Landslide, flood and snow avalanche risk assessment for the safety management system of the railway Trento - Malè - Marilleva

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ABSTRACT

This paper defines the Criticality to identify sites that need further assessment or mitigation works for the safety of the Trento-Malè - Marilleva railway (Northern Italy). The railway is a typical example of a mountain railway exposed to natural hazards due to landslides, flooding and snow avalanches. In 2011 Trentino trasporti S.p.A., that is the quango responsible for the overall management of the railway, recognized the need of defining a systematic approach in the planning of the inspection activities, site-specific studies and mitigation works of natural hazards, and for this purpose has developed a classification method based on the concept of risk. The method defines five classes of "Criticality" C (none, mild, moderate, high or very high), to which the whole rail has been categorized. Criticality C is the product of the hazard H and the "works" O (C = H x O), where the factor O is greater than one in case of obsolete or even of absent substructures.

KEYWORDS

railway; landslide; flood and snow avalanche; safety management; risk assessment

INTRODUCTION

The railway line Trento - Malè - Marilleva in Trentino (Northern Italy) is 65 km long, 1,0 meter gauge line, connecting the town of Trento to Marilleva (Figure 1). The railway line has generally a single track and it is equipped with the safety system ATP (Automatic Train Protection), which automatically stops the trains in case of they exceed the speed limit, or do not respect a signal. The average rail traffic is of 49 trains/day, the commercial speed is approximately of 35,0 km/h and the maximum speed is of 90 km/h.

The line is passing within mountainous terrain through the Rotaliana plain, the Non Valley and Sole Valley. It was opened to the public in 1909, completely reconstructed in its own place at the end of the 1950s, and extended by 10 km to the current configuration at the beginning of the present century. It is a typical example of a mountain railway: it has a total rise of 700 m (from elevation 220 m a.s.l. in Trento to 900 m a.s.l. in Marilleva), a path made partly along hillsides, hairpin bends, 5783 m of tunnels (of which 2670 m in one single tunnel), 2580 m of bridges and viaducts, curve radius of 80 m and track gradients up to 50 ‰.

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Figure 1: Location of the railway line Trento-Malè-Marilleva (Northern Italy).

tions on the line. On some sites identified by Tt as "sensitive" due to greater hazard potential (either natural or related to the structures), the workers are asked to intervene before the passage of the first morning train (no night trains are operated on the line). If necessary, they have to adopt appropriate measures, such as the enforcement of slowdowns or interruption of train rides and the subsequent implementation of works aimed at risk mitigation, always in order to ensure the safety of the railway. In relation to the causes and severity of events that have originated the hazard, the workers are supported by the service personnel of Tt and consulting technical experts.

In 2011 Tt recognized the need of defining a systematic approach in the planning of the inspection activities, site-specific studies and mitigation works of natural hazards, and for this purpose in the biennium 2011-2012, with its internal Technical Service resources, it has developed a classification method based on the concept of risk. The method defines five classes of "Criticality" C (none, mild, moderate, high or very high), to which the whole rail has been categorized. At that time, the Alpine Space project PARAmount (2015) dealing with risk management strategies for infrastructures was being carried out, and Tt had a few meetings with some partners, in particular with the Austrian Federal Railways, to exchange experiences in the management of natural hazards. This exchange would be more effective if Tt had been involved as an Observer and could participate to more meetings.

Even though quantitative risk assessment (QRA) is increasingly encouraged in the geotechnical engineering community (see for example Lacasse S., 2013; Maciotta et al., 2015), qualitative procedures providing risk levels are still adopted with the purpose to identify sites that need further assessment or mitigation works, and do prioritize the activities (Bidwell et al, 2010; Winter et al, 2013).

This paper describes the method, how it was implemented by reviewing the data already available to the company (from previous studies or maps carried out by PAT at large scales – accordingly the classification by Fell et al., 2008 large scales are intended from 1:5000 to 1:10000) and how in some cases the Criticality values were updated after site-specific inspections and studies carried out at a detailed scale (1:500 to 1:1000).

METHODS

The method defines the criticality C as the product of an "hazard factor" H and a "work factor" O. The hazard factor H derives from the well-known formula to evaluate the total risk (Varnes D.J., 1984):

$$R=H\cdot E\cdot V$$

Formula 1

where R is the total risk, H the hazard, E the elements at risk and V the vulnerability.

Only natural (geogenic) events were taken into account and specifically they were landslides (including: rock falls, slides, Deep Seated Gravitational Slope Deformations-DSGSDs), floods (distinguishing in: debris flows in the stream channels on the slopes of the valley, quick or slow flooding at the bottom) and snow avalanches. Moreover, an unique level of risk exposure equal to one along the whole line was assumed, in the sense that for example no distinction was made for the presence of one or two tracks (generally at the stations), rail station or stop, with the consequence that the vulnerability, referred to as the degree of loss caused by the occurrence of an event of given intensity, was assumed equal to one independently on the characteristics of the exposed element and of the intensity I of the event. These two assumptions on the elements at risk and on the vulnerability actually prevent the estimation of risk and accordingly the definition by Fell et al. (2008) would reduce this method to an evaluation of the hazard. The hazard H was assumed as the product of the frequency F of occurrence of the natural event and the intensity I:

$$H=F\cdot I$$

formula 2

Frequency F and intensity I were classified independently of the presence of mitigation works (e.g. rockfall protection fence, slides stabilized with retaining walls and drainage, etc) that may reduce the intensity or even avoid the occurrence of the event. In fact, since the planning and scheduling of construction and maintenance of mitigation works is one of the specific tasks that Tt has been asked to pursue for the safety of the railway line, it was decided not to reduce the hazard H due to the presence of mitigation works, but to amplify it with a work factor O every time the structures were evaluated not to be either effective or functional to mitigate the risk. The product C:

$$C=P\cdot O$$

formula 3

was defined Criticality. The purpose of the method was to obtain a ranking of criticality in order to appropriately manage, mitigate or prevent the consequences of an hazardous event. Scores were then given to frequency F, intensity I and works O, with the general rule that the larger the score the more critical the event to be prevented or mitigated with proper activities and works. More specifically, the absolute values of the scores, especially for the work factor O, were assigned by "trial and error" in order to be able to identify classes of criticality that were coherent with the planning based on the engineering judgment and successfully experienced in Tt for past events.

The frequency F scores were 0, 1 or 2. Based on the occurrence evaluated by analyzing the databases published by national or local geological services and by reviewing the data stored in the archive of the company, score 0 means that the event is impossible (no slope, cliff or stream are present) or not likely to occur, score 1 was for an event that had occurred rarely (once) or supposed possible, score 2 for an event that had already occurred more often than once.

Table 1: Intensity I scores.

Event					Intensity
Landslides	A	Rock Fall	A1	Boulders and large boulders	2
			A2	Cobbles	1
	B	Slide	B1	First-time failure	2
			B2	Active	1.5
	C	Deep Seated Gravitational Slope Deformation - DSGSD			2
Floods	D	Debris flow in stream channels			2
	E	Quick flooding			1.5
	F	Slow flooding			1
Snow Avalanche	G	Snow Avalanche			2

Intensity I scores varied between 1 and 2 (Table 1). Score 2 was given to rapid and extremely rapid (Cruden et al., 1996) landslides, such as rock falls and first-time slides, and to DSGSDs. Even though these landslides may be inactive, quiescent or moving very slowly, they were scored 2 because of their large volumes and of a generally poor knowledge of the failure mechanisms that were acting. The score 2 to DSGSDs could be then reduced after specific studies. Snow avalanches and debris flow in stream channels were also scored by 2, given their rapid evolution and the tremendous consequences that would result from an impact with a passing train or simply with the tracks. Reactivated slides and quick flooding were given score 1.5, while the smallest score 1 was for slow flooding and falls of small rocks that can cause only minor damages to the trains without altering their normal cruise speed.

The hazard factor H was then amplified by the work factor O, which was equal to 3 in the case of obsolete structures (i.e. not effective and/or not-functional for the purpose of risk mitigation) and even to 4.5 if structures were absent.

The resulting criticality C was then classified in 5 classes (Table 2) from nil (C0, C=0), which corresponds to the absence of dangerous phenomena, to very high (C4, C>18), which corresponds to very intense phenomena without mitigation works.

Table 2: Criticality C scores.

Criticality	C0-Nil	C1-Mild	C2-Moderate	C3-High	C4-Very high
Score	0	1-4	4-8	8-18	>18

The high weight given to the work factor O in determining the criticality C level invites Tt to assume the role of controller of the safety of the railway line. Namely, Tt cannot cancel the natural hazard, but can mitigate its consequences with works, monitoring, inspections or maintenance activities, depending on the budgets. The ranking of C makes Tt constantly aware of the hazard conditions present along the line, as well as of the presence, the effectiveness and functionality of the remedial works. According to the C classification, Tt can manage and mitigate the consequences as budgets permit.

The mild criticality C1 includes C scores ranging between 1 and 4, and then includes also the events of high intensity (I=2) and high frequency (F=2) with effective and functional mitigation (O=1). On the other hand, as soon as the aging of the works reduces their effectiveness (obsolete works such as old wood crib walls) C increases by a factor of three.

For each C class, Tt has defined the actions to be carried out by the Transport Service, Work Service and Teams of Workers. For example, when criticality C4 occurs, the Transport Service Director, in agreement with the Technical Head, orders a temporary rail service interruption until the Team Workers have adopted short-term countermeasures. The rail service will then be reactivated with a continual monitoring by the workers, and meanwhile the Work Service will involve geotechnical engineers and engineering geologist for planning and designing the long-term mitigation works. In the case of criticality C0, the rail service is regular, no actions are required by the Work Service and Team Workers carry out the regular inspection of the line with a 15-day interval.

RESULTS

To date, along the entire railway line, 34 critical situations have been recognized, from mild to high, for a total length of about 7 km (i.e. more than 10% of the track). Figure 2 classifies the 34 critical situations in terms of type and criticality C score. Thirteen of the 34 critical situations are due to first-time slides, and ten of them are classified highly critical (C=C3, between 8 and 18). The other ten C3 critical situations includes rock falls (3 C3 out of a total of 4 critical situations due to rock fall), one DSGSD, debris flows (5 out of 6) and snow avalanches (1 out of 2).

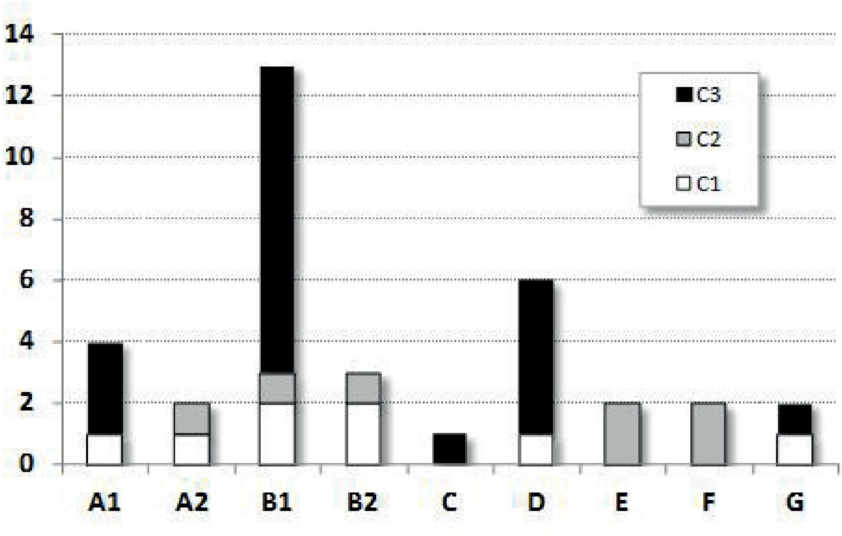

Figure 2: Classification of the Criticalities. A1: large dimension-rock falls; A2: small dimension-rock falls, B1: first-time slides, B2: active slides, C: DSGSDs, D: Debris flows, E: Quick flooding, F: Slow flooding, G: snow avalanches.

It is worth noting in Table 3 that the absence of mitigating works (O=4.5) is the major cause of the high criticality, and it should be borne in mind that in presence of DSGSD, due to its general large volume of soil, it is usually impossible to plan stabilization works, but monitoring or minor and local mitigating works, such as to align, restore or replace tracks, are the more effective actions.

Table 3: Work factor values for the C3 criticalities.

	A1	B1	C	D	G
O=3	1	2	0	1	0
O=4.5	2	8	1	4	1

In 2014, for 9 of the 34 critical situations, Tt charged geotechnical engineers and geologists to carry out site-specific analyses with the double aim of studying the most critical sites and of validating the method. For this purpose 5 high, 1 moderate and 3 mild critical sites were selected. Results are shown in Table 4.

It is clear that the site-specific studies investigated the hazards at a larger scale (1 to 500, 1000) and then many sites could be divided in sub-sites with different hazard scores. In three cases the moderate or high criticality classes were confirmed, in one case it reduced due to the presence of effective works, in two cases it reduced only partially. In four cases the C classes increased because the works were actually recognized to be obsolete or absent, but fortunately for only a part of the investigated area.

Table 4: Method Validation. C class: "<" reduced, ">" increased, or "=" unchanged after the site-specific study.

	Before site-specific study					After site-specific study					
Case	Type	I	F	O	C	Type	I	F	O	C	C class change
1	A1	2	2	4.5	18	A1	2	2	1	4	<
2	A1	2	2	3	12	B2	1.5	2	4.5	13.5	=
						A2	1	2	3	6	<
						A1	2	2	4.5	18	=
						B2	1.5	2	4.5	13.5	=
3	A2	1	2	1	2	A2	1	1	4.5	4.5	>
						B2	1.5	2	1	3	=
						A2	1	1	4.5	4.5	>
4	B1	2	2	3	12	B1	2	2	3	12	=
5	B2	1.5	1	4.5	6.75	B2	1.5	1	4.5	6.75	=
6	B1	2	1	4.5	9	B1	2	2	4.5	18	=
						E	1.5	2	4.5	13.5	=
7	B1	2	2	3	12	A2	1	1	1	1	<
						B1	2	2	3	12	=
8	B1	2	2	1	4	A2	1	1	1	1	=
						B1	2	1	4.5	9	>
						B2	1.5	1	1	1.5	=
						B1	2	2	3	12	>
9	A1	2	2	1	4	A1	2	2	3	12	>

CONCLUSIONS

The proposed method provides Tt with a systematical tool to identify and manage the critical situations due to natural hazards. In particular, it gives a major role to the work factor, because it represents the factor which Tt may control by planning the monitoring, inspections and mitigation works. The validation of the method by means of site-specific studies revealed that the work factor must be supported by a design of the structures in order to assess their effectiveness and that the type of the natural event must be identified by geomorphological surveys carried out at a detailed scale, according to Fell et al (2008). With these improvements the criticality could be computed by means of deterministic analyses (for example by slope stability analyses) instead of using scores based on engineering judgment and experience. So far the results have been obtained by using a spreadsheet that calculates the C-score to each interval of track, but it would be desirable to implement the criticality assessment in a GIS in order to facilitate the visualization and the real-time update.

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