model could be developed further by taking into account information imperfection and performing sensitivity analysis.

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