3D modelling study on landslide risk of rocky blocks, applied experience on rocky outcroppings along hillsides than can affect Generalitat Catalana roadways.

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Abstract. Studying accidents caused by landslides since 2015 by DGIM (GENCAT) has brought to our attention the importance of the landslides that happen on hillsides, outside of cutting slopes of the public domain areas, that affect road safety. Other than the vulnerability of the trace caused by these events, we need to be aware of the following: the scale of the processes (rocky outcropping that occupies large areas on natural slopes), the location of the outcropping outside the railway line, the conditioning access factors due to orography, the budget and time limitations when studying these events have forced the application of 3D modelling from drone images in order to support the traditional methods of data collection through surveys and the rock mass classification through the installation of geomechanical stations in the field. The experience gained from applying these processes has allowed us to establish a study system that is being currently applied to the network. The main qualities of the method, the critical analysis of the previous facts and the future lines of work that this team is facing, are the scope of this article.

1. Introduction

Road infrastructures modify natural ground (raising, demolishing, or transforming) to have a platform that provides correct services. Those elements are named road assets and in the field of infrastructure are classified as: bridges, grading with excavation or filling and tunnels.

Nowadays, the private and public sector has developed, on these assets, different strategies, preventive or palliative determined by the scenario, for maintenance and improvement: site inspections, methodologic tools, etc. to assess and minimise the risk of failure.

Rockfall is a natural process that involves the detachment and rapid forward movement of a rock due to the gravity effect that occurs in stony areas exposed to weathering and other geological processes on natural or artificial slopes. Relief and slope are characteristics that define if the road infrastructure can be exposed to rockfalls or not. Even if the practice of the rockfall failure takes place outside the road infrastructure area should be a key point on the infrastructure investigation, even more, considering the constant change due to climate change and the difficulties of access and assessment.

Catalonia is a mountainous territory and landslide is a common incident in the area. This phenomenon, which is highly difficult to study and predict, is recollected on the risk assessment library of DGIM and it becomes a real challenge to maintain and explode the road infrastructure service.

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ministry of territory and sustainability through the general ministry of mobility infrastructures in Catalonia (DGIM) is the leading agent of Catalan mobility, managing 6,000 km of road and providing service to more than 840 million users [1].

GENCAT (Government of Catalonia) due to the difficulties of available resources, the problem, and level of accessible services, nowadays, applies a methodology that consists of listing and defining the risk on each rocky outcrop hillside that supposes a hazard to their road infrastructure.

Looking into the geological risk, altitude, and rainfall distribution of each rocky outcrop those which are considered unstable can be identified [2]. The discontinuities and possible failures that are associate with each rocky outcrop can be controlled and analysed and through a risk and consequences matrix table, the influence on the road infrastructure can be judge, furthermore, can be designed the remedial measures required in each scenario.

INES Ingenieros has developed the methodology presented on this paper during 2019 and 2020 under a contract named “Emergency contract for the monitoring and control of the geotechnical investigation of the road network of the Catalan Government Code: EX-CEC-18197”, currently, the method has been applied on different road infrastructures on the Catalan territory. The system categorises the rocky outcrops risk through images and 3D models obtained processing information from a drone. Once the risk is assessed is possible to design the remedial works required. All this process allows to list out the potentially problematic areas. Specifications and details of the work methodology are presented in the following sections. Nowadays has been carried out studies that make possible the evaluation of the results obtained; 12 hillsides are considered the most relevant ones.

2. The significance of rockfall developed on GENCAT network

Even if there is not a clear list out, can be confirmed that landslides have a high impact on the GENCAT road infrastructure management.

The above lower the security on the roads and represents a high direct and indirect cost. Defining some average values, just in 2018 were registered 2,625 landslides in Catalonia, 893 from those where rockfall and 92% had aftereffects on the GENCAT road infrastructure [3]. Even more, mortal victims due to landslides on road infrastructures have increased. From 2001 to 2016 were registered 1 mortal victim every 15 years, but from 2016 this value raised to 1 victim per year.

Even though the accident rate is lower considering other accidents related to the road infrastructure maintenance: animal roadkill, elements on the road, etc. those events develop a public concern, and as a result, there is an unsafety feeling and a discredit on the managing institution.

Due to the reasons explained above, and because of the proactive mindset of the management institution, was decided to develop the following assessment methodology for the natural hillsides that affects the GENCAT road infrastructure.

3. Analysis methodology

The methodology is composed of the following states:
The first step in the methodology is previous documentation analysis. It is necessary to do research on geological context, geomorphological, seismicity, hydrology, climate environment, rainfall, vegetation, and previous studies in the area. Based on this information would be possible to define areas to proceed with on the method.

The main difficulty of the characterization of these areas is the access to get the data required. The admission is limited or even none in some scenarios. It is worth remembering that traditional inspection techniques were unable to study the existence of the instability, because of that, this method performs the assessment through images and digital elevation models (DEM) obtained by SfM technique (photogrammetry).

For this reason, we propose the following workflow. As mentioned before, firstly is the collection of the hillside data by a drone from the air; once the information is collected, we will be modelled in 3D based on SfM technique; and to finalise, the model will be optimised for the assessment. All these steps can be developed using a free licence or low-cost software.

Even if the Structure from Motion technique (SfM) comes from the artificial vision sector, nowadays, is a method based on photogrammetry. Thanks to computational calculations SfM can develop a 3D model from images that do not require to be calibrated or structure, with different perspectives and even with deformations [4]. Because of that, we can define the technique as a more robust and versatile tool to develop the model. Furthermore, SfM can be considered as a photometric high-resolution method that does not involve a high cost compared with other restitution 3D practices.

Afterwards, to develop a proper assessment with the necessary tools and methodologies, the model will need to optimise erasing the vegetation and lowering the information data reproduced so the model can be manageable, feasible and descriptive.

In this way, it is possible to obtain high-resolution images of the unstable hillside and rocky outcrops, even more, can generate a 3D model to assess the probability of rockfall, if there is any risk of the landslide reaching the road infrastructure, and the classification of the slope depending on the level of risk.

After the development of the 3D model and the optimization, the slope analysis can be defined in 4 stages:

- **Sectorization.** Depending on the types of rock outcrops, slope orientation and trace position, the area will be classified into different sectors ‘figure 1’.

![Figure 1. Different areas or sectors on the natural slope.](image)

- **Identification of potential instability.** Identification of sensitive areas to suffer a landslide or natural rocks accumulation ‘figure 2’.
• **Stabilizers mechanisms. Cinematic analysis.** Once we have the points map of the 3D model, we can obtain the dominant orientation plane for each outcrop. One of the tools that can merge the 3D model points with the plans is named “facets” on Cloud Compare [5] which requires some adjustments: dip angle, distance, minimum points number, etc. Through the dominant plan, we can obtain the different types of discontinuities that the outcrop has and all the map of points on the DEM can be classified on those ones. Subsequently, we can proceed with the cinematic analysis of each one. The rockfall stability can be assessed on each type of discontinuity that has been obtained on the model. The failure analysis for each outcrop can be studied with tools as Dips (RocScience) [6] ‘figure 3’.

![Figure 2. Sector B general view and identification of potential instable areas for their study.](image)

![Figure 3. Example of planes, poles and failure mechanism on different outcrops](image)
• **Failure probability. Landslide factor of safety (FS).** Once has been determinate the failure method, considering outcrop block size and geometric parameters, we can proceed with analysing the stability of each outcrop against different failures. Each failure will have different software and it will require to be assessed in a separate way, software that is available for this type of analysis are RocPlane, Roctopple, RocWedge from RocScience [7]. On the simulation there are different configurations due to the failure hypothesis: dip angle, ground cohesion, seismicity, the quantity of water, etc. obtained from the environment study ‘figure 4’.

![Figure 4. Block modulization example for failure analysis.](image)

**Reachability. Possibility for a landslide to reach the road infrastructure.** After knowing the probability of a landslide, is needed to study if each one can achieve the road infrastructure ‘figure 5’. We call this analysis a study of reachability. In the study the rockfall is simulated on different areas of the hillside, software that can reproduce it are RocFall (RocScience) [8], and determinates, through statistics, mass-energy, speed, and the possibility of the rock reaching the road infrastructures ‘figure 6’. The simulation is assessed with the DEM, which is obtained from the DTM.

![Figure 5. Example of road susceptibility analysis](image)
4. Platform risk assessment and remedial measures design.

The risk assessment will consider two main facts: failure probability and consequences of the failure. At this stage the previously calculated data is pondered as per the following:

- **Failure probability**: landslide probability and the safety factor obtained through the outcrop modelling, once defined the dominant discontinuity plan and calculated the dip angle and angle of fracture with the stereographic analysis. We must point out that the dimension of the outcrop or the dimension of the possible rockfall has not been involved. The study is based on the probability of failure and not the dimension of it. Moreover, this stage has not been considered the vulnerability of the process in front of the climate events.

- **Failure consequences**: the risk of the landslide reaching the road infrastructure will assess the consequences. It should be mention that, in this stage, we do not consider other parameters like the visibility on the road, the probability of avoiding the impact… the risk of the landslide reaching the road infrastructure will assess the consequences. It should be mention that, in this stage, we do not consider other parameters like the visibility on the road, the probability of avoiding the impact…

Including both information on a matrix, as represented in the table below, we can estimate the outcrop risk.

| RISK LEVEL | SAFETY FACTOR |
|------------|---------------|
| % Reachability | > 1.5 | 1.5 – 1.2 | 1.2 – 1.0 | < 1.0 |
| 75 – 100 % | High | High | Very high | Very high |
| 50 – 75 % | Medium | High | High | Very High |
| 25 – 50 % | Low | Medio | High | High |
| < 25 % | Very low | Low | Medio | High |
Afterwards, it is possible to proceed with a sensible risk assessment composed of previously calculated variables: percentage of the rock that reaches road infrastructure, angle of response, water quantity, etc. Then can be proposed different options as remedial works.

| Water amount | 50% | 100% |
|--------------|-----|------|
| Angle of response | 15 | 35 | 15 | 35 |
| Zone 1 | 66.7 | 25 | 35 | 28.5 |
| Zone 2 | 75 | 25 | 25 | 75 |
| Zone 3 | 25 | 75 | 75 | 25 |
| Zone 4 | 75 | 25 | 25 | 75 |
| Zone 5 | 40 | 25 | 25 | 40 |
| Zone 6 (27°) | 40 | 25 | 25 | 40 |
| Zone 7 | 28.6 | 25 | 25 | 28.6 |
| Zone 8 | 66.7 | 25 | 25 | 66.7 |

To confirm that all data is clear and has coherence all data must be confirmed on site by a specialist. Lastly, we collect the dimensions and measures on-site to adopt the remedial works applied to each scenario.

5. Conclusions
We can conclude that the development and application of the new technologies have currently a critical role in the management and even on the risk assessment. New technologies are key to identify and evaluate hazards for road infrastructure security. The methodology and tools make possible the identification and classification of the rocky outcrops on non-accessible slopes. The ones whose failure can be a threat to the traffic circulation.

We should emphasise that the methodology is composed of simple computational skill:

- The collection of the data on-site with drones, through high-resolution photography and 3D modulations, allows us to have unique information, high yields, georeferenced data, lower down errors and eliminate the subjectivity on the data collection for stability assessment.
- 3D model not just is applied for characterizing the outcrop and identifying the different sectors of the slopes, furthermore, the 3D model can obtain the needed parameter to study the stability. Because of that, we can conclude that the 3D model is applied for the slope stability study.
- The assessment is based on DEM and DTM obtained through photogrammetric SfM, which means that is extremely sensitive to the input data and management of information and is a specialist who needs to make sure the coherence and quality of the images.
- We recommend saving two non-modified models: the original model and the original model scaled and georeferenced in high quality, so the information can always be compared and revised between them.
- Each outcrop obtains a unique classification, and it will not be homogeneous, because of that, the classification is key for an adequate assessment.
- The dominant plans that define the discontinuities of the rocky outcrop, and the definition of the relevant parameters for the models of stability and reachability, are crucial to obtain a representative solution that can be applied on-site and assessed by a specialist.
This methodology allowed us to provide the first assessment, with simple and clear techniques and low-cost software, on 12 GENCAT hillsides. Consequently, there is a higher security level, a quality data improvement, and the possibility of risk assessment on landslide failure. The data obtained, after all the interpolations made, are considered representative of the infrastructure network.

As previously mentioned, the information is georeferenced. Therefore, slopes data can be saved in the Geotechnical Asset Management System of the GENCAT. So, the data can be implemented on a historical maintenance register. Can be a starting point to obtain a thematic register that depends on the state of the natural slope in front of climate change threads.

To sum up, the purpose of this new method is to identify critical situations, prioritise interventions, reproduce accurate cost estimations and define strategies for road infrastructure maintenance.

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