PRIORITIZATION OF SLOPE STABILIZATION WORK ON QUÉBEC'S ROAD NETWORK

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ABSTRACT
The majority of Québec's population and road network is located in the St. Lawrence River Lowlands. Significant marine-origin clay deposits in this region are prone to slope failure, resulting in a number of landslides affecting Québec roads each year. Although stabilization projects are carried out each year, not all sites requiring work can be addressed in a single year. Consequently, the Ministère des transports du Québec (MTQ) developed an index to prioritize the sites to be stabilized. This priority index enables the department's stakeholders to plan their stabilization work so as to first repair sites with a greater probability of landside or additional movement (e.g. readjustment), where road user mobility would be most impacted. Road user safety is assured at all times. The different factors considered in determining the priority index are presented, as well as the cartographic representation utilized as a decision-making tool.

RÉSUMÉ
Le réseau routier et la population du Québec ont été majoritairement établis dans les Basses-Terres-du-Saint-Laurent, où d'importants dépôts argileux d'origine marine se retrouvent. Ces dépôts étant propices aux glissements de terrain, plusieurs glissements touchent les routes du Québec annuellement. Malgré que des travaux de stabilisation soient réalisés chaque année, tous les sites nécessitant des travaux ne peuvent pas toujours être confortés en une seule année et le MTQ doit donc prioriser les sites à réparer. Un indice de priorité a été développé pour permettre aux intervenants du ministère d'établir leur planification des travaux de stabilisation de façon à réparer en premier les sites présentant une plus grande probabilité de glissement ou mouvement supplémentaire (ex. réajustement) dont la conséquence sur la mobilité des usagers serait la plus grande. Dans cette démarche, la sécurité des usagers est en tout temps assurée. Les différents facteurs considérés pour déterminer l'indice de priorité sont présentés ainsi que la représentation cartographique retenue comme outil d'aide à la décision.

1 INTRODUCTION

As part of its strategy to improve its landslide risk management practices, the MTQ implemented measures to reduce the risks of land movement, in soil and rock, that have the potential of affecting infrastructure sustainability and the safety and mobility of the users of its road network. These measures include improved road monitoring, leading to the reporting of landslides and pre-failure warning signs that may have an impact on its road network.

Each report leads to a detailed stability analysis of the site and to the conceptual design of stabilization work, if necessary.

As not all recommended stabilization work can be carried out as each new site is identified, this work must be done on a priority basis, each year. A priority index was therefore developed to support the decisions of those in charge of planning the work. The aim is to ensure that the first sites to be stabilized are those with a high probability of spatial evolution, and where the potential consequence to users is the greatest.

This paper considers only priority indexes developed for landslides in soils. However, a similar method is being elaborated for rockslides.

The paper first presents the problem of landslides in Québec and the actions that the MTQ has already taken to reduce the risk of ground movements that could affect Québec's road network. Then, the prioritization of stabilization work as an integral part of geotechnical asset management is introduced. The priority index for carrying out stabilization work is then presented as well as its use as a decision-making tool in planning works. The benefits and limitations of the method used to determine priority indexes are discussed before concluding.

2 THE PROBLEM OF LANDSLIDES IN QUÉBEC

In Québec, landslides are particularly problematic because of the presence of marine-origin clay, conducive to landslides. In Figure 1, the dark grey area delineates the territory included within the post-glacial sea limits that existed approximately 12 000 years ago, leaving significant clay deposits. The black dots represent the inventory of landslides that have occurred over the past 35 years.

The majority of the population of Québec, and of the MTQ's road network, is located within these boundaries, where more than 85% of landslides occur each year.

Among the particularities of some marine clays in Québec is their ability to go from a solid state to a liquid state, solely by remoulding. This is called "sensitive" clay. In the presence of sensitive clay, a landslide can sometimes degenerate into one involving an area of up to several hundred metres. Great caution and good knowledge are therefore required when studying the stability of slopes in sensitive clays and when carrying out a landslide risk assessment.

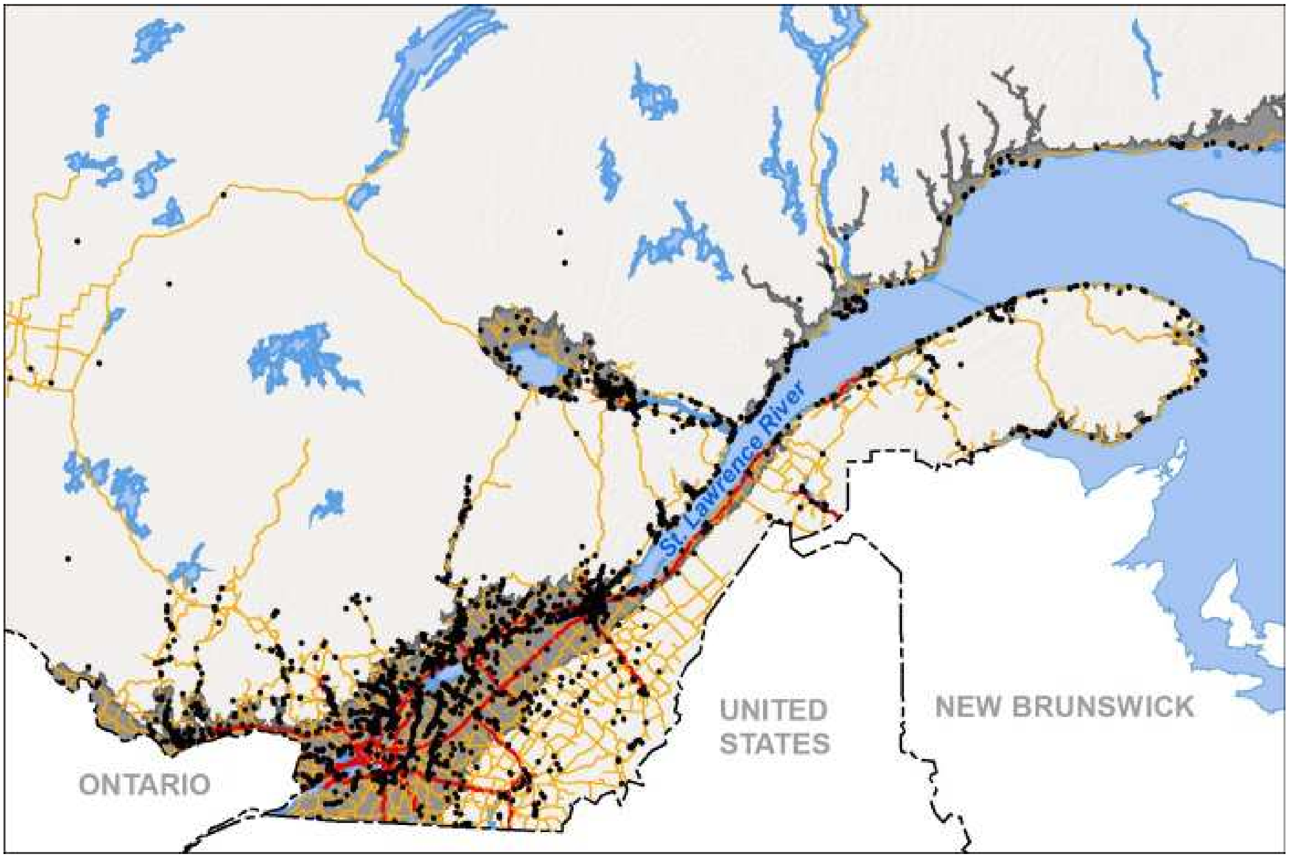

Figure 1. Depiction of the marine clay deposits (dark grey areas) and the inventory of landslides over the past 35 years (black dots) in Québec

Other types of landslides may also occur and affect the MTQ's road network. These include, among others, rotational slides that occur in clays (sensitive or not), superficial planar landslides that occur in all soil types, sudden flowslides of fine saturated granular soils and slow landslides in preglacial clays, whose shear strength exhibits strain hardening.

In addition, pre-failure warning signs of a looming landslide can at times be detected along the road network, making it possible to anticipate it.

Since Québec roads are affected by numerous landslides and pre-failure landslide warning signs of various types each year, the MTQ established a strategy to manage the risk of landslides that can have an impact on the road network under its responsibility.

3 LANDSLIDE RISK MANAGEMENT AT THE MTQ

In recent years, the MTQ has taken several steps to reduce the risk of landslides that could affect the road network.

3.1 Identify the risks

By mapping areas that are potentially exposed to landslides, areas with landslide-related constraints can be identified. This data is available on a map interface and can be consulted when planning the MTQ's roadwork.

For new road construction, the MTQ's geotechnical engineers prepare notices at the very beginning of projects in order to take into account areas at risk of landslide by avoiding the construction of infrastructures in these areas or by first stabilizing any precarious-stability slopes before starting construction.

Staff is given training, in particular, to promote good practices during the construction and maintenance of the road network and to prevent inappropriate actions from creating instabilities.

Improvements have been made to road network monitoring, now making it easier to identify pre-failure warning signs of slope instability or landslides that have occurred so that specialists can quickly study each site and make recommendations. An emergency email address is also available for reporting, allowing specialists to take immediate action.

3.2 Take action when landslides or pre-failure warning signs are reported

The various risk-reduction measures implemented in recent years have resulted in improved responses following risk detection. As soon as pre-failure warning signs or a landslide is reported, the specialists review the available data and photos transmitted. If necessary, they will recommend that field personnel establish a preliminary safety perimeter and will specify a monitoring frequency.

Two specialists then conduct an on-site inspection to gather additional data and confirm the safety perimeter and monitoring.

Upon their return from the site visit, the data collected is presented to other engineers specializing in landslides to confirm the cause of the slope instability observed and the steps to be taken to stabilize the site and reconfirm the safety perimeter and monitoring.

Determination of the safety perimeter and the associated monitoring is carried out in such a way as to ensure the safety of road network users. The perimeter is established by anticipating the next possible land movement and monitoring allows the perimeter to be readjusted following any subsequent movement, if needed, to assure user safety at all times (Figure 2).

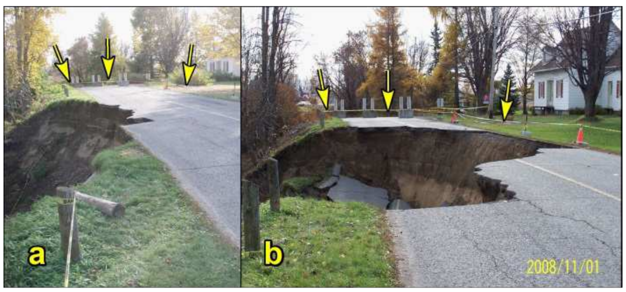

Figure 2. Example of a safety perimeter (closure of the road, indicated by the yellow arrows) having foreseen the spatial evolution of the next land movement to occur: (a) the landslide's initial scar and (b) enlargement of the scar

The slope stability study then carried out is adapted to the complexity of each site and will include, where necessary, a field and laboratory investigation to design the appropriate stabilization work.

The analyses carried out for each of the reported sites identify the requirements of the stabilization work to be realized along the road network.

As the annual requirements for stabilization work sometimes exceed the capacity of the MTQ, not all sites can be stabilized as they are identified. Those responsible for planning the work must thus prioritize certain sites each year.

4 WORK PRIORITIZATION – AN INTEGRAL PART OF GEOTECHNICAL ASSET MANAGEMENT

In its *Geotechnical Asset Management for Transportation Agencies: Implementation Manual*, the NCHRP (2018) defines geotechnical assets as any embankment, slope, retaining wall or constructed geotechnical subgrade (for example, lightweight fill, soil treatments, etc.) contributing to the performance of the transportation system.

Geotechnical asset management considers performance objectives related to the condition of the geotechnical structures, impacts on road network user safety and mobility as well as economic consequences. For this purpose, the United States Department of Transportation (DOT) has for several years considered the various assets located within the limits of the right-of-way (ROW) of the road network. Over time, in order to be able to take into account the off-site natural risks that may affect assets within the ROW (e.g. Figure 3), these organizations have also considered sites where the natural hazard is located outside the ROW (including natural slopes with precarious stability).

Several other transportation organizations in the world, which are already carrying out pavement and bridge management within their organization, have chosen to implement geotechnical asset management in order to be able to consider and manage the natural risks that may affect their road networks (FHWA, 2013).

Figure 3. Example of a landslide whose debris spread halfway across the road

Based on the results of a geotechnical asset management practice established concurrently with the management of other transportation assets, the identified benefits include:

- a systematic process to prioritize actions;
- more informed decisions based on easy access to several data sets;
- a greater knowledge of the risks and levels of risk faced by the organization along its network and the ability to manage those risks;
- reduced impacts on other transportation assets, such as roads and bridges.

In order to benefit from the above-mentioned aspects, the MTQ has been prioritizing stabilization work as part of the recent development of its geotechnical asset management strategy.

5 RISK-BASED PRIORITY INDEX

To better equip the stakeholders in the regional units to prioritize stabilization work, a priority index was developed based on the risks still present from the time of completion of a site's slope stability study to the completion of the stabilization work required at the site.

Indeed, it is hoped that the stabilization work will be done first at the sites with the greatest probability of rapid evolution and where the occurrence of further deterioration would most impact the mobility of road network users.

The aim is to avoid a significant change in site conditions before the work is completed, as illustrated in

Figure 4, for example, where an arc-shaped crack in the shoulder evolved into a landslide.

Figure 4. (a) Pre-failure warning sign of a landslide (arc-shaped crack in the shoulder) and (b) landslide, occurring before stabilization work

The stabilization work conceived at the time of carrying out the initial slope stability study, in the presence of pre-failure warning signs only, must be revised if a landslide occurs. In order to design the landslide repair, the failure surface must be located, the thickness of the debris determined, etc. In addition, geotechnical investigations and supplementary land surveys are likely to be required.

The impact on road network user mobility will be accentuated since the initial perimeter will most likely need to be enlarged to maintain public safety. Above all, the stabilization work will be delayed while the geotechnical study is revised.

There clearly are economic and social advantages to proactively stabilizing a slope or repairing a landslide before further deterioration.

5.1 Definition of the priority index

The priority index was developed using a scale of 1 to 5, with 1 being the highest priority, considering both the likelihood that a movement could occur quickly and the potential consequences to users.

Drawing on the analysis used to determine the priority index values for each of the analyzed sites, the hazard can be assessed according to the situation (presence of pre-failure warning signs or a landslide) and the vulnerability according to the importance of the road connection affected and the degree of impact.

The factors considered in assessing the hazard and vulnerability and the method used to combine the two into a priority index value are presented below.

5.1.1 Hazard assessment

Where there is a landslide, the hazard corresponds to the danger of the scar enlarging before stabilization work is carried out, by readjustment of the slope failure scarp or, more rarely, after a second landslide (Figure 2).

Where there are pre-failure warning signs of a landslide, the hazard corresponds to the danger of a landslide occurring before stabilization work is carried out (Figure 4).

Since evaluation of the hazards' probabilities of occurrence involves several uncertainties, it was decided that, for each case studied, the likelihood of the hazard occurring be estimated, by adding the aggravating factors present at each site studied, (i.e. the factors that result in decreased slope stability with respect to the conditions considered when conducting the slope stability study). Using this method, the assessed hazard is augmented simply by the presence of an aggravating factor and an assessment of its importance, since it is extremely difficult to accurately predict and quantify the importance and evolution of aggravating factors for each site.

The assessment is based on the knowledge of experts who have sufficient quality data for each site (as a result of the slope stability study) and who have a good understanding of the hazard`s behaviour.

Thus, a high hazard factor for a given site indicates that it is more likely that a movement will occur and that it will likely occur sooner at that site than at a site with a low hazard value.

The factors considered in hazard assessment are presented below.

5.1.1.1 Anticipated failure mode

In the presence of pre-failure warning signs, specialists first identify whether a sudden failure is possible, as is the case in the post-glacial clays of Québec, whose resistance presents strain softening. A sudden failure is also possible in granular soils through superficial planar landslide or sudden flow of saturated fine granular soils.

In the presence of a landslide, depending on the type of soil in which the failure occurred, the possibility that a second movement occurs through readjustment of the scar scarp or following a second failure when the scarp is sufficiently high and steep, is assessed and considered an aggravating factor.

Any partial stabilization measure reducing the possibility of a readjustment or second movement occurring, such as a flattening of the slope failure scar, is taken into account in the hazard assessment.

5.1.1.2 Presence of an initiated movement

If the pre-failure warning signs of land movement indicate that a landslide has been initiated (eg. a crack with vertical offset, inclinometer measurements that confirm a movement or border of soils that is present at the foot of the slope) the possibility of a landslide occurring, and occurring quickly, is greater, as is the hazard.

5.1.1.3 Presence of water concentrations

The natural water conditions in the soils of the slopes analyzed are taken into account during the stability analysis, to determine the safety factor and to design the slope stabilization or landslide repair.

Subsequently, potential water concentrations at the site are an aggravating factor that can further reduce slope stability, or even cause movement. For example, when the slope is located at a low point in the topography towards which surface water converges, water inflow can be substantial and is considered an aggravating factor.

The proximity of a mountain is also an aggravating factor since at certain times of the year, large amounts of water can be conveyed to the slope during snow melt or heavy rains. A dramatic and sudden increase in water levels, which can result in fine granular soils whose low permeability allows for the development of interstitial pressures, is also considered an aggravating factor.

On the other hand, any drainage or water mitigation measure put in place will reduce, at least in part, the possibility of a movement occurring and will therefore be taken into consideration.

5.1.1.4 Presence of erosion

Erosion due to the presence of a watercourse at the foot of a slope is one of the primary causes of landslides. The presence of erosion is therefore taken into account and quantified according to evidence observed during the field visit (erosion faces or undercutting) or the slope's position relative to the watercourse (inside of bend, outside of bend or straight section).

5.1.2 Vulnerability assessment

The safety perimeter and monitoring set up after the slope stability study are intended to ensure user safety. Indeed, the safety perimeter is designed to anticipate the scope of the next most plausible movement to ensure that users are protected should the movement occur. In addition, site-specific monitoring is established to allow the perimeter to be readjusted, if necessary, and both the perimeter and the monitoring can be adjusted according to climatic conditions (e.g. during rainy periods and during snowmelt).

Vulnerability is therefore assessed in relation to the impact that the safety perimeter adjustment would have on user mobility if the anticipated movement occurred prior to completion of the stabilization work.

The factors considered in determining vulnerability are presented in detail below.

5.1.2.1 Anticipated maximum spatial evolution

Depending on the situation at the time and the type of movement anticipated (e.g. superficial planar or rotational landslide, landslide scar readjustment, etc.) the specialists estimate the maximum spatial evolution that could be reached by the movement as well as its possible evolution, in order to assess the impact on the roadway and consequently on user mobility.

Depending on the case, the anticipated maximum spatial evolution could be limited to the slope of the road embankment, could reach the shoulder, a lane or, in rare cases, necessitate a complete road closure. The assessment would also take into consideration the ability to move traffic along a diversion lane or detour path.

Consideration of the impact of the next anticipated movement, rather than just the current one, increases the vulnerability of some sites compared to others (i.e. those for which a subsequent movement would be expected to result in a larger encroachment on the road). This would favour their prioritization over those sites for which a subsequent movement would have a lesser consequence, which is actually the desired outcome.

5.1.2.2 Road and traffic importance

The level of importance of a road axis is taken into account. The fact that a segment of the road is part of the Strategic Road Network would have a greater weight than if it is located outside this priority network.

The functional classification of the road (highway, national road, collector, etc.) is also considered. Highways always have a greater weight, whether or not they are part of the Strategic Road Network. The annual average daily traffic (AADT) is also taken into account.

In the particular case of roads identified as a unique road connection (that is, in the absence of a detour road, the loss of the road connection would entrap or isolate a portion of the population), when the road connection may be lost as a result of a landslide or enlargement of a landslide scar, MTQ authorities are automatically notified, making it possible for stabilization work to be carried out without delay.

Organizations typically consider these parameters in managing their transportation assets because doing so is felt to provide a better return on investment (Lowell et al., 2005).

5.1.3 Priority indexes assessment

The priority index assessment matrix allows for a range of possible outcomes to be compared according to the values assigned to the hazard and vulnerability criteria, namely, the probability of occurrence and the severity of the consequences, respectively (Figure 5).

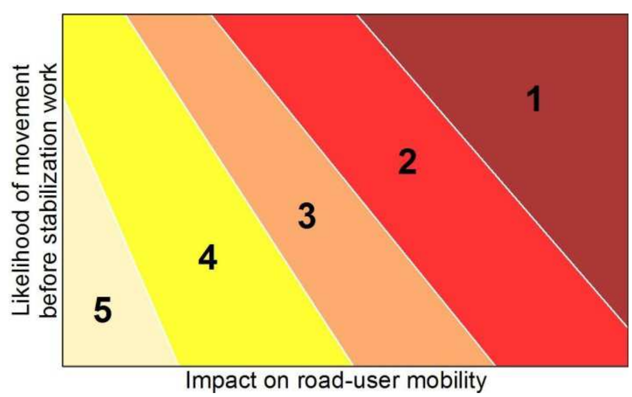

Figure 5. Illustration of the matrix for determining the priority indexes

The higher the likelihood that a movement will soon occur and the greater the impact the movement would have on road network user mobility, the higher the priority of the site to be stabilized (a value of 1 represents the highest priority and its pictogram is darkest in colour). Figure 6 shows the pictograms associated with the 5 priority levels.

Figure 6. Pictograms representing the priority of carrying out stabilization work and the associated index value, from the highest priority (index of 1, dark red pictogram) to the lowest priority (index of 5, pale beige pictogram)

It should be noted that if, prior to stabilization work, a significant change in site or movement conditions occurs due to, for example, erosion action, the hazard and vulnerability assessments would be revised, resulting in a potentially higher priority.

The use of a matrix to determine priority indexes has the advantage of reducing subjectivity and maintaining consistency between the assessments made for different sites. The use of this type of matrix makes it possible to evaluate the priority level of each site based on parameters common to all. This method also has the advantage of reflecting the fact that a hazard with an unlikely probability of occurrence could still merit a high priority if the potential consequences associated with it are considered highly significant. Conversely, a hazard given a very high probability of occurrence may not have a significant potential consequence and thus would not warrant priority stabilization.

The matrix used was calibrated by a committee of landslide specialists who examined and compared nearly a hundred cases of landslides or pre-failure warning signs. Although there are many different types of slides along the road network, there remain areas of the matrix where few cases are found and, therefore, calibration of the matrix will continue as and when new sites are evaluated. The same committee evaluates all cases upon completion of stability studies, which enhances consistency and allows, at the end of the process, the sites' priorities to be compared with each other.

6 DECISION-MAKING TOOL

Once the priority index values have been identified, they are presented on a cartographic interface (Figure 7) to assist decision-makers in planning the stabilization work. Thus, at a glance, the user knows the location of all sites to be stabilized and the priority associated with each.

When clicking on the pictogram, the user accesses more information about the site, such as safety perimeter to be respected, monitoring program, nature of the stabilization work to be planned (slope flattening by cutting or counterweight, addition of erosion protection, etc.) among others.

Stabilization work will first be done at highest-priority sites. Planning the works or determining the order in which the sites are stabilized may be relatively easy for a territory whose sites' index values are roughly evenly distributed between 1 and 5.

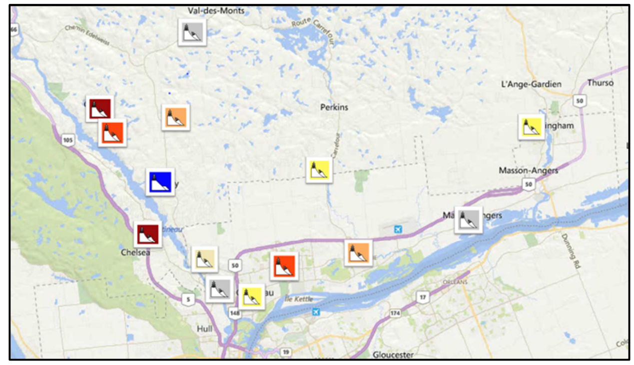

Figure 7. Fictitious example of pictograms presenting the location of sites as well as the stabilization priority index value associated with each one, for a given region

On the other hand, for regions where a majority of sites would have equal priority index values, the specialist engineers would be involved to assist in the decision-making process, and a more refined prioritization of these sites would then be performed.

Once the highest-priority sites are stabilized, the resources needed to carry out the work recommended for the lower-priority sites are dedicated accordingly. Among these, where it is believed that impact to the road will not occur soon, due to the distance between the road and the slope, preventive stabilization can be carried out. It is preferred to stabilize sites while the hazard is farther from the road, since it allows for the integration of more environmentally friendly and less expensive solutions (e.g. vegetation engineering techniques, slope flattening by cutting and thus possibly no encroachment into the river, etc.). Waiting too long to stabilize lower-priority sites could result in the need for more extensive stabilization work requiring more space or an encroachment into the river, for example (e.g. rockfill counterweight).

However, as long as the slope stability study is not completed, the conceptual design of the stabilization work is not known and the site therefore has no priority index value. Instead, it is identified as a site under study (Figure 8, (a)).

Likewise, a site for which stabilization work has already been completed will no longer have a priority index value associated with it, but rather a different pictogram (Figure 8, (b)) and related information defining the inspection and maintenance recommended for the built work.

An inventory of locations where stabilization work has been carried out is very important for an organization since after several years, the vegetation covering the works can leave them go unnoticed. For the different types of future roadwork planned near stabilization works built a few years ago, knowledge of the location of the works will enable specialists to make recommendations and cautionary notes to avoid generating slope instability during the roadwork. The location of the completed stabilization works can also be incorporated in updates to the existing cartography of landslide potentially exposed areas.

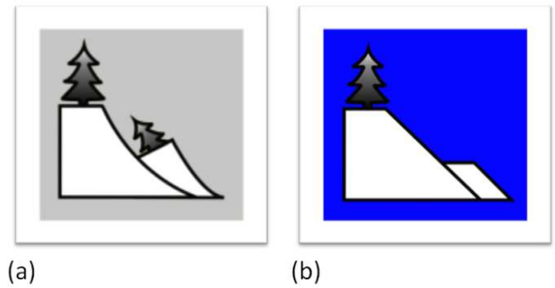

Figure 8. Examples of the pictogram representing (a) a site under study and (b) a stabilized site

7 BENEFITS AND LIMITATIONS

The development of priority index values for stabilization work results from a simple, neutral and reproducible systematic approach that allows:

- consideration of the same criteria by all engineers recommending and designing stabilization work;
- more rigorous supervision of individual perceptions;
- detailed documentation of decisions.

However, this approach is based on a methodical anticipation of possible situations, rather than on numerical models or calculations. It may thus happen, before completion of the stabilization work, that a site with pre-failure warning signs and a priority index value of 4 fail before a site also showing pre-failure warning signs but having a priority index value of 2. Indeed, since this is a possibility, a higher priority is no guarantee that a movement will occur at that site first. On the other hand, since the priority index depends on the slope hazard and vulnerability, a higher priority indicates that the probability of occurrence of the slide was higher for the site with priority 2 or that its consequences on road user mobility were greater. As such, it seems both relevant and appropriate to recommend stabilizing a priority 2 site before stabilizing a priority 4 site.

Simplification of the identification and assessment method to make it a straightforward, easy-to-use and reproducible tool can lead to less accurate results. However, this loss of precision is counterbalanced by having a committee of specialists carrying out the assessment and by the standardization and supervision inherent to the method.

8 CONCLUSIONS

The MTQ developed a priority index scale to assist those in charge of planning stabilization work on its road network and to enable them to make informed decisions. A priority index value, ranging from 1 to 5, is determined for each site requiring stabilization work.

The method developed is simple, reliable and reproducible. For a given study site, an assessment is made of the likelihood that a movement will occur before stabilization work is completed, as well as of the impact the movement would have on road user mobility. As a result of this method, stabilization work can be prioritized through an objective and systematic assessment.

This natural risk management approach that allows the prioritization of stabilization work is an integral part of the development of geotechnical asset management at the MTQ.

The work presented in this paper has focused on stabilization work to prevent or repair landslides in soils but a similar exercise is under way to develop a prioritization of stabilization work on rock faces.

9 ACKNOWLEDGMENTS

This publication was authorized by the departmental authorities of the authors concerned.

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