Published by Avanti Publishers

Global Journal of Earth Science and Engineering

ISSN (online): 2409-5710


# The Influence of Built Environment on Landslides. A Case Study: Converney-Taillepied

E. Prina Howald[1,*], J. Torche[1] and Y. Madrari[2]

*[1]Territorial Engineering Institute (insit), Department of Built Environment & Geoinformation (EC+G), School of Engineering and Management Vaud (HEIG-VD), Yverdon-les-Bains, 1401, Switzerland*

*[2]Fribourg Canton, Fribourg, 1700, Switzerland*

## ARTICLE INFO

*Article Type*: Research Article

*Keywords*:
Landslide
Geoslope
Soil landslide
Natural hazards
Stability analysis

*Timeline*:
Received: June 11, 2021
Accepted: August 28, 2021
Published: September 30, 2021

*Citation:* Prina Howald E, Torche J, Madrari Y. The Influence of Built Environment on Landslides. A Case Study: Converney-Taillepied. Glob J Earth Sci Eng. 2021; 8: 12-34.

*DOI*: https://doi.org/10.15377/2409-5710.2021.08.2

## ABSTRACT

Permanent deep soil landslides are regular downstream movements over a long period. The soil mass moves along an existing sliding surface, contrary to spontaneous landslides that are quite fast downstream movements, starting after a triggering event.

The present study aims to define the effects and the relevant impact that urbanization can cause on the evolution of an important permanent landslide. It reports existing knowledge and describes the phenomenon and its behavior according to increasing urbanization and geotechnical mechanisms.

The intense urbanization (terraces, building reinforcements due to maintenance needs, surface drainage systems, deep drainage boreholes, infrastructure development) has contributed to stabilizing the landslide as a whole. However, geological and hydrogeological factors and the choice of areas where urban density can become higher are equally crucial for landslide stability.

The *Converney-Taillepied* landslide upon Belmont-Sur-Lausanne, Paudex, and Lutry (Vaud Canton, Switzerland) has been selected as a case study. Several historical events occurred in those areas when they were only rural, while over the past hundred years, the geography has been deeply modified by urbanization.

Once the overall study of the *Converney-Taillepied* landslides is finished, this work will focus on the most critical areas resulting from the latter. The project analyzes the present conditions of the phenomenon, its characterizations, and the definition of different scenarios to determinate and analyze the different stability factors. Then it proceeds with the analysis of decisive mechanisms that will be able to affect positively or negatively the landslide condition.

Final results suggest that the presence of the built environment on the landslide after the delicate building phase could have a stabilizing effect.

*Corresponding Author
Email: erika.prinahowald@heig-vd.ch
Tel: +41 79 336 17 15

# 1. Introduction

During the 20th century, the demographic growth of the population of the Arc Lémanique was very strong. The canton of Vaud recorded an increase in population from 213,000 to 415,000 between 1860 and 1957 [1]. It was, therefore, necessary to use the territory located in a landslide zone in order to meet the needs of the population. This is the case of many communes located in the Lavaux (Swiss, Canton of Vaud).

The occupation of this type of territory must be determined with caution. The phases of construction and overloads caused by the built environment have an important impact on the overall stability of the landslide. As landslide areas are common in the canton of Vaud, the State of Vaud has asked HEIG-VD to study the impact of the built environment on landslide stability. Consequently, in order to meet this demand, this paper analyzes the Converney-Taillepied. This case is very interesting because the evolution of the built environment in this sector was very pronounced during the 20th century.

This project aims to define criteria related to urbanization and urban density, to describe in which way they will affect the evolution of an important soil landslide and its behavior, as well as the necessary protection and prevention measures. The question mark is whether the effect of urbanization makes it possible to consider a reduction of the risk and to lower the degree of danger of a given zone.

In the quest to erase this question mark, this work will consider several cartographic, geological, geotechnical, climatic, and hydrogeological data [2] [3] [4] [5] [6] [7]. Preliminary phases, particularly various visits made on different affected sites, have been essential for correct project development. An important documentation work has been implemented, with both the affected municipalities and the engineering firms acting on behalf of authorities or privately, in order to obtain some terrain models for stability analysis finally.

The work structure starts from contextualization and description of the Convernay-Taillepied landslide, its history, and its different characteristics. Then, there are developed scenarios for evaluating the stability of the critical areas throughout the *Geoslope* software.

# 2. Case Study – Converney-Taillepied Landslide

### 2.1. Position and Size

The studied area is located in the canton of Vaud, between Lausanne and Chexbres, western Lavaux (Figure **1**). The main municipalities that are affected are Lutry (8845 citizens), Belmont-Sur-Lausanne (3177 citizens), and Paudex (1349 citizens).


**Figure 1:** Geographic situation landslide position in Switzerland and zoom on its area.

Converney-Taillepied landslide extends beyond the Signal de Belmont-Sur-Lausanne, up to the Lutry and Paudex shores. It covers mainly the southern slope of Monts de Lutry (Figure **2**).

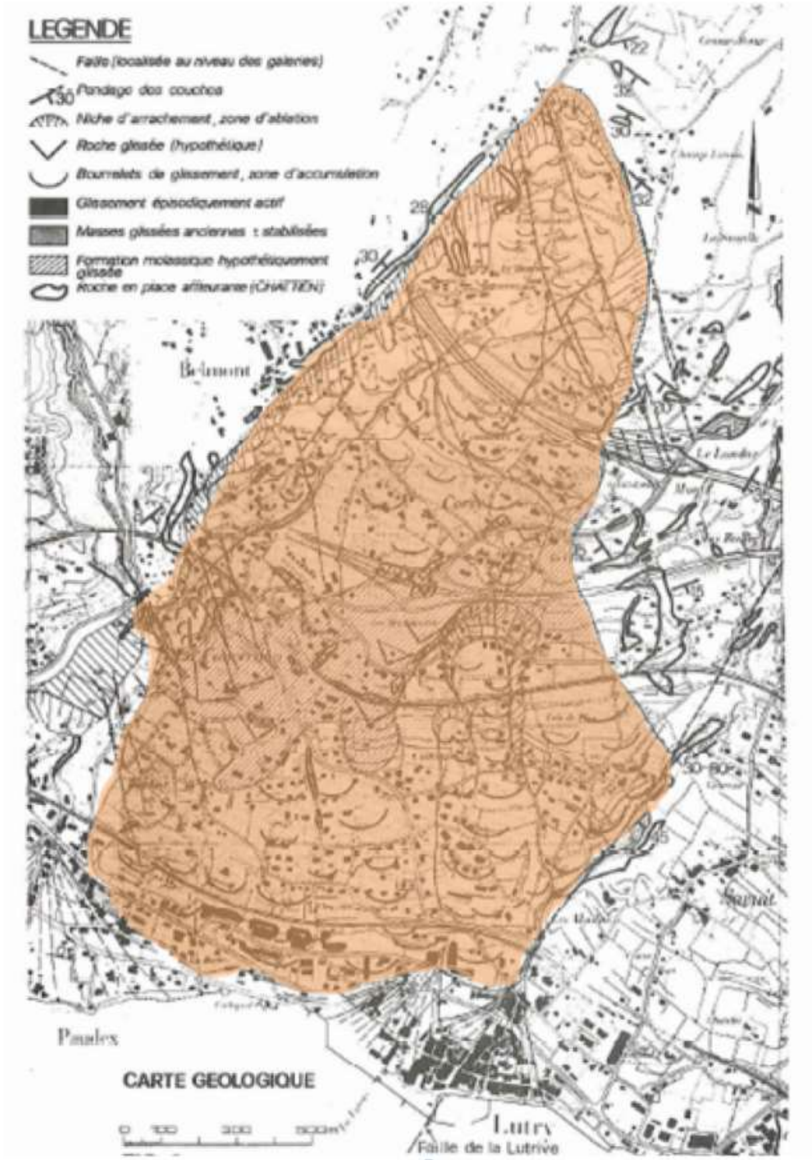


**Figure 2:** Converney - Taillepied landslide position [2].

The landslide area begins at 750m a.s.l. and it widens to 800m between Les Ecaravez and Corsy, then it strongly flares at the altitude of the Conversion.

Converney-Taillepied landslide is an extended permanent sliding of glacial outwash material, which is mainly located on the coal molasse. It covers an area of 2,5 $km^2$ on the Lavaux slopes, with a depth between 10 and 40 m, and it has a characteristic velocity of 2 cm/year.

Four important transport infrastructures cross it: the N9 Léman highway, built between 1968 and 1974, the la Perraudettaz freeway intersection, made between 1971 and 1976, in the top half of the landslide, and the two railway lines Lausanne-Berne and Lausanne-Simplon in the bottom half. Moreover, two sections of cantonal roads (780 and 770) are present and should be added to these national roads crossing the landslide.

## 2.2. Landslide History

The most ancient news regarding these ground movements is dated 24th August 1618: " grand dégâts du côté d'orient, et même la maison de la conversion glissa aussi " ("great damages on the eastern side, and even the home of the Conversion slipped" - [8]). The article also refers to a 50 hectares soil sliding that happened in 1758.

Ground movements were observed on the right bank of Le Flonzel creek at Converney in 1910. These movements were again observed in 1930, destroying a cottage. Moreover, the larger water pipe of Lausanne was almost swept away by the landslide.

For more than two centuries, a coal mine in Belmont, underneath the sliding mass, had been exploited. These operations began in 1710 and stopped permanently in 1947. At this time started the uncertainty and the initial assumptions about the permanent landslide in this area.

The construction of an apartment building in Taillepied in 1962 reactivated the landslide, having the first cuts, vertical and 6 m deep, as the triggering factor. The lack of awareness of this landslide has led to significant overspending on this project. It was necessary to invest in important building solutions: foundations of bored piles down to the lake sands layer, with a maximum depth of around 30 m, and diaphragm anchored walls. In addition, compensations were paid to people who had been affected by the landslide during extensive excavations.

Subsequent movements observed in the area happened in 1965 when distortions of the railway embankment (Simplon line) were recorded due to a deep landslide in this area, then on the night of 24$^{th}$ and 25$^{th}$ July 1980 when a villa and the railway nearby the Bochat tunnel were threatened. Finally, the last incident was noted at Champs-Charmot in the commune of Belmont-sur-Lausanne in 1990.

Identifying the landslide was possible due to the knowledge and reflections of geologist A. Bersier [9], as well as the execution of major civil engineering projects (highway N9, apartment buildings construction of Taillepied in 1962, and Champs-Chamot in 1990). A. Bersier was the first to hypothesize the presence of a single Converney-Taillepied landslide. After that, in 1983, Noverraz and Weidmann have led research on this topic that is still relevant nowadays. [10].

The reactivations of this slide are quite sudden. Recent inclinometer measurements show that slight movements remain at a depth of about 14m on the right bank of Le Flonzel, under the village of Belmont.

### 2.3. Important Elements of the Built Environment on the Landslide

At the beginning of the 1900s, the main infrastructures on the landslide area were two railway lines (Lausanne-Berne and Lausanne-Simplon) built in 1862, Taillepied, which then consisted of only a few houses. At that time, the Converney-Taillepied landslide was, therefore, mostly free of anthropic infrastructure.

As early as 1920, houses were built in the area west of Lutry, along the lake. These constructions would gradually climb the slope of the slide to occupy the area. After the Second World War, this phenomenon was to become increasingly widespread.

To compensate for the lack of housing, large rental buildings were built in Taillepied in 1962. The construction of these buildings turned out to be more expensive than expected, following the reactivation of the landslide that happened during construction.

In 1971, another construction work began on the N9 highway in Converney, with a large excavation in the landslide mass. As a result, many deep drill holes were drilled as well as sub-horizontal and vertical drainage. The purpose of the latter was to prevent any movement of the slide-mass from the highway trench. The road infrastructure was closely monitored (displacement measurement, inclinometer, piezometer, etc.).

Later, in 1973, the Perraudettaz motorway junction was built, located in the La Conversion sector. Consequently, no major problems were detected, mainly because the site is located in a stable part of the landslide.

Since 1983, the influx of new construction on the slope has continued to grow until it occupies the entire slope of the slide area. Nowadays, the Taillepied area is still under pressure from the newest constructions (Figure **3**).

**Figure 3:** Various constructions in Taillepied neighbourhood.

# 3. Landslide characterization

## 3.1. Landslide Mechanisms

The Converney-Taillepied slide is a slow slide resulting in a progressive deformation of the ground, not always perceptible to the human eye. That is why it has been ignored or forgotten for such a long time. The presence of this landslide is partly due to the geology of the soil, which favors this context. The rocks of the area mainly consist of molasses, which contains alternating levels of marl and argillites as well as sandstone banks. It is characterized by low cementation and plastic behavior. The alternation of hard cracked and soft impermeable benches is favorable to landslides. In addition, the dip of the layers in the downstream direction of the slope favors this context.

In some localized regions, the landslide undergoes sudden and brutal acceleration phases. The origin of these accelerations can be multiple:

- Variations in the groundwater level
- Periods of drought followed by periods of heavy rain
- Erosion caused by the rivers crossing the landslide
- Poorly executed excavations during earthworks (example of the Taillepied in 1962)
- Poorly distributed load on the slipping mass
- The cuttings from the galleries from coal mining operations are made of loose material.
- Etc.

## 3.2. Geomorphology

Figure **4** shows the relief of the landslide as well as its different areas of activity.

Geo-morphologically, the landslide occurred on the important ridge dividing Lutrive and Paudèze basins, more specifically on the southern slope of this ridge towards Leman lake. The general mean slope is 15%, except laterally on the sides of Signal de Belmont, where the slope has major values.

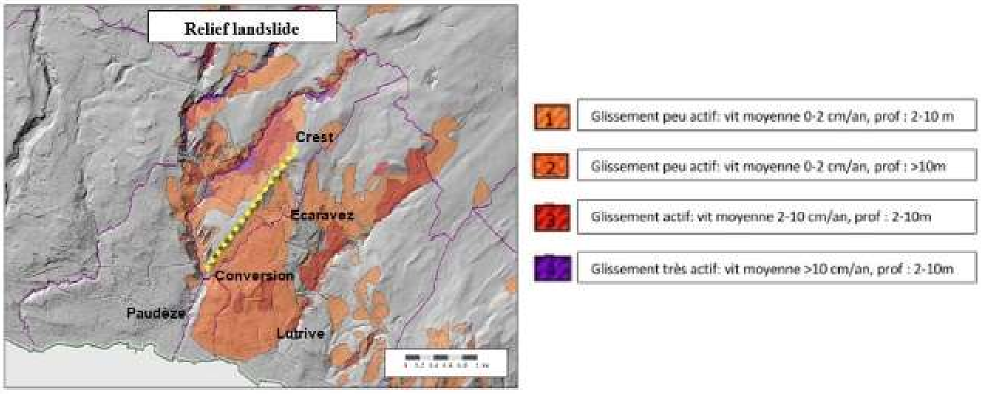


**Figure 4:** Geomorphological framework of Convernay-Taillepied landslide [3].

The landslide defines a very important depression at Ecaravez, and there is a pronounced swelling in all the Conversion areas where several hills with smooth shapes arise. The sliding mass flows towards the lake with soft undulations that make it possible for a gentler landscape to start from the Conversion hills. On the other hand, towards the east side, there are the progressively steepest sides of Lavaux.

### 3.3. Geotechnics and Tectonics

Stratification plays a decisive role: layers are fractured, sub-vertical compared to Lutrive fault, and horizontal to Landar, the dip is between 25° and 30° towards the eastern side of Belmont ridge. Both conditions restrict the detachment niche length. The fact that the side is cut along a “dip slope” layer surface explains the pointy shape of the upper detachment niche. According to the geological map, the dip always keeps component to the South, a component that roughly corresponds to the mean slope of landslide. Due to these dip conditions, the Converney-Taillepied landslide is a huge slip, layer on layer, with a small internal dislocation. [11]

There are also two other secondary tectonic elements: The Paudèze fault on the western side and the Lutrive fault on the eastern one, which both takes their name after the two watercourses flowing through the landslide.

These two elements restricted the tectonic uniformity of the freshwater molasses of the Upper Chattian age: on the East, the coal molasse disappears under the Red Subalpine molasse, and on the Western side of Paudèze, coal molasse overlaps Lausanne marine Aquitanian molasse.

These two important flaws are responsible for a marked tectonization of the coal molasse. An important straightening of rock layers and a strong fracturing of all the mass reduce the quality of the intrinsic mechanical strength.

These flaws played an important role in triggering soil movements. The Lutrive secondary flaw follows the evolution of the Lutrive river, and the Paudèze secondary flaw does the same. It follows the evolution of the Paudèze river downstream of the N9 highway bridge.

### 3.4. Hydrogeology

The Converney-Taillepied landslide is located between two rivers, named Paudèze and Lutrive, which rejoin the lower part of the landslide. Le Flonzel is the only stream that runs on the landslide body before flowing into the Paudèze, which rises from Ecaravez.

In the Converney area, pressurized water inflows have been detected in some drillings and also in the exploratory wells (with a discharge of more than 1 l/min). The sliding mass is also an aquifer, and the permeability is very low and discontinue. The soil composition seems very important: indeed, the sliding mass is made of marl and sandstone, which are sedimentary rocks. They can contain a large amount of water due to their quite high porosity but prevent water from freely circulating, explaining the low permeability.

In the Taillepied region, inside the sliding masses, there is extremely active water circulation. True underground streams have been found with an estimated flow rate of 100 l/min. An abnormal hydraulic gradient has been observed in the lacustrine sand, and it reveals the presence of a confined aquifer.

The waters circulating inside the landslide are very rich in carbonates, which explains the presence of some sedimentary tuff deposits that come from carbonate ions dissolved in water. These tuff sediments are present on La Conversion and Taillepied plateau, which allows inferring the existence of prolonged water circulation within the landslide.

There are two almost independent aquifers: a water flow distributed within the landslide and a semi-confined aquifer inside the underlying sands.

### 3.5. Climate Conditions

Rainfall has an influential role in landslide stability: it has a tight connection with landslide evolution. In the case of strong rainfall, water infiltrations cause variations of the phreatic aquifers.

When an important amount of water leaks into the soil, the cohesion force, and friction force decrease due to the vertical thrust, triggering the soil slip. Moreover, when the amount of water leaking into the slope is larger than the one that is pouring out, interstitial pressure is generated, and it triggers a sudden landslide. Annual amounts of rainfall show important variations, highlighted by some drought periods: the first one between 1962 and 1963 and the second between 1989 and 1990 both followed by a strong rainfall period (Figure **5**). These periods coincide with two important events of Converney-Taillepied landslide history: one related to the Taillepied district (1962), and the other happened in the Champs-Chamot (1990).

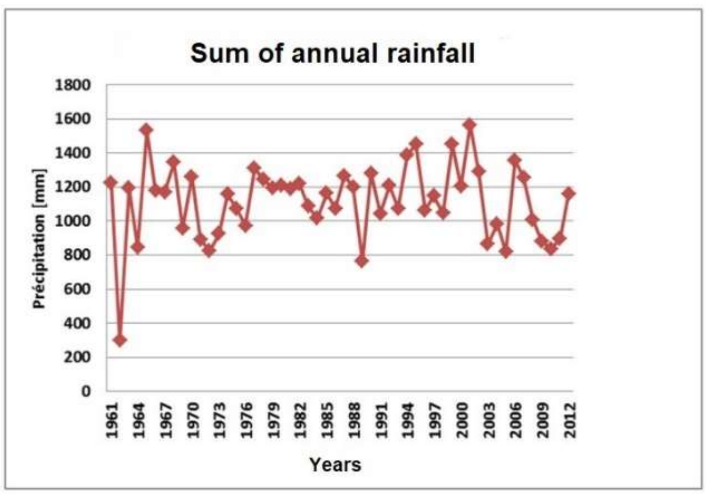


**Figure 5:** Annual rainfall - Pully station (Taken from www.meteosuisse.admin.ch - Data processing and chart made by Yasmine Madrari).

## 4. Methodology

This study aims to evaluate the impact of the built-on stability of the Converney-Taillepied slide. This was made possible thanks to Geoslope software. The first step of the study was to collect sufficient data to get as close as possible to reality with the computer simulation of the landslide.

Data collection of the geotechnical parameters of the soil composing the landslide allowed modeling the landslide in the software. Hypotheses on certain parameters had to be established due to a lack of information.

The main sources of this information are the results of boreholes that have been carried out over time and geological maps.

The second type of data needed to carry out the project was data on the evolution of the built environment over time. This information was mainly collected from the municipal archives [12] [13] [14].

### 4.1. Scenarios Choice

As mentioned in chapter 2.3, the constructions on the Converney Taillepied area have been done step by step. At the beginning of the 20th century, the area was poorly developed compared to its present state. That is why three timelines were studied to assess the effect of the constructions on landslide stability. These timelines, or so-called scenarios 1, 2, and 3, correspond to three different construction states on the landslide:

- Scenario 1 corresponds to the landslide situation in 1873. It refers to the most ancient map available, knowing that the first references of this landslide go back to 1615. The main infrastructures at this time were the two railway lines and a small residential area in Corsy.
- Scenario 2 refers to a key period of 1983. The first extensive studies were started in that year by F. Noverraz and M. Weidmann. In 1983, the constructions were significantly larger than in 1873. New residential areas can be found in Taillepied, Corsy, Collonge, as well as in Bochat-Conversion. A cantonal road and the N9 highway were also built. Moreover, several important constructions were dug in the sliding mass (ex: Bochat tunnel in 1980)
- Scenario 3 refers to 2011. In 2011, new residential areas were built. They extend from the south to the north of the landslide slope.

The study was carried out according to two sections, AA' and BB' (Figures **6** and **7**), which cover the strategic areas of the landslide.

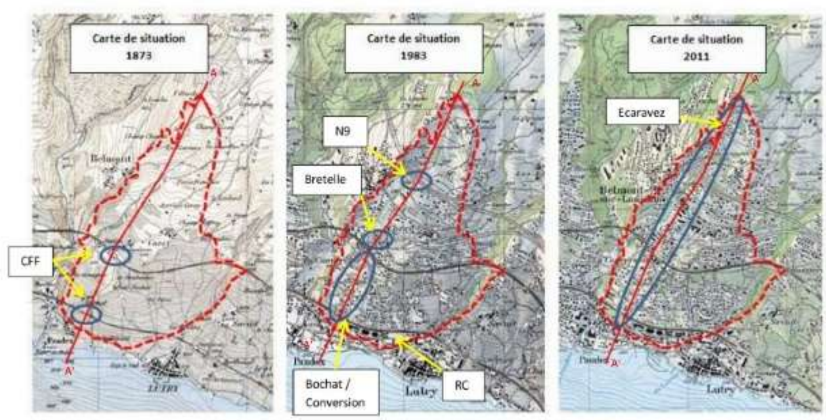


**Figure 6:** Anthropogenic scenarios impacts for section A-A' - modify from [17].

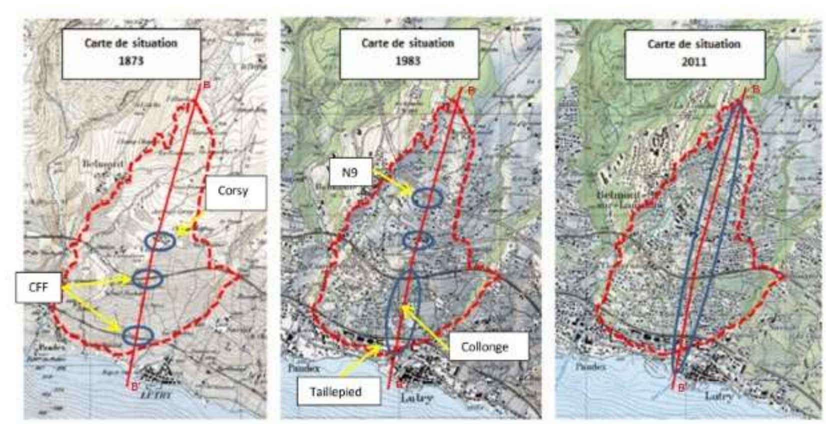


**Figure 7:** Anthropogenic scenarios impacts for section B-B' - modify from [17].

### 4.2. Stability Analysis

Stability analyses were carried out with the Geoslope software (extension SLOP / W) (Figure **8**), which is based on the limit equilibrium theory, to calculate the safety factor of soil or rock slopes. The model's goal is to analyze the stability with the evaluation of minimum safety factors according to different scenarios.

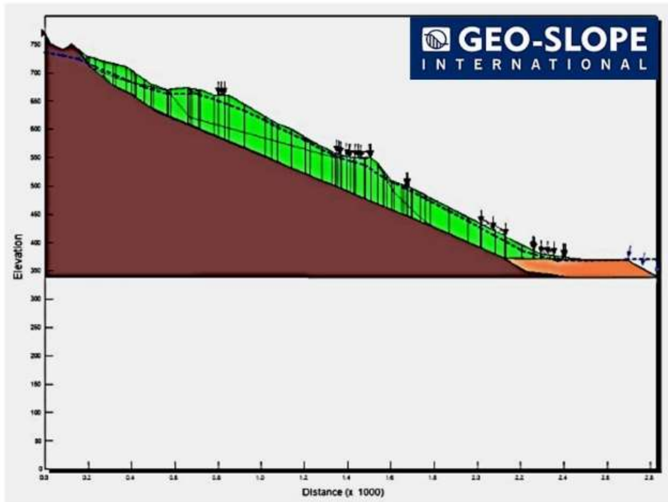


**Figure 8:** Longitudinal section and overloads modeling on Geoslope.

The Janbu theory has been applied as the computational method. This method is based on the following hypothesis:

- rigid and plastic behavior.
- bi-dimensional computation.
- stability depending on horizontal and vertical forces equilibrium.
- forces between segments acting at 1/3 of segment height.

Two calculation assumptions were made on the conditions of the molassic formation.

The first hypothesis assumes that the molassic formation is in place. The stability analysis, therefore, refers to three recent sliding masses. The masses are named Mass 1, Mass 2, and Mass 3 from upstream to downstream. These masses are visible in green hatched in Figures **9**, to **11**.

The second hypothesis considers that the molassic formation is slippery (old landslide). The stability analysis refers to an old sliding mass, visible in green hatched on Figure **12**.

Hypothesis 1 and 2 were applied to the three temporal scenarios. (Figure **9** to **12**).

Longitudinal modeled sections represent soil stratification. Several boreholes have been executed on the entirety of the landslide to define the depths of each soil composition. Through these boreholes, it is also possible to define the sliding mass depth, which varies according to local conditions for each different section.

For each soil type, geotechnical characteristics regarding shear strength have been analyzed according to the Mohr-Coulomb model (Figure **13**):

Bulk density γ [KN/m³],

Internal friction angle Φ [°],

Cohesion C [Kpa].

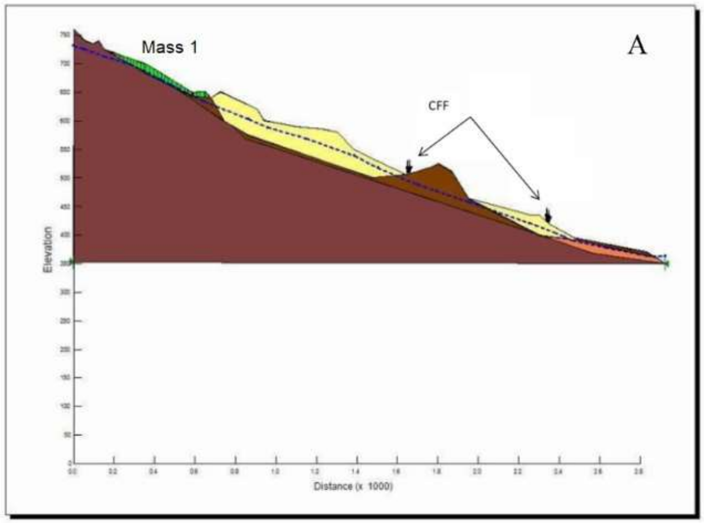


**Figure 9:** Scenario 1 models for Section A-A' with hypothesis 1-A.

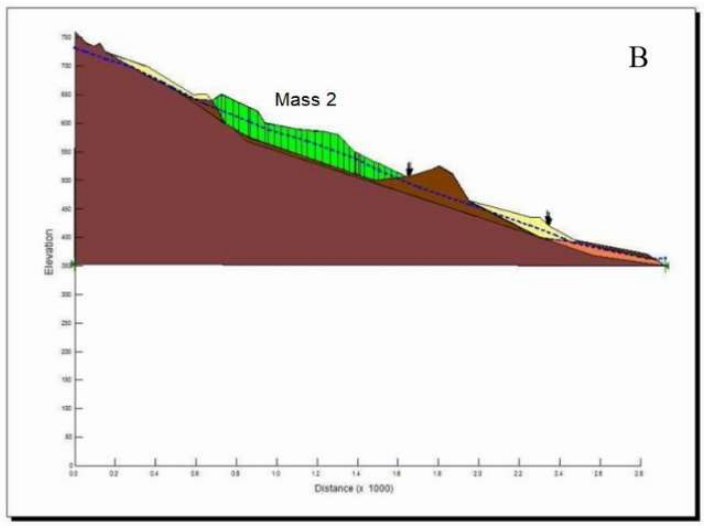


**Figure 10:** Scenario 1 models for Section A-A' with hypothesis 1-B.

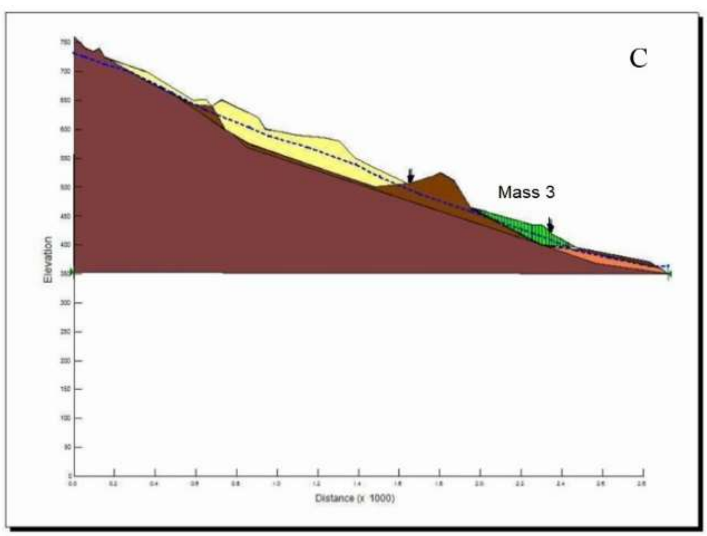


**Figure 11:** Scenario 1 models for Section A-A' with hypothesis 1-C.

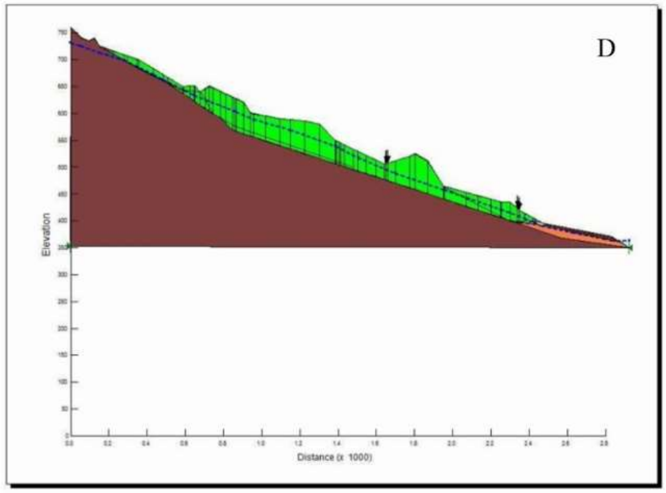


**Figure 12**: Scenario 1 models for Section A-A' with hypothesis 2.

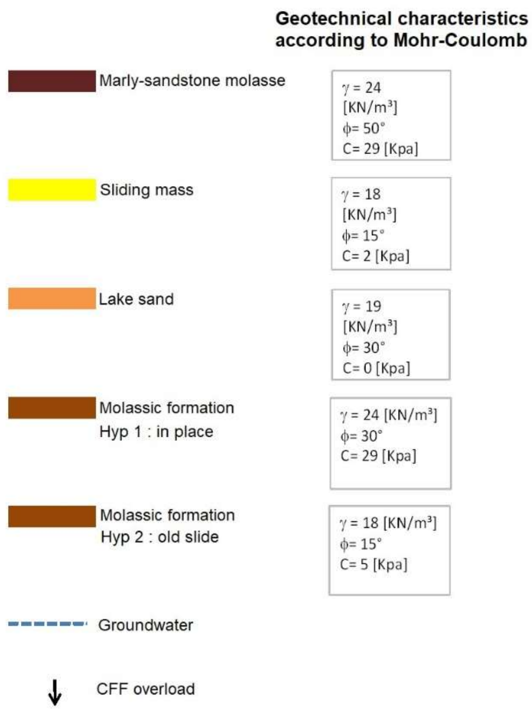


**Figure 13:** Geotechnical characteristics legend and values.

The phreatic aquifer is hard to model: piezometers are not present in all boreholes. Most of those in which piezometric level is noted correspond to a depth between 7 and 40 m.

The groundwater flow force is assumed to be parallel to the slope of the land to simplify the calculation model, although this is rarely the case in practice.

To evaluate overload due to existing buildings, the landslide is divided into two dominant zones according to the land use index (IUS Indice d'Utilisation du Sol in french):

- The low urbanization density zone (IUS = 0.4) where continuous two floors villas are considered with the hypothesis that 50% of them have basements;
- The medium urbanization density zone (IUS = 0.8), where four floors of buildings are considered, with the hypothesis that 50% of them have basements.

Overload calculation was executed according to load evolution, from roof to foundations, considering self-weight and the houses' useful loads as well as soil characteristics based on its nature [15] [16].

Overloads due to infrastructures (SBB railway lines, cantonal roads, N9 highway, and Perraudettaz connector) are given and also modelized along the longitudinal sections.

Table **1** shows overloads present in the landslide area with some relative values.

Distances between infrastructures and residential areas are respected, but for the modeling, the load inside residential zones is continuous, which does not correspond to reality. Nevertheless, offsetting considerations are taken into account.

The data was then inserted into the Geoslope software so that it could calculate the stability coefficient of each slide mass using the Janbu method. The only variable in the calculated coefficients is the evolution of the loads due to the constructions over time. The study aims to determine the impact of the evolution of these overloads on the stability of the slide. Therefore, it is not appropriate to compare the stability coefficients with past events, as these were triggered by parameters that were not modeled (e.g., rise on groundwater level following severe weather conditions).

**Table 1: Overloads present in the landslide area with relative values.**

| | Buildings Overload [kPa] | | | Infrastructure Overload [kPa] | |
|---|---|---|---|---|---|
| | Sliding Mass | Molassic Formation | Lake sand | SBB Railway | Highway |
| Low density zone | 25 | 16 | | 20 | 15 |
| Medium density zone | 48 | 57 | 55.5 | | |

**Table 2: Stability analysis results (24 safety factors) for the two different sections and with the two-starting hypothesis.**

| | Hypothesis 1 | | | Hypothesis 2 |
|---|---|---|---|---|
| | Mass 1 | Mass 2 | Mass 3 | |
| **Section A-A'** | | | | |
| Scenario 1 | 1.293 | 1.043 | 1.375 | 1.399 |
| Scenario 2 | 1.293 | 1.043 | 1.358 | 1.409 |
| Scenario 3 | 1.297 | 1.063 | 1.379 | 1.418 |
| **Section B-B'** | | | | |
| Scenario 1 | 1.33 | 1.133 | 0.974 | 1.048 |
| Scenario 2 | 1.33 | 1.134 | 1.003 | 1.059 |
| Scenario 3 | 1.306 | 1.145 | 1.005 | 1.061 |

## 5. Results and Discussion

Twenty-four stability factors for sections AA' and BB' with the two hypotheses 1 and 2. Figures **14** to **33** show the evolution of the built environment on the different sections of the landslide over time. As a reminder, scenario 1 corresponds to the state of construction in 1873, scenario 2 to 1983, and scenario 3 to 2011. The sections AA' and BB' are respectively shown in figure **6** and figure **7**.

Table **2** summarizes the Geoslope results.

### 5.1. Hypothesis 1: Section AA'

The first observation that can be made is that the terrain at the AA' cup level is stable. All the stability coefficients are higher than 1 and vary from 1.043 to 1.379 depending on the sliding mass and the chosen scenario. It is also noted that whatever the loads on the slide, slide masses 1 and 3 are more stable than mass 2. Therefore, mass 2 has a greater predisposition to landslides than the other two masses.

No construction was carried out on slide mass 1 between 1873 and 1983. That is why the coefficient of stability of this site in Scenarios 1 and 2 does not vary.

However, in 2011, the site had many relatively well-distributed residential buildings along with the profile of Mass 1 (Figures **14** to **16**). The coefficient evolves in a slightly positive way (1.293 to 1.297). Although the constructions have overloaded the slide, the stability coefficient has developed positively. These constructions are therefore beneficial for slip stability.

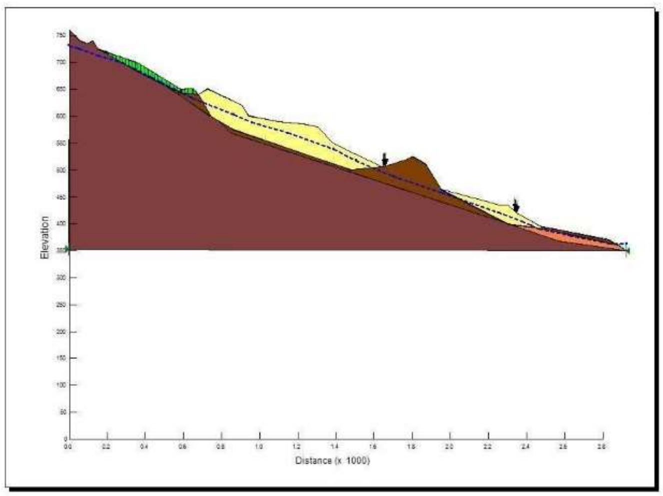


**Figure 14:** Section AA' scenario 1 sliding mass 1.

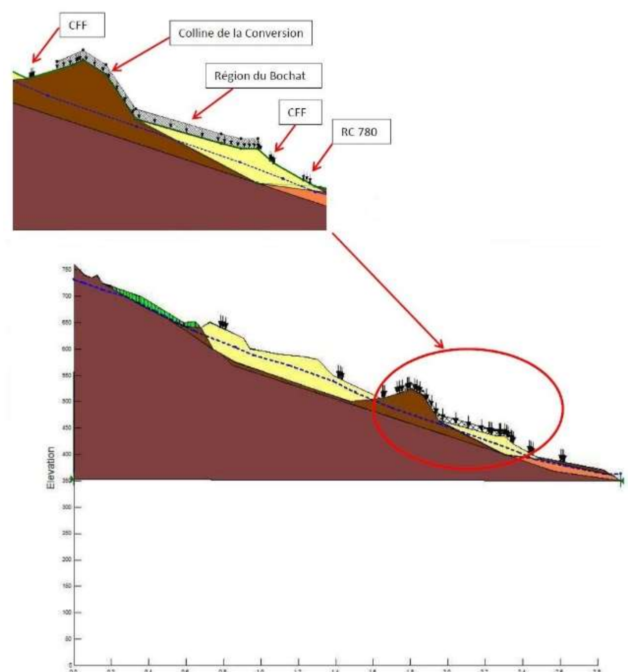


**Figure 15:** Section AA' scenario 2 sliding mass 1.

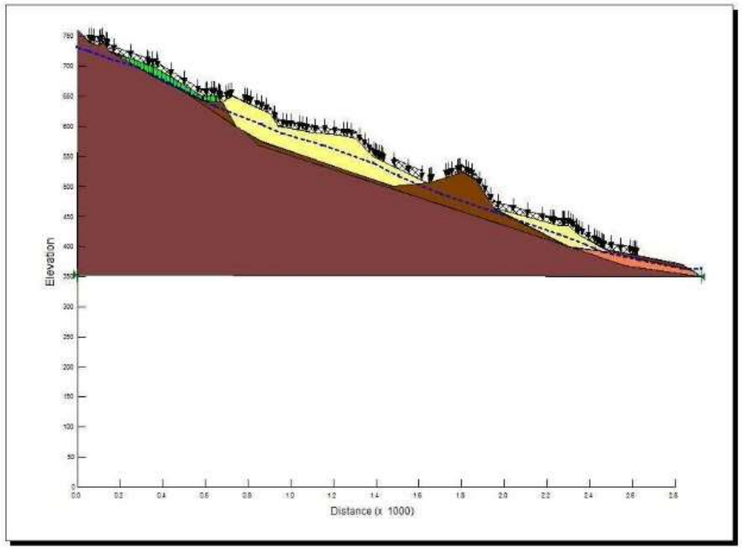


**Figure 16:** Section AA' scenario 3 sliding mass 1.

Between 1873 and 1983, the coefficient of stability of slide mass 2 also did not change. The situation is identical to slide mass 1, with the difference that two notable constructions were carried out during this period: the N9 highway upstream of slip mass 2, and the Perraudettaz slip road at La Conversion downstream. Numerous precautions were taken during the work on these two infrastructures. Deep drilling down to bedrock was carried out during the construction of the N9, as well as the installation of sub-horizontal and vertical drainage. The construction of the Perraudettaz slipway was carried out smoothly, as it is located in the most stable part of the slide. The precautions taken during this work probably compensated for the destabilization of the landslide due to the overloading of the infrastructures. Consequently, the coefficient does not vary.

In 2011, mass 2 is massively built on (Figures **17** to **19**). The constructions are evenly distributed along with the entire profile. The coefficient of stability increases slightly from 1.043 to 1.063. This increase is certainly due to the presence of the constructions all over the area. In fact, the district construction makes the soil impermeable (building right-of-way, roadway, rainwater drainage, etc.). This impermeabilization leads to a drop in the water table level, and therefore a decrease in the risk of landslides.

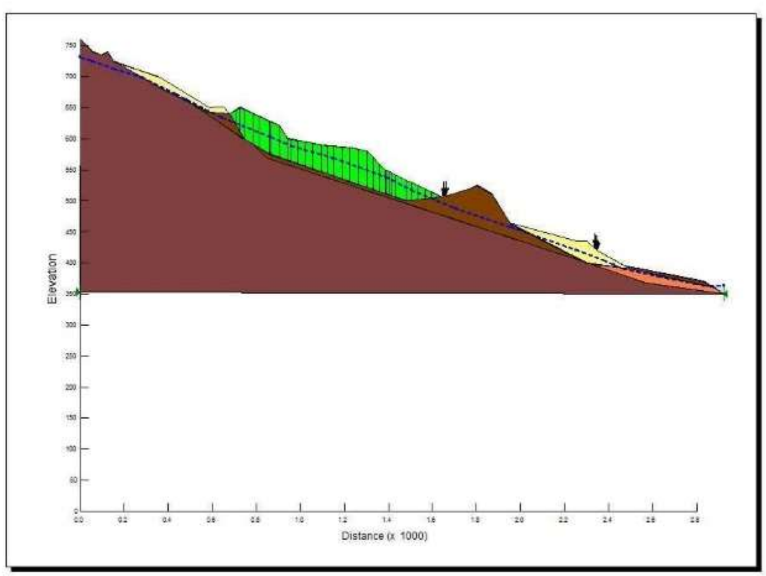


**Figure 17:** Section AA' scenario 1 sliding mass 2.

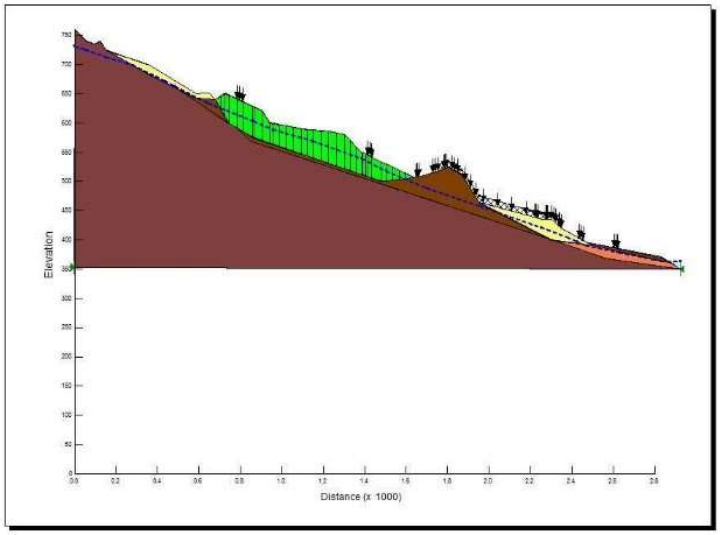


**Figure 18:** Section AA' scenario 2 sliding mass 2.

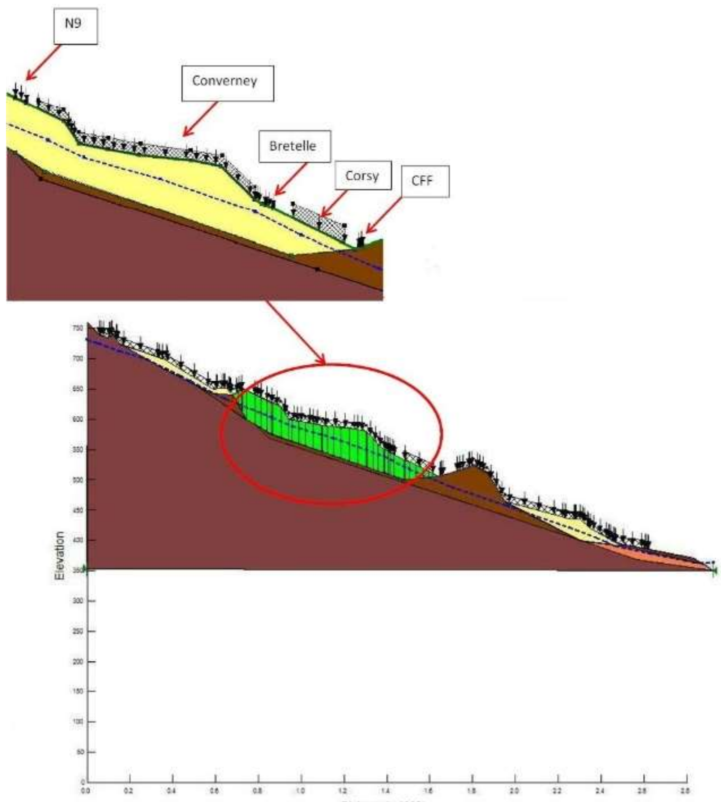


**Figure 19:** Section AA' scenario 3 sliding mass 2.

The situation of mass 3 is the most interesting of the AA' cup. In 1873, the only overload on mass 3 was on the SBB Lausanne-Simplon line. In this case scenario, the stability coefficient was 1.375. Following the construction of the buildings in the Bochat and La Conversion sectors (scenario 2), the coefficient decreased by 1.2%. In 2011, the Taillepied district expanded, and the stability coefficient rose to a slightly higher value than in Scenario 1, with a value of 1.379.

If we look more closely at the sections in Figures **20** and **21**, we can see that the new loads of scenario 2 compared to scenario 1 are mainly concentrated upstream of a steeper slope of the sliding mass 3. This configuration logically unbalances the slide, hence the lower stability coefficient.

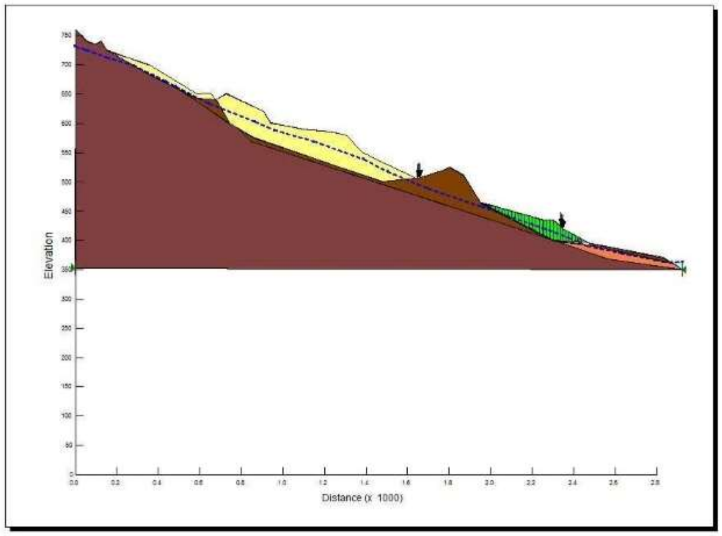


**Figure 20:** Section AA' scenario 1 sliding mass 3.

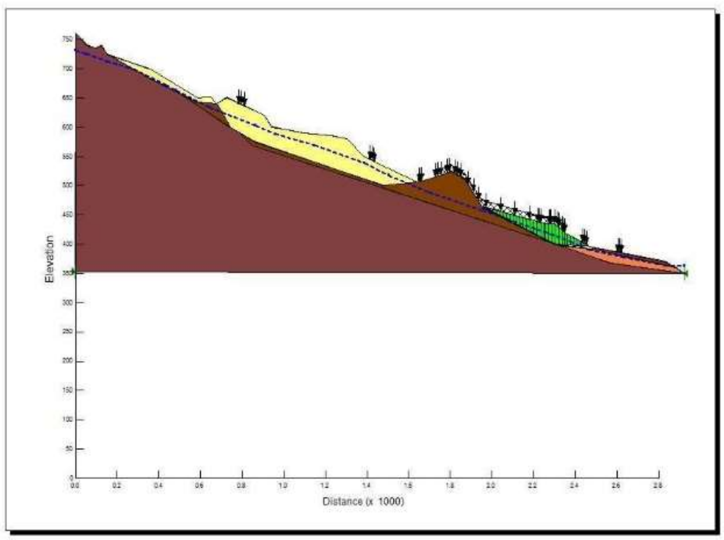


**Figure 21:** Section AA' scenario 2 sliding mass 3.

It can also be noted that the extension of the Taillepied neighborhood in scenario 3 (Figure **22**) has made the system more balanced between the head and foot of the landslide. This balance is reflected in a logical increase in the stability of the sector. This example shows us the major importance of the location of the constructions on a landslide.

### 5.2. Hypothesis 1 : Section BB’

The coefficients of stability of the three masses at the BB' section are contrasted. They vary from 1.330 to 0.974. The slide masses M1 and M2 are stable, with values higher than 1.1. On the contrary, slide mass M3 is unstable in scenario 1 and stable in scenarios 2 and 3. The instability of this area is certainly due to the terrain's morphology, characterized by a steep slope.

Between 1873 and 1983, the evolution of the M1 from section BB' is similar to M1 from section AA'. In fact, no construction took place on this terrain during this period (Figures **23** and **24**). The coefficient of stability does not change.

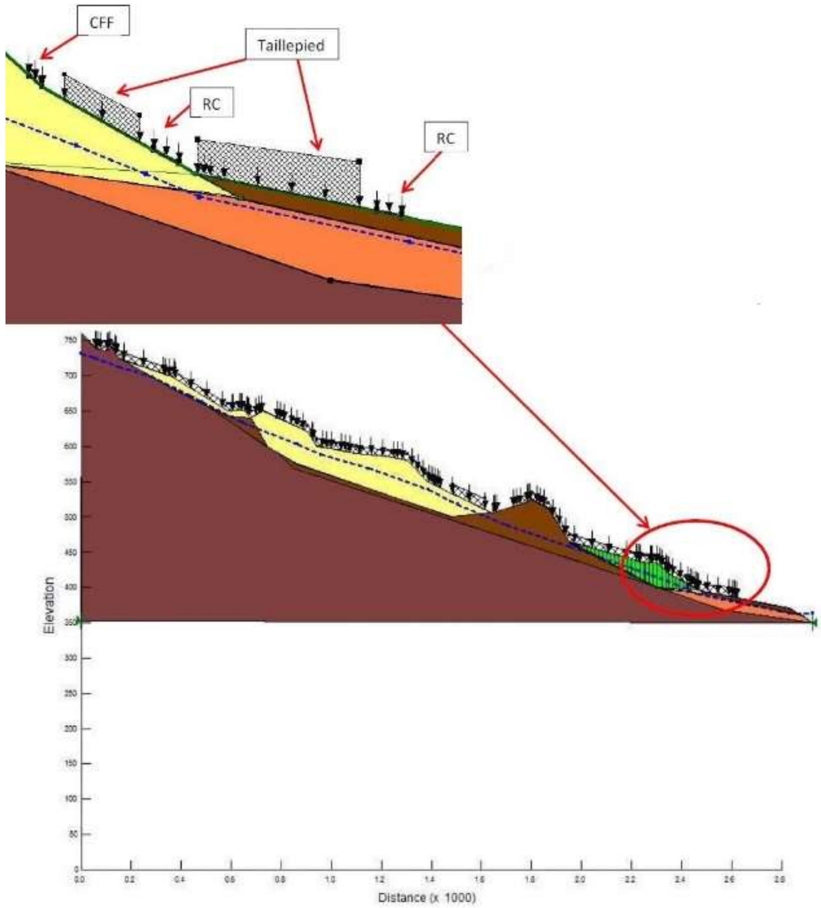


**Figure 22:** Section AA' scenario 3 sliding mass 3.

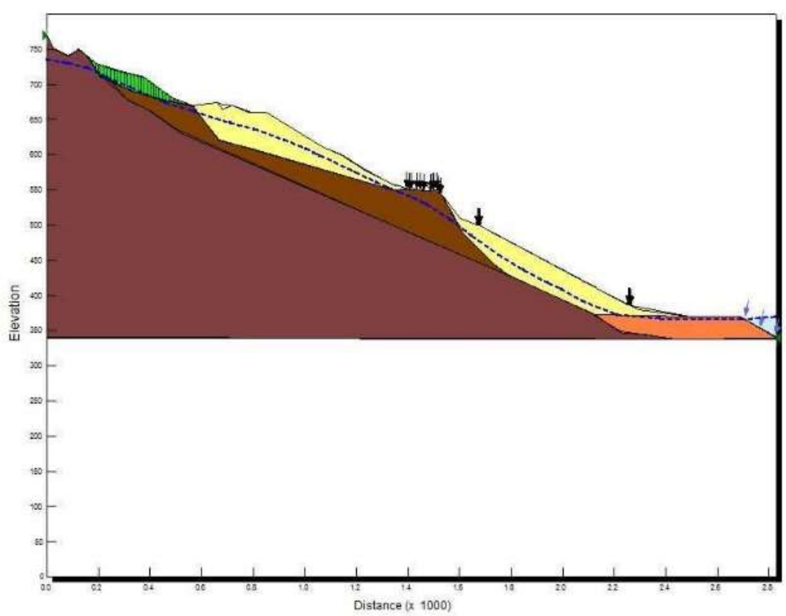


**Figure 23:** Section BB' scenario 1 sliding mass 1.

However, between 1983 and 2011, M1 was massively built on. The distribution of new constructions destabilized the area. The coefficient of stability decreased? from 1,330 to 1,306. The reason for this slight decrease is the concentration of overloads in the main pull-out niche of the landslide (Figure **25**).

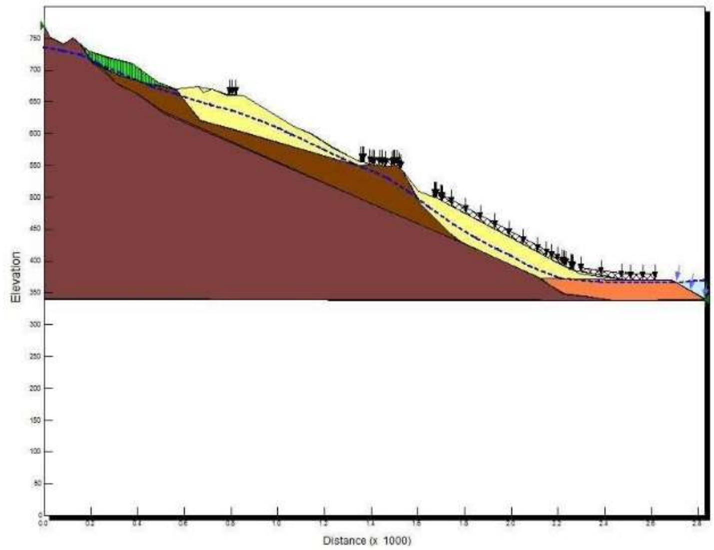


**Figure 24:** Section BB' scenario 2 sliding mass 1.

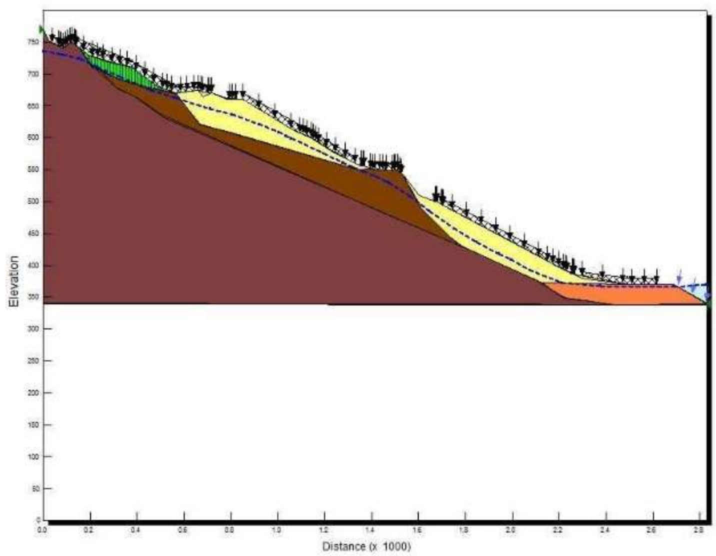


**Figure 25:** Section BB' scenario 3 sliding mass 1.

No infrastructure was recorded on Mass 2 in 1873. In 1983, the situation had changed little. Some building overload appeared downstream of the landslide and the passage of the N9 highway (Figure **26** and **27**). The stability coefficient hardly changed from scenario 1 to 2 (1.133 to 1.134). As for section AA', measures taken during the construction of the N9 highway compensated for the destabilisation of the terrain due to the overloading of the infrastructure. In 2011, the area was massively built up. The distribution of buildings is relatively homogeneous over the entire slide mass. The downstream area is slightly less occupied (Figure **28**). For reasons similar to section AA's mass 2, the stability coefficient also evolves favorably (1.134 to 1.145).

In 1873, slide mass M3 only shows the overload of the two SBB lines and a residential area in Corsy upstream. The stability coefficient was then less than 1. The slope of this sector is steep (Figure **29**), which explains the lower overall stability. That is why the area is unstable, although it is only lightly occupied. Between 1873 and 1983, new residential areas were realized, as well as the cantonal road (Figure **30**). The distribution of the overloads induced by these new constructions is well balanced on the slide. The stability coefficient increases significantly and becomes positive again (1.003). The area is para-stable, but a slight imbalance caused by a poorly positioned new construction or an increase in the water table can trigger a landslide.

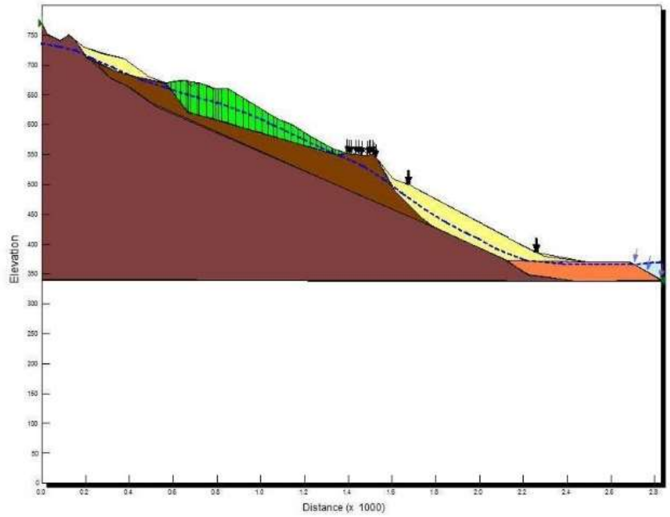


**Figure 26:** Section BB' scenario 1 sliding mass 2.

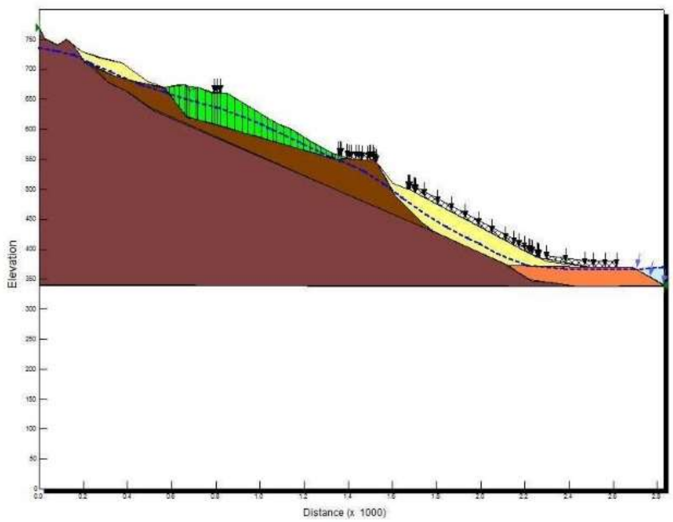


**Figure 27:** Section BB' scenario 2 sliding mass 2.

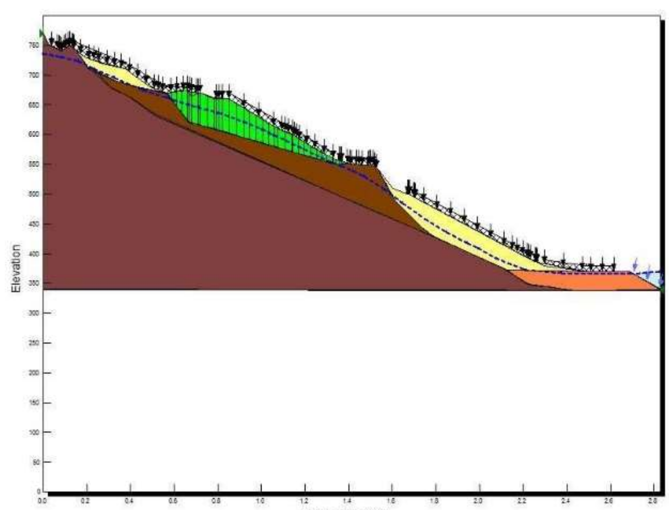


**Figure 28:** Section BB' scenario 3 sliding mass 2.

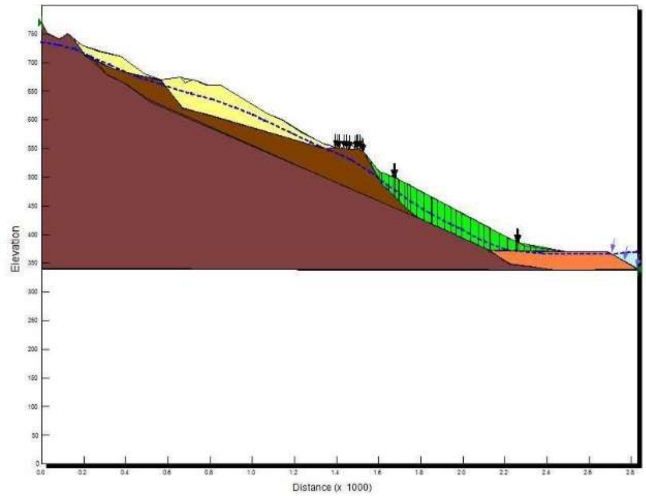


**Figure 29:** Section BB' scenario 1 sliding mass 3.

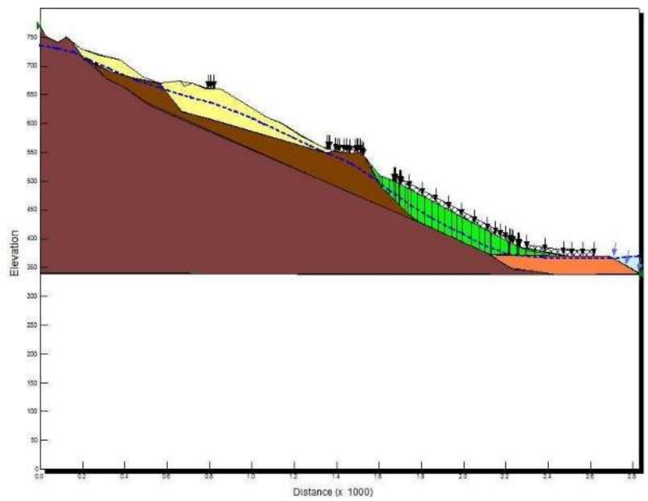


**Figure 30:** Section BB' scenario 2 sliding mass 3.

As the building stock has not changed much in this area between 1983 and 2011 (Figure **31**), the stability coefficient has changed very little, from 1.003 in 1983 to 1.005 in 2011.

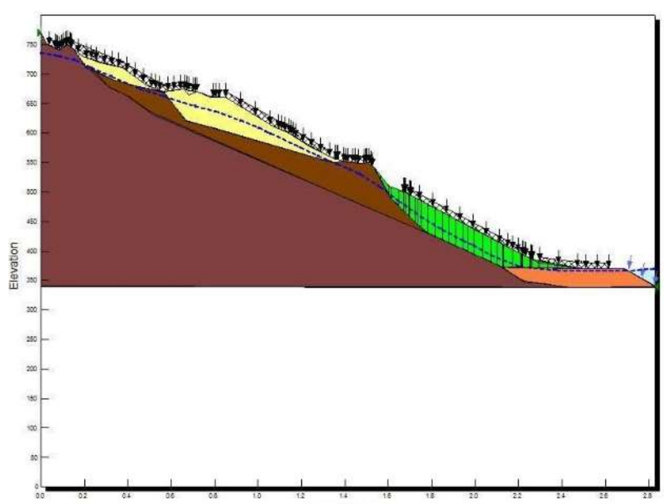


**Figure 31:** Section BB' scenario 3 sliding mass 2.

### 5.3. Hypothesis 2

The calculations of hypothesis 2 are based on an ancient sliding mass and no longer on three distinct sliding masses. The results obtained by GeoSlope show that the stability factors are, in all cases, higher than 1. Section AA' (Figure **32**) is the more stable of the two, with values close to 1.4 in all three calculation scenarios. Section BB' (Figure **33**) is much less stable, with values varying between 1.048 to 1.061, depending on the calculation scenario. The stability of the terrain is lower in section BB', partly due to the steeper overall slope.

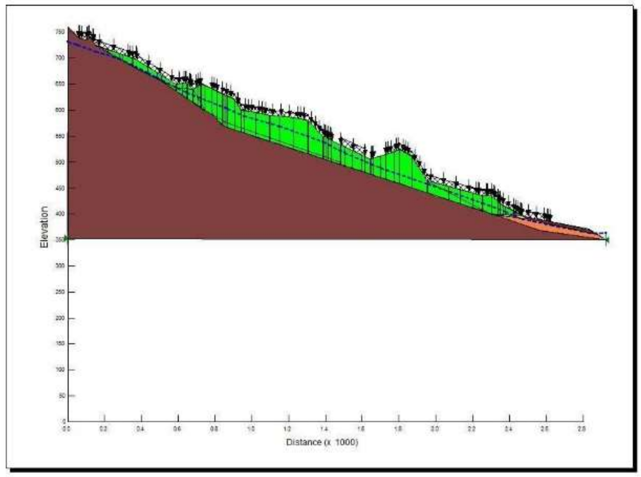


**Figure 32:** Hypothesis 2 Section AA'.

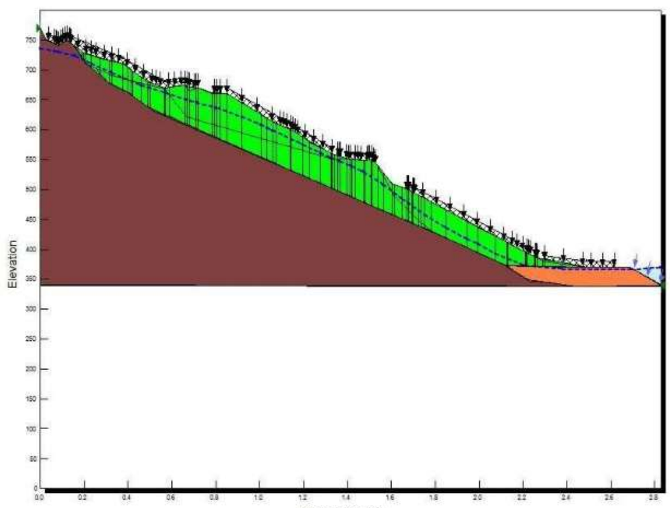


**Figure 33:** Hypothesis 2 Section BB'.

Both sections show a positive evolution of the stability coefficient over time. In 1983, the existing buildings were mainly concentrated at the foot of the landslide. The upstream part of the landslide was not urbanised. The N9 highway and the Perraudettaz ramp road are the biggest overloads in the middle of the landslide. The stability coefficient evolves slightly positively (+0.010 for section AA' and +0.011 for section BB').

In 2011, the building density increased over the entire landslide. The upstream and the middle of the slide were massively built upon. Therefore, the stability coefficient has once again increased slightly.

In view of the densification of the buildings on the landslide and the evolution of the stability coefficient, it can be concluded that the buildings have a very slight improving impact on the stability of the landslide. The coefficient increases by 0.019 for cut AA' and by 0.013 for cut BB'.

# 6. Conclusion

The analysis of the behaviour of the landslide in relation to the building proved to be more complex and depends on many factors such as the morphology of the terrain, the thickness of the landslide mass, the level of the water table the type of soil, etc. It is worth mentioning that changes in water levels remain the main factor influencing the slide. Lowering or raising the water table by a few meters in the Geoslope software is sufficient for the stability coefficient to change considerably.

The study of the stability of the slide masses of sections AA' and BB' over time reveals part of the impact of the constructions on the slide. This impact can be negative or positive on the overall stability. There is no doubt that the effect of the overloading of the constructions can destabilize the landslide mass, mainly if this overloading is in an unfavorable position, for example, upstream of a steep slope. Rapid and haphazard urbanisation can lead to tragic events, such as the landslide event in Sierra Leone on 14$^{th}$ August 2017 which killed 500 people and left over 600 missing [17].

Nevertheless, the constructions carried out on the landslide tend to lower the water table. Indeed, the urbanisation of a site makes part of the land impermeable (roads, buildings, piping, etc.), increasing the stability coefficient.

The effect of buildings on a landslide is therefore multiple. The effect of overloading is obviously detrimental to the overall stability of the landslide mass, but it is partly compensated for by the sealing of the area. However, this improvement in the stability factor consists of a variation of only a few percent. This improvement is not without risk. Indeed, special measures must be taken during certain critical phases of the construction, in particular during the excavation of the soil. If the measures are insufficient or unsuitable, the work can suddenly reactivate the ground, as was the case during the work at Taillepied in 1962.

Land use planning also plays a crucial role in landslide stability. The choice of densification zones is decisive for the equilibrium of the landslide and must be the subject of a thorough study.

Building on a landslide while improving stability is therefore possible. Nevertheless, the knowledge of the characteristics of the landslide must be mastered because the negative impact of a poorly designed project is more significant than the positive impact of a successfully completed project.

# Acknowledgements

The authors would like to thank: Mr Christian Gerber for his valuable comments during the intermediate phases of this work; Belmont-Sur-Lausanne municipality and especially Mr Dominique Gamboni, Lutry and Paudex municipalities for the support provided during the data collection (making archives and plans available) and for all the additional explanations; Mr Emmanuelle Marquelet, from Norbert SA firm (Lausanne) for all the support and explanations.

# References

[1] Pasche L, Moreau A. Vaud passe le cap des 800 000 habitants. Numérus, 2019; Hors série, Février.

[2] Karakas B, Français. Commune de Belmont, étude de stabilité du territoie communal. Belmont-sur-Lausanne, Mai 1999.

[3] Karakas B, Français. Glissement de terrain Champs-Chamot, travaux de consolidation et mesures de contrôles. Belmont-sur-Lausanne.

[4] OFROU. VSS. Union des professionnels Suisse de la route: coefficients caractéristique du sol, 2013.

[5] Bafu. Bafu. 2013; [En ligne]. Available: http://www.bafu.admin.ch.

[6] Géoplanet. Géoplanet. [En ligne]. Available: http://www.geoplanet.vd.ch. [Accès le 2013].

[7] Swisstopo. Swisstopo. 2013; [En ligne]. Available: www.swisstopo.admin.ch.

[8] Mottaz E, Meyer L. Dictionnaire historique, géographique et statistique du canton de Vaud, [Réimp. de l'éd. de Lausanne, 1921] éd., Lausanne: Slatkine, 1982.

[9] Bersier A. L'origine structurale des collines et alignement morphologiques orientés du Plateau vaudois. Bulletin de la Société Vaudoise des Sciences Naturelles , 1942; 62: n° %1258.

[10] Noverraz F, Weidmann M. Le glissement de terrain de Converney-Taillepied (Belmont et Lutry, Vaud, Suisse). Bulletin de Géologie de Lausanne, 1983; n° %1269.

[11] Pralong J-P, Reynard E. Lecture et analyse du paysage : Lavaux (Vaud, Suisse). Lausanne, 2004.

[12] Français BK. Modification du PGA. Belmont-sur-Lausanne, Septembre 2012.

[13] de Vaud C. Guichet cartographique cantonal. 2013; [En ligne]. Available: http://www.geo.vd.ch/theme/localisation_thm.

[14] Ruffy V. L'aménagement du territoire de deux communes vaudoises : Lutry et Savigny, son évolution. Géographica Helvetica, 1964; 19: pp. 57-86. https://doi.org/10.5194/gh-19-57-1964

[15] SIA, SIA 260 Bases pour l'élaboration des projets de structures porteuses, Zurich, 2013.

[16] SIA, SIA 261 Actions sur les structures porteuses, Zurich, 2013.

[17] Cui Y, Cheng D, Choi CE, Jin W, Lei Y, Kargel JS. The cost of rapid and haphazard urbanization : lessons learned from the Freetown landslide disaster. Landlslides, 2019; 16: pp. 1167-1176. https://doi.org/10.1007/s10346-019-01167-x