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Deepening an old, verticalised pit: rock slope instability hazard assessment using a digitally augmented structural database (Flône limestone quarry, Belgium)

Approfondissement d'une ancienne fosse verticalisée : étude d'aléa d'instabilité rocheuse sur base d'une base de données structurales « augmentée » (carrière de Flône, Belgique)

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ABSTRACT: We present a rock slope instability hazard study of the Flône pit (Belgium) by means of a deterministic kinematic stability analysis. The specificity of this study resides in the "digital augmentation" of the field mapping structural database (x 5) by semi-automatic point cloud analysis. Results show that the main instability hazards in the actual pit are flexural toppling and, to a lesser extent, wedge sliding. Planar sliding, although minor, will constitute a significant hazard for interbench rupture during future excavation due to the presence of an anticline structure at depth. The augmented — and georeferenced — structural database has enabled us to generate a synthetic rock slope instability hazard map that constitutes the basis for the recommendation of targeted monitoring solutions during future excavation works.

RÉSUMÉ : L'aléa d'instabilité des fronts rocheux de la carrière de Flône (Belgique) a été étudié par analyse cinématique déterministe. L'augmentation numérique (x5) de la base de données structurales par analyse semi-automatique en nuages de points a permis de montrer que les principaux aléas d'instabilité sont le basculement et, en moindre mesure, le glissement en coin. Le glissement planaire, bien que mineur actuellement, constituera cependant un aléas important de rupture inter-bancs lors de l'approfondissement, de par la présence d'une structure anticlinale identifiée en profondeur. Enfin, notre base de données structurale géoréférencée et augmentée a permis de générer une carte synthétique des aléas d'instabilité des talus rocheux, qui constitue la base de recommandations de solutions de surveillance ciblées lors des futurs travaux d'excavation.

KEYWORDS: rock slope instability hazard, drone, LiDAR, digital mapping

0 FOREWORD

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1 INTRODUCTION

With increasing environmental awareness, optimising the extraction of readily available resources — prior to searching for new ones — is key to ensure future sustainable extraction activities. Nonetheless, optimising resources by deepening a pit and/or verticalising its fronts goes along with increased instability hazard and may endanger the personnel working at a given site.

Lhoist Group plans to optimise the exploitation of the Hermalle site pure limestone resource. The Hermalle quarry is located in a very narrow and steep location at the border of the Meuse River in Belgium (Figure 1). It is a 2.5 km long, 300 m large elongated pit whose westernmost part (the "Flône" pit) has not been exploited since 2007. Since then, the 3 upper benches have been already set in their "final" position (i.e. 20 m vertical each, with 5 m interbench distance - Figure 2), making it inaccessible for geological-structural mapping.

Although no major instability hazard has occurred since this time, it was imperative for security reasons to:

(i) assess the instability hazard in such narrow and steep conditions,
(ii) gain a view of the resource at depth, prior to restarting extraction activities in the Flône pit.

Although geological interpretation of "virtual outcrops" has been successfully tested to map inaccessible areas such as cliffs (e.g. Xu et al., 2001, Trinks et al., 2005) or caves (Triantafyllou et al., 2019) or for detailed structural mapping at outcrop scale (Martin et al., 2019), to our knowledge only few studies (Smith & Holden, 2020) have attempted to integrate a deterministic kinematic stability analysis into such mapping. In addition to this, here we also link this kinematic stability analysis with hazard mapping of the quarry.

2 GEOLOGICAL CONTEXT

The Hermalle quarry exploits Visean limestones and dolomites along the Midi-Eifel thrust zone, the Belgian part of the Variscan Front Thrust that delimits the European Variscides to the south, with the Caledonian basement to the north. The exploited rocks pertain to the lower to middle Visean Terwagne, Lives and Neffe formations. Below and above these formations occur the Tournaisian dolomites of the Engihoul formation and the Namurian shales of the Chokier formation, respectively. This folded sedimentary succession crops out in the quarry as steeply S-dipping strata with normal stratigraphic polarity, or steeply N-dipping with reverse polarity in the south and the north of the pit, respectively. The northern front also shows a tight, upright fold, with an axial surface dipping towards the pit (see also cross-section of Figure 5, Section 4).

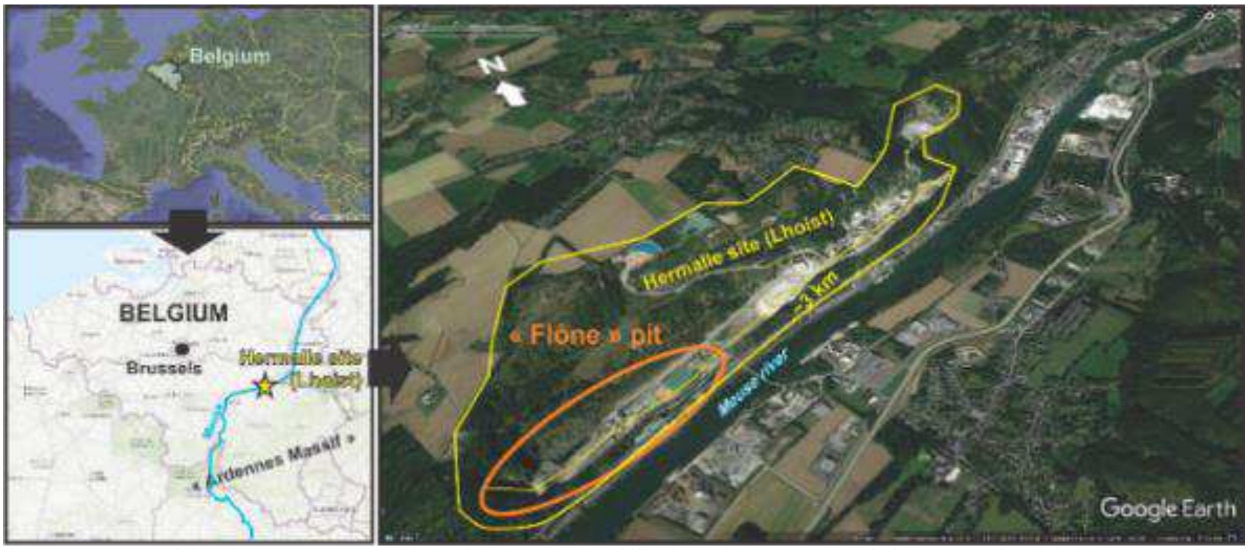

Figure 1. Context of the Flône pit (orange), object of the present instability hazard assessment study by means of a digitally augmented structural database.

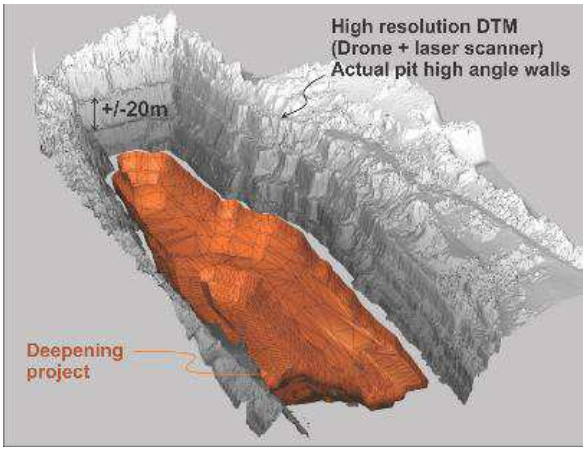

Figure 2. Flône actual pit geometry (grey) and deepening project (orange).

3 METHODOLOGY

3.1 *Digitally augmented structural database*

The high-density point cloud has been constructed by merging a fix station laser scanning acquisition from the base of the pit with an aerial (drone) photogrammetric survey. This dual acquisition has allowed us to increase and homogenise point density, especially in scanning dead angles for geological and geotechnical study purposes.

Our structural database, based on:

(i) field mapping: 157 dgps stations, 211 planes – s0, s1, fractures, faults – and 24 lines – slickensides, fold axes, and

(ii) archive integration: lhoist pit photographs and structural database,

has then been digitally 'augmented' by semi-automatic, point-cloud based picking of ~1000 plane orientations using cloudcompare software (Figure 3).

The georeferenced point cloud not only allows us to retrieve data from inaccessible areas such as each of the three 20 m high, verticalised fronts of the flône pit, but also enables us to refine the geological model and perform targeted detailed kinematic slope stability analyses, precisely locating the subsets of problematic structures directly in gis. Remote data measurement is reliable, efficient and a powerful methodology for both geological and geotechnical studies.

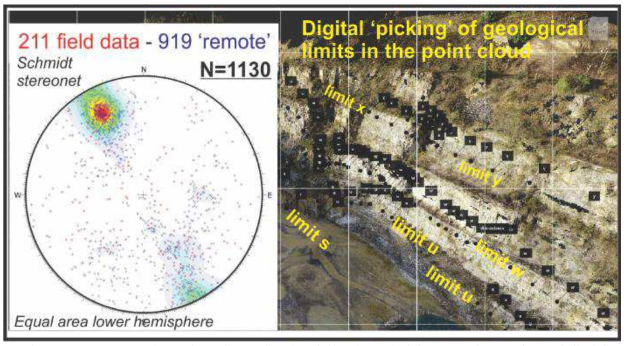

Figure 3. 3D point cloud geological limits picking and results of field & remote structural database

3.2 *Interpretative geological cross-sections*

In order to evaluate simultaneously the evolution of the limestone resource at depth and the instability hazard during excavation of the future pit, four interpretative cross-sections (see Figure 4 for their location) have been produced, of which two are presented in Figures 5 and 7. These sections allowed discussion of the instability hazard to be integrated with the future design of the pit and hence served as a basis for making recommendations for monitoring and additional investigations, as well as general recommendations regarding future excavation works.

3.3 *Rock slope kinematic stability analysis*

Three rock slope instability hazards have been investigated by means of rock kinematic stability analysis using the Rocscience software suite: planar sliding, wedge sliding and flexural toppling. Investigation of general failure mode was not part of this study, considering the overall strong character of the exploited limestones and dolomites as deduced from our field mapping.

For each actual front (South, North, West and East) of the Flône pit, we have computed plane, wedge and flexural toppling kinematic stability analysis based on >1000 planes covering the 4 mapped tectonic units. To perform the kinematic stability analyses based on Markland's test (Hoek and Bray, 1981), we have considered an average slope dip of the quarry fronts of 75°, a friction angle of 30°, and the georeferenced structural database that enabled detailed instability hazard maps to be produced.

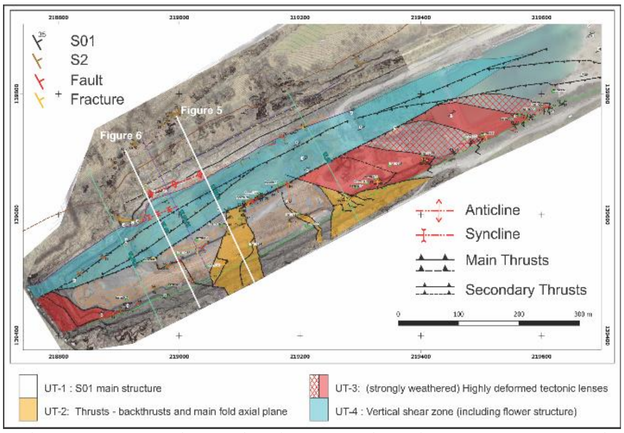

Figure 4. Structural map showing Tectonic Units UT-1 to UT-4, and location of the cross-sections presented in Figures 5 and 6.

4 RESULTS

4.1 *Geological – structural mapping and cross-sections*

Based on our new field structural mapping and augmented structural database, we were able to distinguish four tectonic units in the Flône pit (Figure 4), each characterised by a different degree of deformation: UT-1 is composed by dominant S0/1 planes, UT-2 is in addition crosscut by one family of high angle (back-)thrust faults, UT-3 shows complex (recumbent) fold geometries and is cut by two or more fracture/fault orientations, and UT-4 corresponds to decameter scale, steeply dipping deformation zones (e.g. inverted flower structures) where S0/1 is no longer visible.

The presence of high angle thrusts and backthrusts crosscutting the S0/1 and recumbent folds and intense shearing affecting the western- and easternmost part of the pit was previously unrecognised (Lhoist, 2008), and allowed us to draw a more consistent tectonic interpretation of the Flône pit. The cross-section shown in Figure 5 draws a representative view of the structure across the pit.

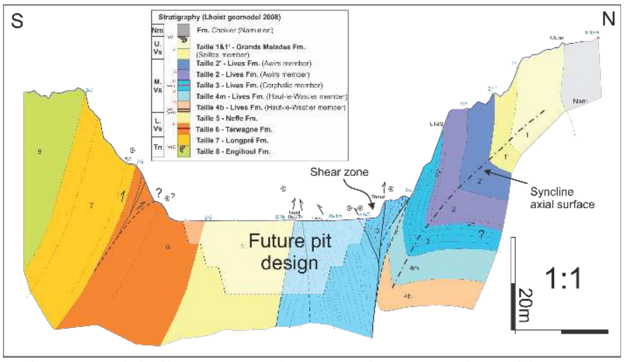

Figure 5: Digitally augmented structural cross section with remote structural data (see Figure 4 for cross-section location).

4.2 *Instability hazard assessment*

Rock kinematic stability analysis (deterministic approach) based on a near comprehensive georeferenced structural database (see Figure 6 for the case of the south front) has shown that the main rock instability hazard in the Flône pit concerns flexural toppling on the north and south fronts (46 and 47% respectively). The east and west fronts, which are dominated by UT-2 and UT-3, only show moderate wedge failure hazard (11%), mainly where S0/1 intersects (back-)thrusts. Planar sliding hazard is generally low (2 to 10%) on all fronts, but our interpretative cross-sections have highlighted that this hazard may significantly increase during future excavations – Figure 7. In particular on the northern front, deepening of the pit could generate significant inter-bench failure due to the presence of the anticline flank dipping moderately downwards through the future pit (see example cross-section).

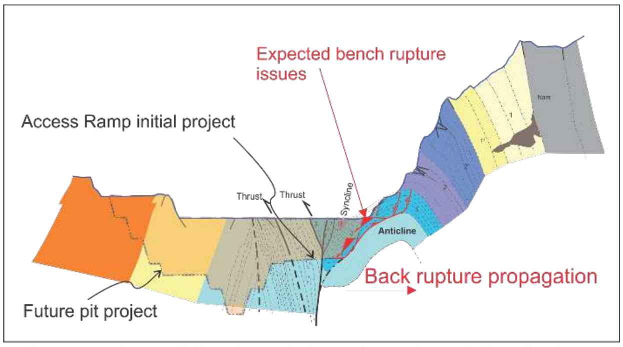

Figure 6. Planar sliding hazard along the main anticline flank (see Figure 4 for cross-section location).

5 DISCUSSION

Point cloud based structural data acquisition has enabled augmenting our field mapping database by a factor of 5 in the Flône quarry to re-assess the geological model and support our rock instability hazard assessment. The virtually augmented structural database makes it possible to largely reduce the uncertainty related to the usually poor representativity of structural data at the scale of a quarry where the majority of the outcrop surface is inaccessible. Similar structural data acquisition based on point clouds has been successfully conducted in other inaccessible environments, such as rock slopes (Tiruneh et al. 2013; Bordehore et al., 2017; 8; Tung et al., 2018), caves (Triantafyllou et al., 2019), road cuttings (Riquelme et al., 2016) or for geological model development (Cawood et al., 2017). However, these works did not integrate deterministic kinematic stability analysis in their assessment. Only very recently, Smith & Holden (2020) provided a similar analysis, but these authors looked at the different mechanisms one by one, without finally integrating or mapping the hazard results. For our study, the georeferenced structural database then enabled us to extract and map the subsets of planes that were prone to failure, providing an integrated instability hazard map necessary for safe extraction activities of the pit.

Whilst this geometric approach is very powerful, it should nevertheless always be complementary to – and not be replaced by –geological/geotechnical field expertise, as instability hazard not only relies on geometric parameters, but also on mechanical parameters that can be estimated directly in the field (e.g. Marinos & Hoek, 2000; Marinos et al., 2005). Our combined geological and geotechnical surface analysis has enabled us to anticipate future hazards in defining a targeted monitoring programme depending on the locations of the instability hazards identified across the pit.

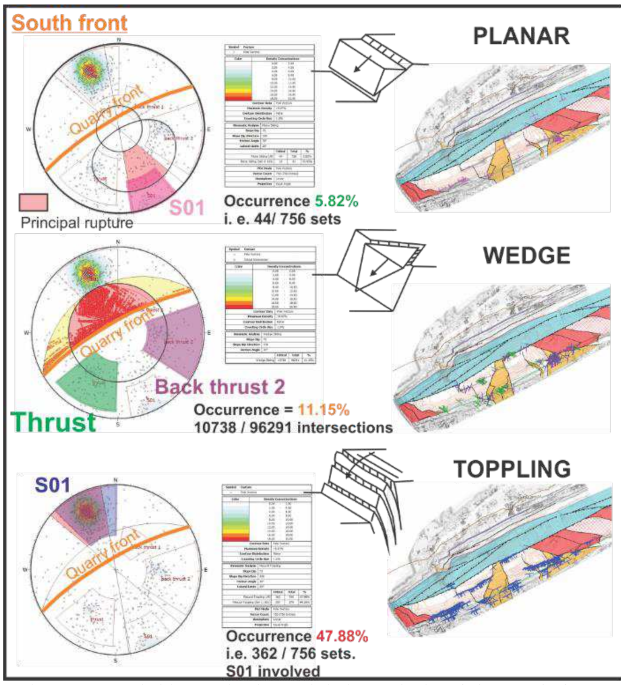

Figure 7. Rock kinematic deterministic analysis of the south front: results and GIS mapping of the involved planes.

6 CONCLUSIONS

Digitally augmented structural databases based on georeferenced point cloud analyses now enable deterministic rock kinematic stability analysis to be performed even at the scale of a pit with a high degree of confidence due to the enormous amount of robust structural data that can be gathered in an efficient way, but field geological mapping and rock mass characterisation should prevail to make a consistent stability assessment.

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