Regional-Scale Landslide Hazard Analysis in Sensitive Clays Using an Integrated Approach

Ali Saeidi(✉), Blanche Richer, Rama Vara Prasad Chavali, Maxime Boivin, and Alain Rouleau

Université du Québec À Chicoutimi, Chicoutimi, QC, Canada
ali_saeidi@uqac.ca

Abstract. The Saguenay region in Quebec is largely covered by sensitive marine clays that are highly susceptible to large retrogressive landslides. This work addresses the development of a methodology to forecast slope failure and zonation of landslides in sensitive clays. This is demonstrated by applying an integrated approach to the Saint-Jean-Vianney (SJV) area located in Saguenay. Developing the 3D model, assessing geotechnical parameters through back analysis using the Rocscience-Slide software, and creating a risk zonation map are the three crucial phases of the proposed methodology. The first phase involved generating a 3D geological model of the surficial deposits of the selected area using borehole data and geophysical methods. In the second phase, realistic values of geotechnical parameters of the soil were obtained by performing a back analysis of a previously occurred landslide in the area of interest and combining it with experimental results from clay specimens retrieved from the same landslide. In the final phase, a zonation map of slopes is created using the derived geological model and geotechnical factors to assess the slopes at risk. This screening tool enables the identification of high-risk zones that would require a more detailed investigation. The proposed approach provides a useful tool for slope stability analysis in areas with similar geological conditions.

Keywords: Back analysis · geological model · geotechnical parameters · landslide · sensitive clays

1 Introduction

Eastern Canada has extensive deposits of postglacial marine clays. These clays are quite common in the Saguenay region in Quebec, where they have been deposited by the Laflamme Sea. The gradual reduction of the initially high porewater salinity upsets the balances of the interparticle electrical forces and impacts the particle alignment leading to numerous landslides, including the Saint-Jean-Vianney (SJV) landslide of 1971 causing the death of 31 people [1]. This prompted the researchers to focus on the development of various hazard assessment approaches in the region for recognizing and minimizing landslide risk. In landslide hazard assessment, in-situ conditions such as ground topography, slope geometry, geotechnical properties of soil deposits, and terrain

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stratigraphy influence the landslide behavior. These site-specific conditions depend on the geological and geotechnical characteristics of the soil deposits. The development of a 3D geological model helps to describe complex geological phenomena. For a precise regional assessment of landslides, the accuracy of the 3D geological model is essential. Topographic maps, geostatistical interpolation of site surveys, and light detection and ranging (LIDAR) surveys facilitated topographic information, while stratigraphic data is attained through various subsurface investigation techniques, such as boreholes and geophysical surveys. In geophysical surveys, the transient electromagnetic (TEM) method can distinguish between different soil layers as well as identify changes in the porewater salinity of the soil deposits [2]. TEM is often favored because of its simplicity, rapidity, and cost-effectiveness.

Precise determination of engineering properties of the various soil layers of an entire slope is essential for risk evaluation. Among various approaches available, back analysis of an occurred landslide is considered a better approach for estimating the engineering characteristics of soil slope [3]. The slope geometry, prior to and after the landslide, further assists the accuracy of estimated soil characteristics. The development of a 3D geological model along with the estimation of accurate geotechnical parameters through combined back-analysis and laboratory testing data enhances the precision of the landslide zonation maps. Sensitive clays influence the delineation of areas in different susceptibility zones in Québec, however, some areas even in the absence of sensitive clays may fall into the landslide susceptibility zones [1].

This paper proposes a methodology for zoning sensitive clay-covered areas and forecasting a regional-scale landslide occurrence. This methodology consists of new developments consisting of two crucial features of forecasting the occurrence of landslides: the development of a reliable 3D model and the evaluation of engineering characteristics of the soil. The initial phase involves the development of a reliable 3D geological model using subsurface investigation techniques in the SJV area. Subsequently, more accurate characteristics were acquired with the back examination of an occurred landslide in the study region along with geotechnical characteristics of sensitive clays specimens retrieved from the landslide site. The generated geological model and geotechnical data are used for the mapping of the landslide susceptibility areas utilizing the method established by the Ministry of Transport, Quebec [4, 5]. The proposed approach enables the identification of high-risk zones and facilitates slope stability analysis in areas with similar geological conditions.

2 Site Description

The SJV area is situated 2.5 km north of the Saguenay River, about 10 km west of Chicoutimi, and is considered a study area to apply the proposed methodology. This area with thick sensitive clay deposits is well known for two catastrophic landslides: the first in 1663 and the second on May 4, 1971, which destroyed 42 houses in the village resulting in the loss of 31 lives. In the context of the fifty years of the tragedy of Saint-Jean-Vianney, in 2021, the City of Saguenay initiated plans to commemorate the memory of the victims through the development of a geotourism park for promoting geomorphological and geological elements in the landslide area.

3 Methodology

The proposed methodology is implemented for the SJV area in three different phases: (i) development of a 3D geological model, (ii) determining the geotechnical parameters of soil layers of the study area, and (iii) development of the landslide zonation map. The crucial data related to regional stratigraphy, borehole data, soil types, and their geotechnical characteristics and reports from relevant sources are collected. A preliminary stratigraphic model is developed to calibrate TEM data utilizing the subsurface investigation data of known locations.

Geological information on the formation of each soil layer in the study area is used to interpret the stratigraphy of the area between specific known locations. After proper interpretation at all locations to obtain identical borehole logs and TEM surveys, the 3D geological model is developed by importing stratigraphy data sets into 3D modeling software. A series of consolidated undrained triaxial tests are performed on sensitive clay specimens retrieved from the SJV area to determine the shear strength parameters. Topographic profiles before a landslide are constructed through a combination of methods including aerial photography, LiDAR surveys, existing landslide database, and identifying the changes in buildings or structures prior to and after the landslide event. The motive is to determine the accurate pre-slide conditions and subsequently through stability analysis obtain post-failure landslide topography that reflects the observed failure topography in the field with a factor of safety of 1. The corresponding shear strength parameters of sensitive clay are considered to be realistic values for the given slope. The 3D geological model facilitates to recognition of slopes at danger owing to their slope forming conditions (Slope angle >14° and slope height >5 m). Analyzing the statistical data of past landslides in the region enables the estimation of the potential distance of retrogression for individual slopes. To assess retrogression distance, a third-order moving average is applied to the distance of retrogression observed in past landslides within the vicinity [5]. By using this method, it is possible to identify areas at the top and bottom of a slope that may be potential hazard zones.

4 Results and Discussions

4.1 Collection of Geological and Geotechnical Database and Development of 3D Model

The Saguenay-Lac-Saint-Jean regional database indicates the presence of a clay layer (~ 30 m) in the SJV area, along with an intercalated discontinuous till layer (1 to 5 m) overlying the bedrock [6]. The LiDAR survey performed in 2017 provided the topographic data of the SJV area. The preliminary interpretation of regional stratigraphy was developed using this LiDAR data since there were no major changes in topography after this LiDAR survey in 2017. The borehole data points indicating stratigraphy of the SJV area are also added to the stratigraphy at specific locations. For more detailed information related to the stratigraphy, the electrical resistivity profile obtained from the TEM survey was used. Though Palacky [7] provided a chart indicating electrical resistivity values for various soil types (clay, sand, gravel, and rock), the present study interpreted site-specific resistivity range for various soil types to improve the accuracy of

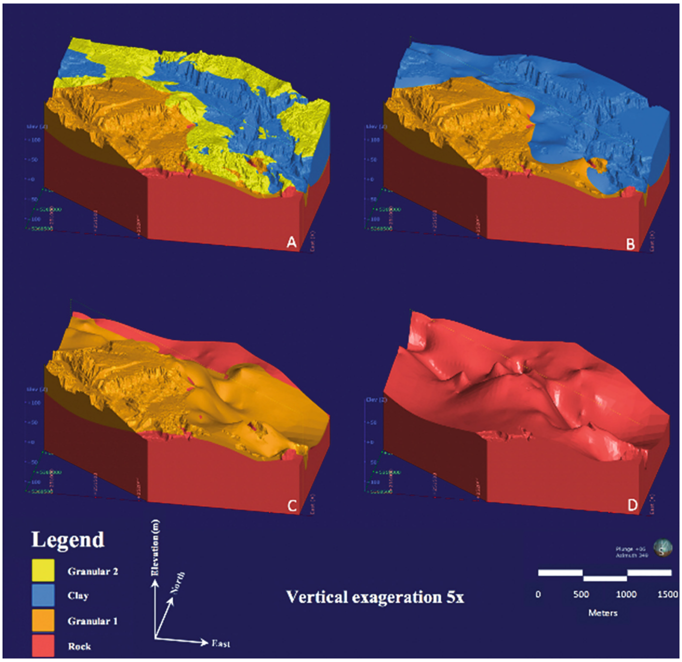

Fig. 1. 3D geological model of soil layers of the SJV area. A) a model featuring all soil deposits, B) a model that excludes the Granular 2-layer, C) a model that excludes both the Granular 2 and Clay layers, and D) a bedrock model without any overlaying deposits

the stratigraphy. To interpret the stratigraphy between data points, both ArcGIS [8] and Arc Hydro Groundwater tools [9] were employed. Out of the 218 boreholes examined, 12 of them showed evidence of a till layer. However, due to the challenge of distinguishing the electrical resistivity values of till from sand and gravel, the till deposit was categorized as a granular layer. Due to the intricate stratigraphy in the SJV area and the limited accuracy of the TEM survey which operated at a resolution of less than one meter, the study was only able to interpret four layers. The expanded dataset was imported into the Leapfrog Geo software from Seequent [10], utilizing a methodology established by Chesnaux et al. [11]. Figure 1 illustrates the resulting 3D geological model comprising various geological deposits.

4.2 Assessment of Geotechnical Characteristics of the SJV Area

The results of consolidated undrained triaxial tests on sensitive clay of SJV area provided the average values of cohesion and friction angle as 8 kPa and 32° and the obtained results agree with the findings of Lefebvre [12]. These results were used for initial iterations of back analysis through an analytical slope stability approach [13]. The unit weight of sensitive clay was found to be 18.6 kN/m^3. For the back-analysis, an occurred landslide was selected along the Aux Vases River to develop model slope geometry. Using aerial photographs between 1971 and 1975, the slope geometry prior to the landslide was

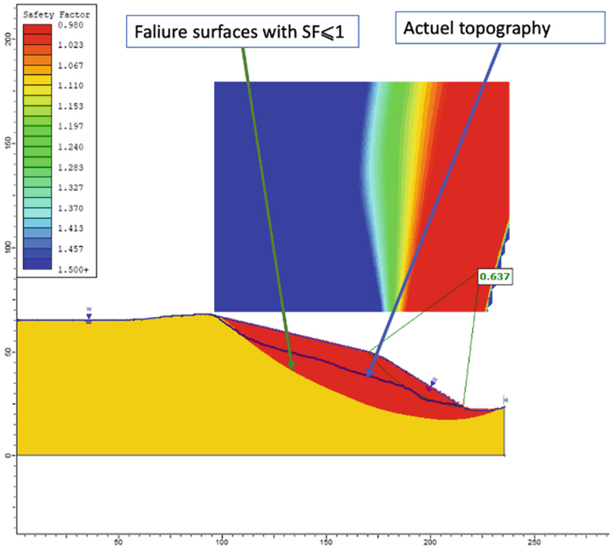

Fig. 2. Critical slip surface of the slope interpreted with Corps of Engineers #2 and actual failure topography

constructed. Figure 2 shows the slope geometry model which was used in the slide software, Rocscience [14]. Based on the prior knowledge of shear strength parameters of sensitive clays in eastern Canada, cohesion value was fixed as 8 kPa and iterative stability analysis was performed using varying values of angle of internal friction to obtain the closest approximation of the failure surface at a factor of safety $\leq$1. All possible failure surfaces at FS $\leq$1 are shown in Fig. 2. The analysis revealed that the "Corps of Engineers #2" method is the best suitable conceptual approach for interpreting the slip profile that is closest to the observed data [15].

As shown in Fig. 2, the failure profile with a safety factor (SF) of $\leq$1 is located deeper than the interpreted profile based on the actual topography. Nevertheless, it is the closest match and bears a strong resemblance to the present-day slope profile. Therefore, the best failure profile of the landslide was obtained with the "Corps of Engineers #2" conceptual analysis, which identified the shear strength values of cohesion and angle of internal friction as 8 kPa and 35°, respectively.

4.3 Development of Landslide Zonation Map for the SJV Area

Utilizing the criteria of a height of $\geq$5 m and a slope of $\geq$14°, the City of Saguenay generated stress maps to pinpoint areas with potentially hazardous slopes [16]. An analysis was initiated on landslides that took place along the Aux Vases and the Petit-Bras rivers using LiDAR topography and old aerial photographs. Through this analysis, the landslide parameters and retrogression distance were estimated. A statistical third-order moving average method [5] was implemented to estimate the typical retrogression distance along the banks of the rivers. Landslides that occurred along the western bank

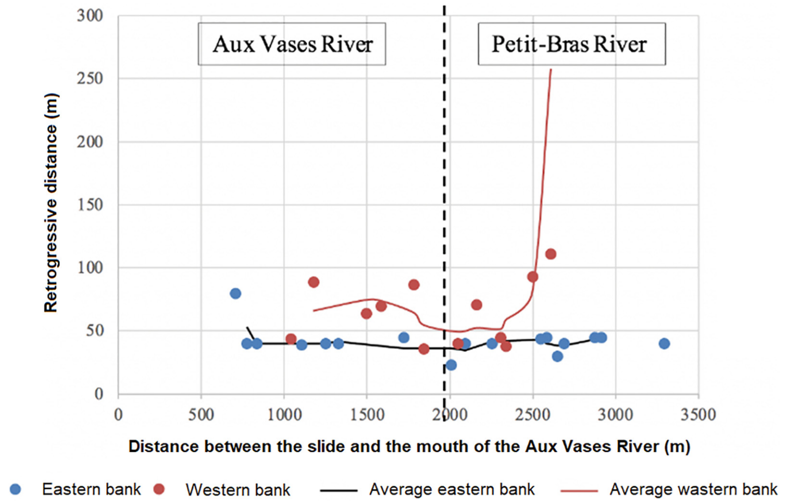

Fig. 3. Distance of retrogression for the landslides based on their location along two rivers

have a greater retrogression distance compared to those observed along the eastern bank (Fig. 3).

The SJV landslide in 1971 occurred on the western bank of the river. This methodology along with the derived retrogression distance graph considering the variable geometry associated with the retrogression distances of previously occurred landslides facilitates the identification of zones susceptible to landslide risk. The derived susceptible zones from this method are more realistic and accurate since precise geotechnical and geological characteristics were considered for the analysis. The zonation map was developed following the criteria established by MTMDET which indicates that the slope height must be greater than or equal to 4 m and the slope angle must be greater than or equal to 14° [4]. Variable widths were used to classify zones susceptible to landslides. The stress zones on the western side are roughly 80 m wide, whereas on the eastern bank, they are 40 m wide (Fig. 4).

5 Summary and Conclusions

The development of an approach to forecast slope failure and zonation of landslide hazards at a regional scale in sensitive clays of the SJV area was presented in this paper. The methodology involves the development of a 3D geological model using borehole data and a geophysical (TEM) survey; the estimation of actual geotechnical parameters of previously occurred landslide using back analysis; and finally, the development of a landslide susceptibility zonation map for SJV area along with the stress zones. The combined interpretation of borehole and TEM data improved the accuracy of the geological data, which enhanced the effectiveness of the developed 3D geological model as a tool for stability analysis of the SJV area. Back analysis using “Corps of Engineers #2” was determined to be a reliable method for the SJV area and offered real-scale estimates

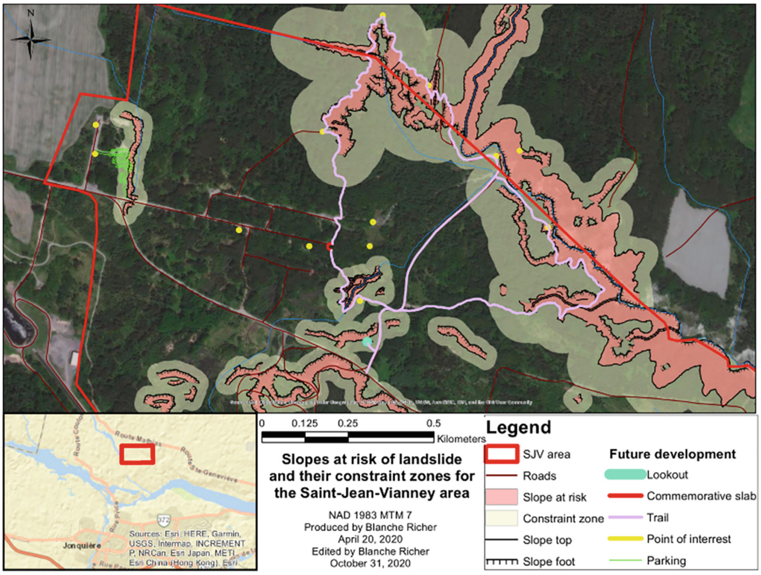

Fig. 4. Landslide risk zonation map for SJV area

of the geotechnical parameters. This conceptual analysis yielded appropriate values of two parameters related to shear strength; the estimated values of cohesion and angle of internal friction, as 8 kPa and 35°, respectively, produced a conclusive failure surface. Nevertheless, numerical modeling with the incorporation of strain-softening would provide a more dependable approach for analyzing slope stability in sensitive clays. The landslide risk zonation map facilitates a preliminary screening tool for the development of new projects within the study area.

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