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Failure risk analysis of riverbank ripraps with Monte Carlo simulation

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ABSTRACT: The potential failure evaluation of river embankment structures such as ripraps, resulting from erosion or over-flows during flood events, is the main issue of their stability and safety assessment. Moreover, a changed sediment transport in rivers as a possible result of climate change influences the failure risk of riprap. This bank failure can lead to uncontrolled erosion and flooding with disastrous consequences in residential areas or damage of infrastructures. Thus, probabilistic analysis of failure mechanisms of ripraps due to flood events and sediment transport is a principal step to assess embankment stability. In this article, the concept of a probabilistic assessment model based on Monte Carlo simulation is presented to define the failure risk of bank protection by ripraps. This probabilistic simulation estimates the resistance of ripraps regarding the varied flood and sediment transport in future. The probability of failure in different modes such as direct block erosion, toe scouring and overtopping has been defined by taking into account the changed bed-load transport due to a probabilistic function of the design discharge. A sensitivity analysis was performed by varying slope, block size, bed-load characteristics, geometry of the cross section and hydraulic parameters. The failure probability of ripraps is assessed by a probabilistic function of the design safety factor.

1 INTRODUCTION

Future changes (including increase or decrease) of sediment transport in rivers (e.g. related to their peak discharges) will influence the behaviour of flood protection measures and affect their failure risk. Failure of the flood protection measures might result in uncontrolled flooding and lateral erosion with displacement of riverbed. These processes can have catastrophic consequences on urban areas and infrastructures along alpine rivers. The potential failure evaluation of river embankment structures, resulting from erosion or over-flows during flood events, is the main issue of the stability and safety assessment of the related flood protection measures. Therefore, probabilistic analysis of failure mechanisms of ripraps due to flood events and sediment transport is a principal step to assess future embankment stability.

1.1 *Failure mechanisms of riverbank ripraps*

According to Julien (2002) and Lagasse et al. (2006) riprap failure mechanisms are identified as direct block erosion, translational slide, slump, and side-slope failure. Direct block erosion by flowing water is the mostly considering erosion mechanism. Direct block erosion can be the result of abrasion, reverse flow, local flow acceleration, or toe scouring. The size of blocks might be a reason of direct erosion. The resistance against the flow decreases if they are not large enough. Steep slope and too uniform gradation of riprap also are the other causes of direct block erosion. Figure 1 shows the direct erosion of individual blocks by flowing water.

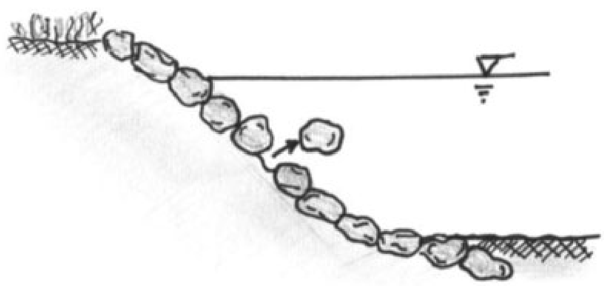

Figure 1. Direct block erosion of riprap (modified from Julien 2002).

A translational slide is a failure caused by the downslope riprap material movement. The initial phases of a translational slide are showed by cracks in the upper part of the riprap blanket that extend parallel to the channel. Translational slides are caused by steep slope of the riverbank and excessive hydrostatic pore pressure. However, this failure process mostly occurs due to toe scouring and instability of the riprap caused by the weakness in the toe foundation. Translational slide mechanism can be seen in Figure 2.

Modified slump failure of riprap is the mass movement of material within only the riprap blanket and the blocks seem to slide on each other. Probable causes of

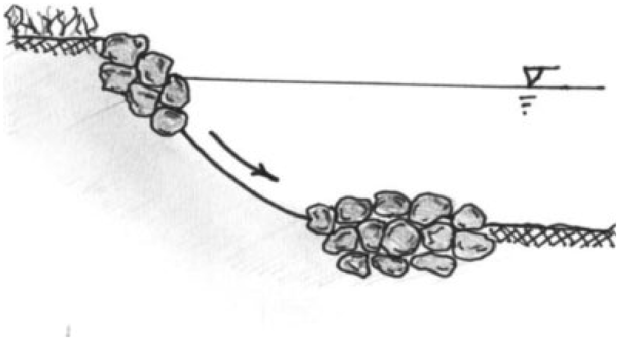

Figure 2. Translational slide in riprap (modified from Julien 2002).

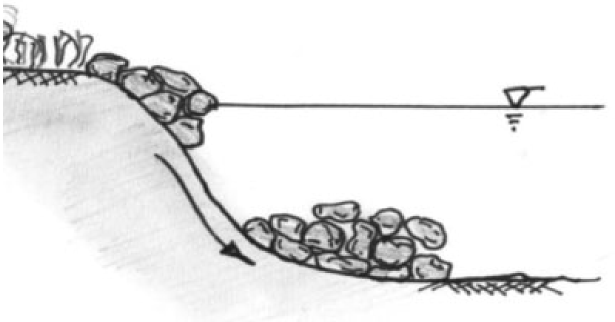

Figure 3. Modified slump in riprap (modified from Julien 2002).

modified slump are steep slope of embankment and lack of toe support.

Slope instability of the riprap is causing mostly due to overtopping. It would be a rotation-gravitational movement of material along a surface of rupture. It relates to shear failure of the underlying base material that supports the riprap. While overtopping occurs, the water saturates the riprap and the material behind it. Once the level of the water decreases the water in the saturated part tend to move faster and the slide-slope in riverbank riprap takes place.

1.2 *Riprap design methods*

There are different methods developed to design riverbank ripraps. Some practical design methods reviewed by Maynord & Neil (2007) based on their application on sedimentation engineering.

According to Maynord & Neil (2007), several methods such as Centre for Civil Engineering Research and code's Manual (CUR) (1995) refer riprap design to general uses. In CUR Manual an equation developed by Pilarczyk (1990) for stability of riprap is addressed regarding strength and destabilizing forces.

Froehlich and Benson (1996) also worked on wide angle of repose to refer the slope of embankment impact on stability of riprap. They proposed a "particle angle of initial yield." Escarameia and May (1992) in Wallingford Design Manual for River and Channel Revetments, presented the general equation for design river bank ripraps and gabion mattresses. Brown and

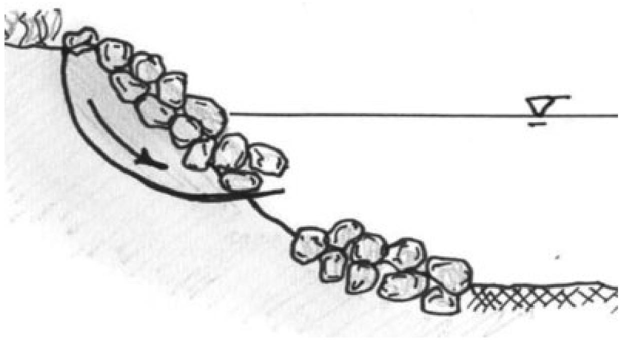

Figure 4. Slide-slope in riprap (According to Julien 2002).

Clyde (1989) used both the Manning-Strickler equation and the Shields relation to make a combined formula for the size of stable rocks. Straub (1953); Grace et al. (1973); and Reese (1984) applied similar approach earlier.

Most of the methods presented above addressed riprap stability in general, without taking into account the stability of individual blocks. The following methods more focused on details of forces and moments on each block of riprap, including lift force. Ahmed (1988) focused on safety factor based methods. He worked on the flume data for flow along a riprap with 1V:1.5H side slope. He concluded that non-safety-factor approaches by Anderson et al. (1970) and the California Division of Highways (CDH 1970) gave better agreement comparing to safety factor based methods. U.S. Corps of Engineers Manual (USACE 1994) presented also a method for sizing riprap in rivers and channels based on different coefficients regarding to incipient failure, vertical velocity distribution, and thickness. Application is limited to the slopes of 2 per cent or less.

Stability of loose rock riprap also studied by Froehlich (2011) regarding the protection of stream banks from erosive forces because of flowing water and evaluation based on the ratio of static moments resisting overturning. The ratio of moments in his research defined a safety factor which indicates the potential of riprap failure. Abt et al. (2008) studied the round-shaped riprap stabilization in overtopping flow as well.

Stevens et al. (1976) presented a safety factor based method by taking into account the stability of individual blocks in riprap. It was based on that each block is stable if the amount of the moments causing the possible displacement of a block is less than the moment of submerged weight.

Froehlich (2011), Ulrich (1987) and Stevens et al. (1984) also considered the weight of the submerged rock as the only resisting force. Wittler and Abt (1988) modified Stevens' analysis adding contact and frictional forces from nearby blocks.

Probabilistic methods for design of riverbank riprap were developed by Li et al. (1976), PIANC (1987), and later by Froehlich and Benson (1996). Combination of different mechanisms and taking uncertainties into account is one of the advantages of probabilistic methods. The uncertainties in estimation of block size and density and other related parameters will also have to be considered in a risk-based method in future.

2 PROBABILISTIC FAILURE SIMULATION OF RIVERBANK RIPRAPS

Herein, the concept of a probabilistic assessment model based on Monte Carlo simulation was set up. The objective is to define the failure risk of ripraps based on future changes on sediment transport and water discharge. This probabilistic simulation estimates the reliability of ripraps in view of changed flood and sediment transport in future. The failure modes considered as the base of the riprap failure, can be categorized in direct block erosion, overtopping, and toe scouring.

The Hypothesis is to study the stability of riprap by comparing the conditions before and after flood. The initial condition will change till the section reaches its equilibrium condition after flood. It means that, at the end, the final sediment transport capacity of the section will be equal to the sediment supplied in the channel.

The procedure starts with a histogram of the predicted 100-years flood (Q_{100}) for the next 40 years regime of a specific river. Next step is generating Q_{100} based on Monte Carlo simulation technique and then, water depth (h) corresponding to the generated Q_{100} is calculated by Manning-Strickler:

$$Q = K_s A R_h^{\frac{2}{3}} J^{\frac{1}{2}} \tag{1}$$

which defines the discharge (Q) based on initial slope (J), hydraulic radius (R_h), roughness coefficient (K_s), and cross section area (A). A distribution of h values with their corresponding probabilities can then be obtained by this method. Sediment transport capacity of the section is estimated with the Smart and Jäggi formula:

$$q_s = 2.5 q J^{0.6} \left(J - \frac{d_m}{12.1 h_m} \right) \tag{2}$$

which defines the bedload unit discharge (q_s) based on unit discharge (q), initial slope (J), water depth (h_m), and mean grain size of sediments (d_m). Finally, m_s as sediment transport coefficient which gives sediment transport supply from upstream compared to the transport capacity indicated calculate as below:

$$m_s = \frac{Q_{b\,supply}}{Q_{b\,capacity}} \tag{3}$$

If the supply sediment ($Q_{bsupply}$) is more than the capacity of the reach ($Q_{bcapacity}$), deposition occurs. In contrary the toe and bank erosion will take place. To reach the equilibrium condition in the section, the final capacity of the reach should be equal to the sediment supply from upstream. In this case there are two equations of hydraulics and sediment transport capacity of the section (Eqs. 1 and 2) with two variables which include the slope and water depth before and after flood in equilibrium condition. By assuming a fixed point at the downstream, end of the considered river stretch, the bed level change (Δh_s) can be calculated. It will be based on the distance of fixed point from the section. If the final computed water depth (h_{eq}) exceeds the height of riprap (z) overtopping failure occurs. Toe scouring happens if the depth of the eroded sediment is below the level of the deepest block under the bed ($\Delta h_s > z_0$) (Figure 1).

The safety factor of the riprap is computed by Stevens (1976) formula. Direct block erosion occurs when the safety factor is less than 1.0. The probabilistic function of safety factor and the probability of failure in different mechanisms can be obtained by this simulation.

3 PRELIMINARY RESULTS

The riverbank riprap model is developed by a probabilistic approach. Three different failure modes as direct block erosion, toe scouring and overtopping are simulated. The simulation code was set up with mathematical and statistical software based on Monte Carlo simulation method. The hypothesis and sediment transport concept considered to compute the

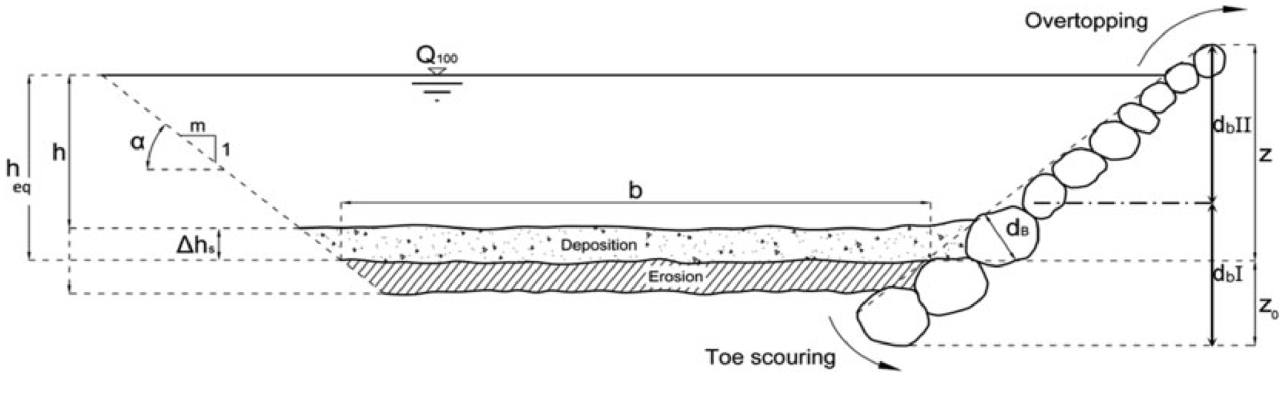

Figure 5. Selected trapezoidal section showing bed and water level variation due to change of sediment and different failure modes.

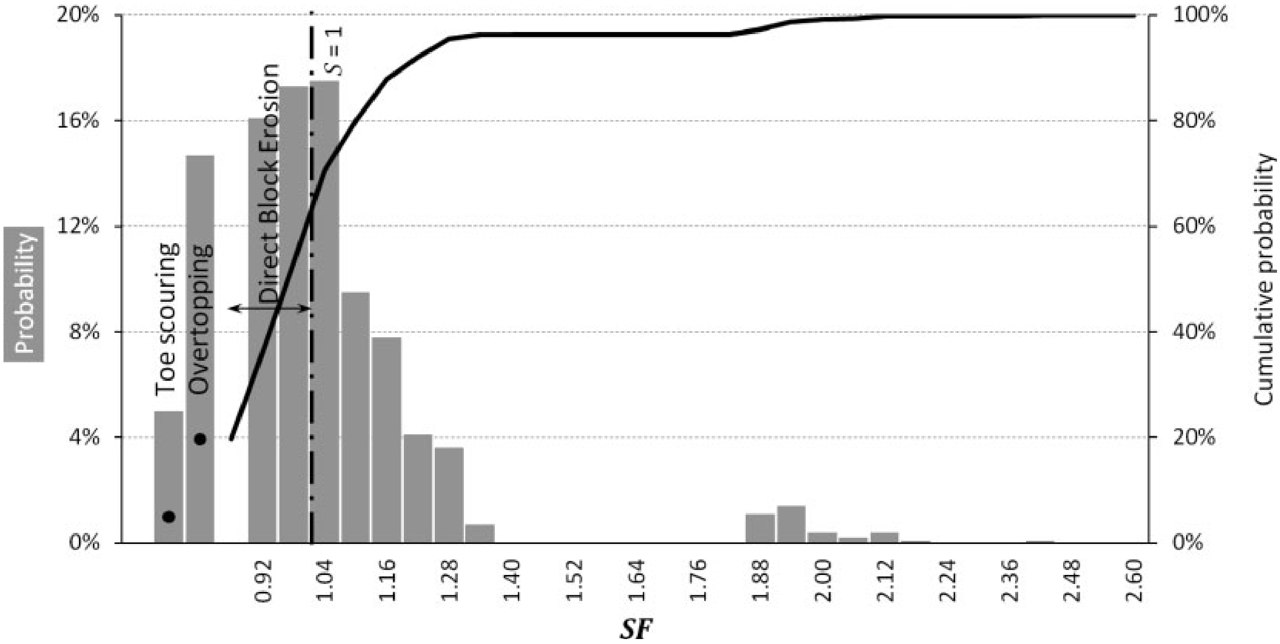

Figure 6. The probability values of safety factor and failure modes in selected trapezoidal section.

Table 1. Description and values of parameters using in hydraulics and bed-load transport calculations.

Description	Variable	Value	Unit
Bed width of the section	b	55	m
Angle of riprap	α	30	°
Slope	J	3%	
Bed roughness	K_s	27	$m^{1/2}/s$
Density ratio	$s = \rho_s/\rho$	2.65	
Angle of repose	φ	60	°
Mean diameter of bed-load sediments	d_m	0.014	m
Discharge of 100 year flood	Q_{100}	800	m^3/s
Sediment transport rate	m_s	0.9	–
Distance between the section and fix point	l	1000	m
Height of- riprap from above the bed level	z	2.50	
Depth of the deepest block below the bed	z_0	−1.90	m
The height of sediment eroded or deposited on the bed	Δh_s	–	m

Table 2. Order and size of the blocks in selected riprap.

Level	h_i (m)	d_b (m)
I	−1.90	0.75
	1.50	
II	2.50	0.40

probability of failure. The parameters used in the simulation such as geometry of cross section, sediment transport and hydraulic parameter described in Table 1 with their reference values of a selected river cross section as a reference.

Table 3. Probability of safety factor SF and failure modes.

Safety Factor Ranges/Failures	Frequency	Percent
Toe Scouring: $\Delta h_s > z_0$	50	5.0%
Overtopping: $h_{eq} > z$	147	14.7%
$0 < SF < 1$	315	31.5%
$SF \geq 1$	488	48.8%

For a selected section the data from a real river was considered as an example. Table 2 presents the size and order of the blocks in the riprap and in Table 3 and Figure 2 the probability values of different failures and range of safety factors (SF) in this trapezoidal section are given. The herein presented model allows for taking the probabilistic values of any variables in to account. Figure 4 shows the probability values of safety factor and different failure mechanisms in selected trapezoidal section.

4 SENSITIVITY ANALYSIS

Sensitivity analysis is performed in this study to investigate the impact of each variable used in simulation. The effect of six variables verified for analysing the variation of failure modes and probabilities. This analysis obtained by variation the reference values by 20 per cent.

These variables are the angle of existed riprap, slope of the channel, diameter of blocks, grain size of bed-load, sediment transport rate and the order of the blocks. This is important to take the water level into account in the case of the size of submerged blocks.

The following graphs and tables show changes of Cumulative Distribution Function (CDF) of Safety Factor and probability of other failure modes. The

Table 4. Order and size of blocks in selected riprap.

Level	h_i (m)	d_b (m)
I	−1.00	0.80
	1.00	
II	2.80	0.40

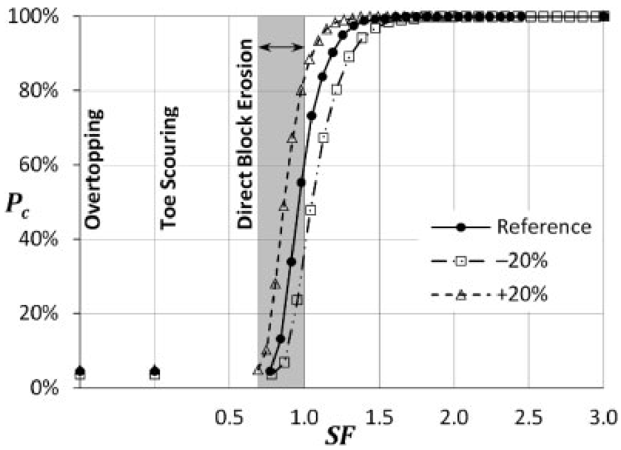

Figure 7. Probability of safety factor and failure modes with different angles of the existing riprap (α).

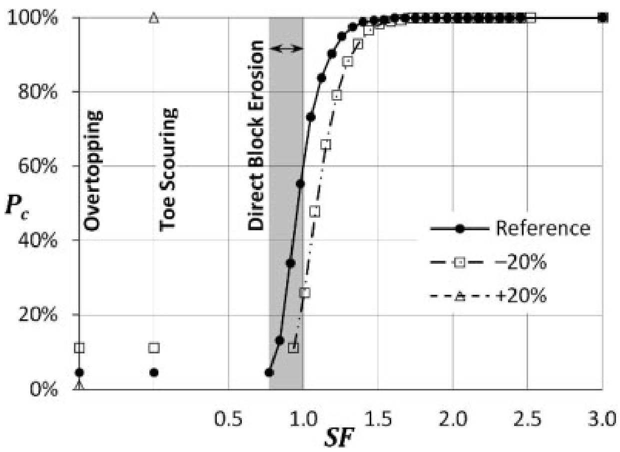

Figure 8. Probability values of safety factor and failure modes with different river slope (J).

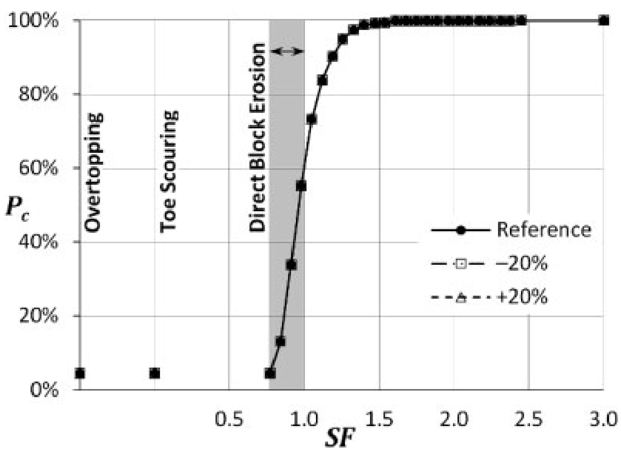

Figure 9. Probability values of safety factor and failure modes with different grain size (d_m).

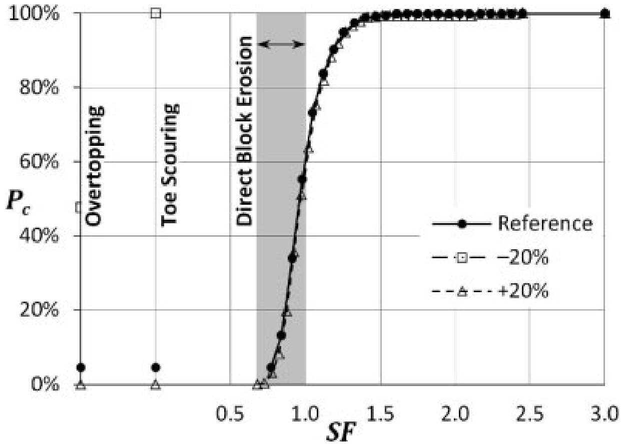

Figure 10. Probability values of safety factor and failure modes with different water level (h_i).

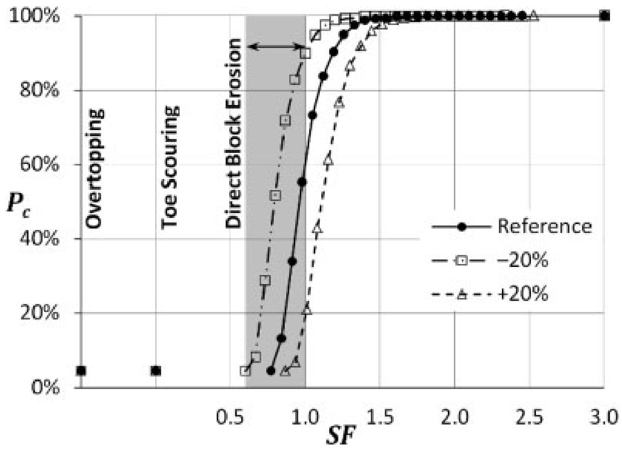

Figure 11. Probability values of safety factor and failure modes with different diameter of blocks (d_b).

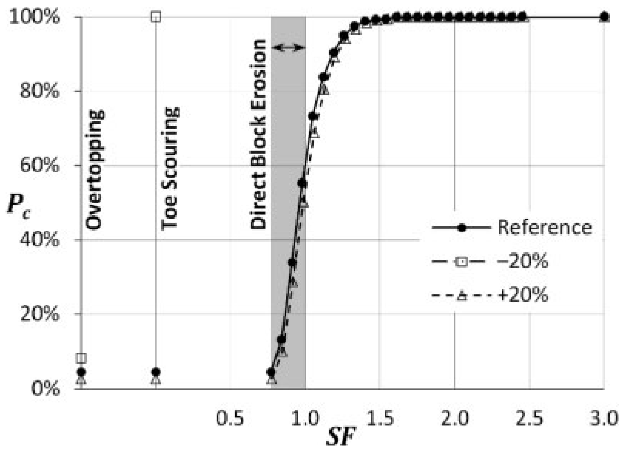

Figure 12. Probability values of safety factor and failure modes with different sediment transport rate (m_s).

values of the reference and fixed values of parameters using in hydraulic computation are shown in Table 1. The only difference here is the value of the L as distance to the fix point which is 500 m and the order of the blocks. The order of the blocks change indicates in Table 4.

The Figures 7–12 show the variation of probabilistic function of failure probability. The sensitivity analysis for the case study indicates that the angle of riprap, shown in Figure 7, has a relevant effect on the safety factor and direct block erosion while the other mechanisms can be neglected. However, the slope of the channel has also a significant impact on the failure of the riprap and not only changes the failure probability but also changes the failure mechanisms. Simulation shown in Figure 8 indicates that by decreasing the slope of channel the failure mode completely changes from overtopping to toe scouring. It means that the slope of channel is one of the dominant parameters. Figures 6 and 8 show that the rate of sediment supply and the height of riprap also have influences on the model. In contrary the grain size of the sediment (Figure 9) has no effect on failure of the riprap. The diameter of the blocks also has an impact on probability of failure (Figure 10) but there is no significant change in failure modes. As the last variable, the sediment transport rate can influences the failure probability when reduced 20 per cent. It can be witnessed that the failure mode changes totally to toe erosion.

5 CONCLUSION

The potential failure probabilities of ripraps have been evaluated by a Monte Carlo Simulation. The case study showed that the most dominant parameters are slope of the channel, height of the riprap and sediment transport rate. They change both the failure mechanisms and the probability of each failure modes. However, the diameters of the blocks and angle of riprap just have an impact on direct block erosion mode.

This simulation method can be implemented in water surface and bed load calculation models. This allows applying the method on other rivers for computing the probability of failure based on prevailing sediment transport regime. The final goal is to have an assessment of the failure risk of riverbank riprap and other flood protection measures under changed flood and sediment yield scenario in future.

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