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BACK-ANALYSIS APPROACH FOR SLOPE STABILITY EVALUATION IN SENSITIVE CLAY: CASE STUDY, LA BAIE REGION IN QUEBEC

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ABSTRACT: Landslides represent a recurring geohazard in eastern Canada. Conducting back-analysis of recent landslide events contributes to the assessment of regions prone to hazards and aids in a more effective infrastructure development planning. The present study focuses on evaluating the geotechnical parameters of a landslide through performing back-analysis in La Baie, Quebec. A systematic methodology was implemented in three steps: a) development of land profiles before and after the landslide, b) determination of geotechnical parameters (soil cohesion and internal friction angle) using the UQAC database, and c) performing a limit equilibrium analysis of the slope using the Rocscience-Slide software to evaluate the critical geotechnical parameters at failure. Concerning the topography before and after the failure, a methodology was developed based on the slope conditions before and after the failure. Land profiles for the old landslide were generated using Digital Elevation Models (LiDAR) derived from aerial images covered by numerous photos and utilizing Pix4D photogrammetry software. Subsequently, the geotechnical parameters of the La Baie region were provided based on a descriptive analysis of various reports and publications from the UQAC geotechnical database. Finally, the developed land profiles and retrieved geotechnical parameters were employed for conducting slope stability analysis. The study's findings determined the critical strength parameters of the sensitive clay slope in the La Baie region, considering the scale effect. The proposed approach can be applied to assess the landslide risk in the region.

KEYWORDS: Landslide, slope stability assessment, back analysis, LiDAR, Pix4D.

1 INTRODUCTION

The scale effect is a significant challenge in geotechnical engineering. One technique for determining the soil parameters on a large scale is back-analysis of landslides (Wang et al., 2013). The back-analysis of past landslides, a regular practice in the realm of geotechnical engineering, involves determining the strength parameters of soil or rock mass. Back-analysis relies on accurate two-dimensional limit equilibrium models and calculates the soil shear strength mobilized at the time of slope failure (Zhang et al., 2010). Understanding the geometry of the sliding mass before and after the sliding event, along with the actual profile of the sliding surface, provides crucial information for the back-analysis procedure (Saeidi et al., 2016). However, obtaining pre- and post-failure topographic profiles of sliding surfaces is often challenging. Remote sensing techniques, now commonly employed for investigating and monitoring the landslides in the back-analysis procedure, offer a solution (Rodriguez et al., 2020). Among these techniques, the Light Detection and Ranging (LiDAR) technique has been frequently used to examine the landslide morphology and generate precise and high-density digital elevation models (Jaboyedoff et al., 2012). Similarly, aerial photogrammetry enables the accurate analysis of landslide movements over large areas at medium to high resolutions and over extended periods (Cenni et al., 2021). Van Westen and Getahun (2003) utilized aerial photographs and digital elevation models to study the geomorphological evolution of the historical Tessina landslide and indicated possible reactivation of existing landslides. Walstra et al. (2007) also used historical aerial photographs to assess the long-term evolution of two landslides and found that the measured horizontal geomorphological displacements from photographs interpretation were consistent with independent survey data. Lollino et al. (2014) conducted back analysis of the Montaguto earth flow by reconstructing the geomorphology using aerial photos and topographic maps. Recently, Sun et al. (2021) combined field investigation data, back analysis of slope strength parameters, and aerial photography-based pre-landslide topography reconstruction to analyze the Wolong landslide.

The aim of this study is to enhance the accuracy of predicting future landslides by determining the geotechnical parameters of sensitive clay at the in-situ scale. The approach proposed in this study involves creating pre- and post-landslide topographic profiles using digital elevation models (generated from LiDAR) and aerial photographs. Geotechnical parameters are subsequently evaluated at a realistic scale using laboratory data and back analysis of land profiles from chosen landslide sites. The rugged topography, historical landslide scars, and the presence of sensitive clays in the La Baie area collectively indicate the susceptibility of the La Baie area to future landslides. The present study employed a back-analysis of landslides to derive the strength parameters of the clay at the site. The results of the back-analysis, focusing on a landslide occurred on the slope of a field near Angéliques Street and Chemin St-Joseph, La Baie ($48.3383° N, 70.8826° W$), were presented in this paper. Due to the limited availability of certain high-resolution data, and the difficulty of employing a single technique for this particular case, a combination of LiDAR and aerial photography techniques was used.

Back-analysis was also conducted for an additional two shallow landslides in the region, and the strength parameters derived from these cases aligned with those obtained for the studied landslide. Although the back-analysis and results of these two cases are not presented in this paper, they corroborated the obtained strength parameters. The primary goal of this study is to ascertain the strength parameters (cohesion (c) and internal friction angle (φ)) of clay at a real scale, aiming for a more precise understanding of the potential for future landslides. The approach outlined in this study involves extracting initial geotechnical parameters from the UQAC database, followed by the creation of pre- and post-landslide topographic profiles using digital elevation models (derived from LiDAR) and aerial photographs. Ultimately, the strength parameters are evaluated at a real scale through the back analysis of landslide land profiles.

2 THE STUDY AREA

The Saguenay-Lac-Saint-Jean (SLSJ) region features a diverse geological composition spanning from the Proterozoic to the Quaternary periods (Rouleau et al., 2013). The Quaternary deposits consist of glacial and proglacial sediments from the Last Glacial Period, alongside marine, littoral, and deltaic sediments from the Laflamme Sea, which inundated the lowlands post-glaciation around 11,000 to 7,000 years BP. The isostatic depression caused by the Laurentide Ice Sheet, combined with rapid global warming and rising sea levels, led to a marine transgression, resulting in the Laflamme Sea's intrusion into the SLSJ region. This transgression deposited sediments indicative of deep and shallow marine environments. Consequently, the central Laflamme Sea region contains extensive deposits of massive or stratified clay, surrounded by sandy material along its periphery (Lévesque et al., 2023; Walter et al., 2018).

Located in SLSJ region, La Baie City is notably recognized for these post-glacial fine sediments, primarily composed of silt, silty clays, and clay, are the most prevalent soil type in the area. They can be up to 10 meters thick, reaching over 100 meters in the lowlands, and up to 30 meters in the La Baie area, where they are highly susceptible to landslides. Over the past decades, several shallow landslides have occurred in the area, resulting in material damage, except for the 1996 landslide following the Saguenay flood, which claimed the lives of two children (Bouchard et al. 2008). In 2017, the Ministry of Transportation Quebec (MTQ) reported high landslide susceptibility levels in the La Baie region. This study has examined a landslide occurred on the slope near Angéliques Street and Chemin St-Joseph in La Baie ($48.3383° N, 70.8826° W$).

Aerial photographs reveal that the movement initiated in 2006, as evidenced by the changes in the slide geometry shown in Figure 1a. The progression of the landslide from 2010 to 2016 is depicted in Figures 1b and 1c, illustrating the continued sliding due to erosion caused by a nearby stream. Significant portions of land detached from the slope in 2010, reaching a climax during the 2016 landslide. Figure 1d illustrates the final state of the landslide in 2019, with the slip deepening at the center of the scar. Additionally, the stream at the base of the slope has shifted farther from its original position, contributing to the morphological evolution of the landslide

3 THE METHODOLOGY ADOPTED

The present study encompasses three distinct phases; the collection of preliminary geotechnical data, the determination of topography profiles before and after the landslide, and the assessment of the strength parameters of clay at a full scale in the study area. A total of 107 Unconsolidated Undrained (UU) triaxial tests were conducted on clay samples from the La Baie area. Additionally, 488 UU tests from industry and government sources (MTQ) were employed to quantify uncertainties in shear strength parameters. The statistical analysis of the testing data yielded an arithmetic mean value of $108.51\ kPa$ as the undrained shear strength of clay samples in the area. This value served as the starting point for the back analysis aimed at determining the real-scale geotechnical parameters (Sanou, 2019).

Pre- and post-landslide topographic profiles were generated using the ArcHydroGroundwater module in ArcGIS, utilizing various digital terrain and surface models. For the post-landslide profiles, a digital terrain model (LiDAR) from 2016 was obtained from the Donnée Québec website. However, complete digital models for La Baie City are only recently available and not accessible annually. Consequently, an alternative method was devised to create digital terrain models from aerial photos. Upon thorough assessment of various software options, it was determined that Pix4D Mapper (Pix4D's photogrammetry software) consistently produced the most reliable digital terrain and surface models from aerial photographs. To locate the photographs covering the study area, the aerial photograph database of the Saguenay-Lac-Saint-Jean region was scrutinized from 1963 to 2008. A series of aerial photographs from 2006 was also selected to generate a digital surface model using Pix4D software.

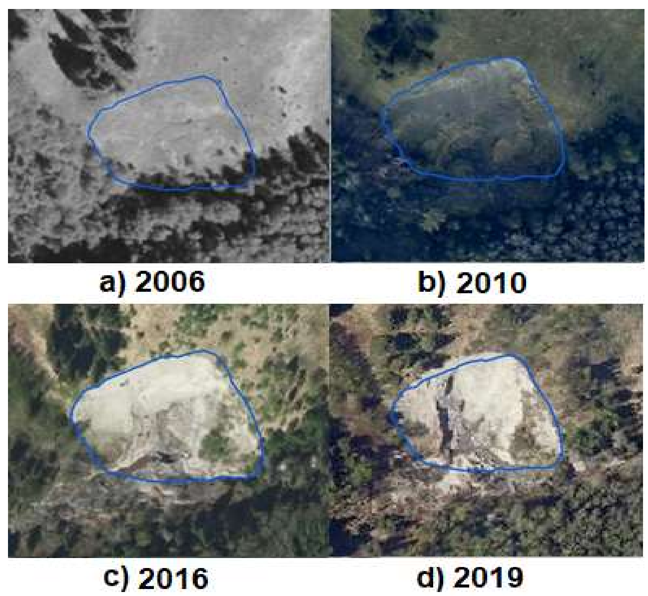

Figure 1. Development and evolution of the landslide under investigation

Additional aerial photographs were obtained from the Ville de Saguenay for the years $2013, 2015,$ and $2016,$ along with their respective camera calibration reports. These were utilized to generate three additional digital surface models for the study area. In total, six digital models ($2006, 2007, 2013, 2015, and\ 2016$) were either acquired or produced to assess the profiles of the landslide.

To determine the geotechnical parameters of the soil at a real scale, back analysis of pre- and post-failure topographic profiles, experimental geotechnical parameters of clay, and slope stability methods were employed. The study utilized Rocscience-Slide software, which conducts a limit equilibrium slope stability analysis (Rocscience, 2016). Initially, the pre-failure landslide topography was modeled and identified the failure surface was identified through conducting slope stability analysis, aiming for representing the field conditions. For the back-analysis procedure, geotechnical parameters obtained from the statistical analysis of laboratory data were used for preliminary assessments. Subsequently, the geotechnical parameters derived from iterative methods were employed to acquire a modeling surface resembling the real case.

Figure 2. Position of landslide topographic sections

4 PRE- AND POST-LANDSLIDE TOPOGRAPHIC PROFILES

Figure 2 illustrates the positioning of representative topographic sections for landslides, comprising three segments perpendicular to the slip and three sections in the direction of the slip. In Figure 3, the before-and-after topographic profiles for section 2 are displayed.

The green profile in Figure 3 represents the land's topography before the landslide. Interpretation of various landslide photographs (Figure 1) suggests that small sections of land began sliding in 2006, with a significant landslide visible in 2010. Consequently, profiles were measured for 2007, utilizing the digital terrain model generated from data provided by Ville de Saguenay, and for 2016, utilizing the digital elevation model produced from the 2016 LiDAR surveys (Government of Quebec 2021), as depicted in Figure 3.

Both profiles are identical on the left where the embankment has not slipped. However, the remainder of the 2016 profile (post-sliding) is deeper than the 2007 profile, indicating that the slip occurred by 2016, leading to a substantial movement of significant amount of material down the slope. Additionally, it is evident that the stream bed shifts over the years, approaching the base of the slope. The erosion of the embankment caused by the stream, significantly contributes to the progressive expansion of the landslide over time.

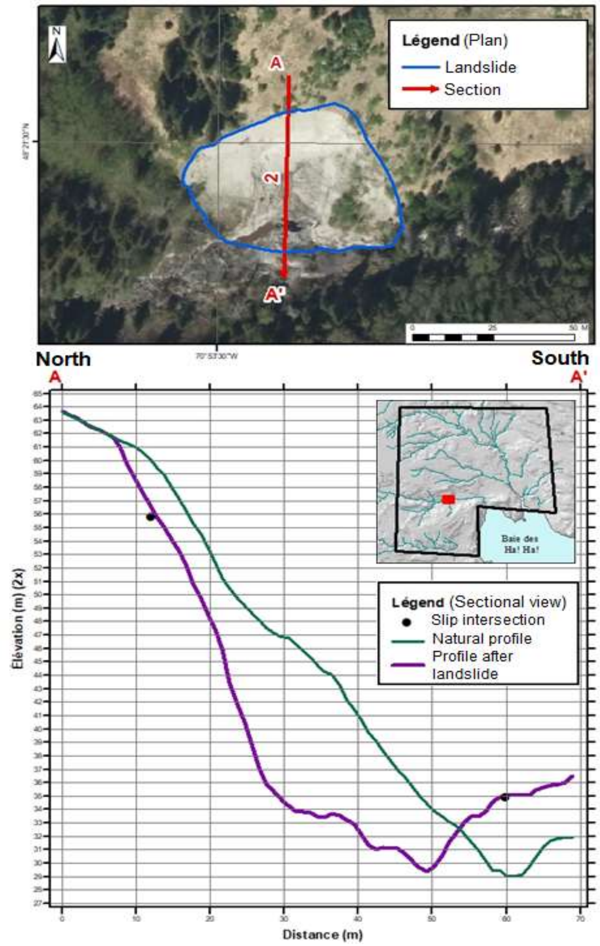

Figure 3. Position of the topographic sections of landslide and analysis of section 2

5 BACK-ANALYSIS AND GEOTECHNICAL PARAMETERS OF THE SENSITIVE CLAY

The geotechnical parameters of the soil slope were assessed through back analysis in relation to the landslide. The slope geometry for back-analysis in the Slide software (Rocscience 2016) was established using pre- and post-topographic profiles of the landslide, obtained from ArcGIS. According to our laboratory database, the bulk unit weight of clay considered for stability analysis is $22.5\ kN/m^3$ (Sanou 2019). Subsequent adjustments were made to the geotechnical parameters until a failure surface resembling the actual failure was achieved, with a safety factor close to 1.0.

Back analysis was conducted on the crucial section 2 of the landslide. To enhance the modeling process in the Slide software, an additional $50\ meters$ were appended to both ends of the pre-failure profile. The modeled geometry of the landslide is illustrated in Figure 4. Given the low permeability of clay and the considerable volume of snow melting, full ground saturation condition was assumed, notwithstanding the absence of information regarding the location of the water table for modeling.

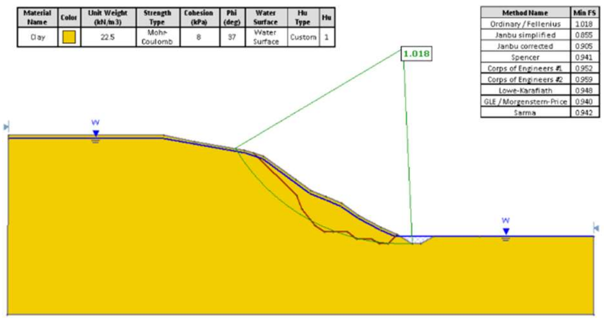

Figure 4. Back stability analysis of the landslide under investigation

In Figure 4, the red line illustrates the post-landslide profile, while the green line signifies the failure surface determined through conducting the slope stability analysis. Multiple iterations involving varied cohesion values and slope stability analysis methods, were carried out using the Slide software. The goal was to minimize the disparity between both failure surfaces, aiming for yielding the most accurate model. The critical cohesion value of clay, representing the actual field conditions, was determined by identifying the failure surface with a safety factor close to 1 that closely aligns with the slip profile. Through conducting slope stability analysis, a critical cohesion value of $8\,kPa$, and an internal friction angle of $36.5\ degrees$, corresponding to a safety factor of 1, were determined using the Fellenius' method (Fellenius, 1936) for the sensitive clay under investigation. The factor of safety obtained from other methods such as Spencer's method, Bishop's method and Janbu's method also indicated that the factor of safety is close to 1.

6 CONCLUSIONS

The present study introduced the application of back analysis to determine the strength parameters of sensitive clay, aiming to assess the potential for future landslides in the La Baie region. The adopted methodology involved collecting initial geotechnical data, developing pre- and post-landslide land profiles utilizing digital elevation models, and extracting geotechnical parameters of clay through conducting slope stability analysis. Remote sensing techniques were effectively employed as a tool for the back-analysis of landslides, proving suitable for various similar cases. Assembling the remote sensing data from the Donnée Québec website and Ville de Saguenay facilitated the development of pre- and post-failure topographic profiles of the landslide, which were essential for conducting the subsequent stability analysis. Statistical analysis of the geotechnical database of UQAC provided the preliminary parameters necessary to initiate the slope stability analysis. The analysis at a real scale for critical topographic profiles predicted the cohesion and internal friction angle of the sensitive clay to be $8\,kPa$ and 36.5°, respectively.

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