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GEOTECHNICAL, GEOPHYSICAL AND SEISMOLOGICAL METHODS FOR SURFACE SEDIMENTARY LAYERS ANALYSIS

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SUMMARY

In this study, geophysical (electrical tomography, seismic refraction …) and seismological methods (H/V spectral ratio) were applied at Saint-Guillaume, a small town located Southern of Grenoble (France), which rests on a slow landslide developing in varved clay. The results obtained from these methods were compared to those deduced from a geotechnical survey spread over the Saint Guillaume area, with which the limits between the topmost clay layer and the underlying stiff limestone and the sliding surfaces were defined. Satisfying correlations have been found between methods, allowing the evaluation of the geotechnical parameters of the landslide, as well as the imaging of its lateral and vertical limits.

INTRODUCTION

For a long time, soft and surficial soils attract geotechnician and seismologist's attention due to their amplification effects on the seismic ground motion (i.e., site effects) and their potential instabilities leading to natural landslides or causing huge settlements of foundation. Therefore, the knowledge of their spatial distribution, their thickness, as well as their mechanical characteristics is of great interest for land-use planning, hazard mapping and geotechnical engineering. As the soft soils may concern sprawling area, classical geotechnical methods (SPT, CPT…) are not always well-appropriated in case of strong lateral variability of the bedrock and of the sliding depth. The limited depth of investigation of these methods is also an inconvenience in case of important thickness of the topmost soil. Abundant geotechnical information that is essential for the analysis of these variabilities is frequently unavailable. That is the case for the small landslides for which only small geotechnical surveys are usually deployed as consequences of the high cost needed, even if the economic and life losses could be important in case of re-activation of the sliding. Moreover, even if drilling boreholes provides detailed information, it stays on expensive and slow methods. For all these reasons, geophysical methods give an alternative that allows covering a wide area at reduced cost of investigation with continuous imaging of the subsurface zone.

The aim of this study is to compare geophysical, seismological and geotechnical data obtained by different ways. In addition to the standard geophysical methods (e.g. electrical tomography and seismic refraction),

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the H/V spectral ratio using ambient noise was applied to the Saint-Guillaume landslide, a small town located to the South of Grenoble (French Alps). This area is still monitored by geotechnical boreholes drilled in a few part of the landslide, but due to the strong lateral variation suspected from in-situ and geological analysis, the geotechnical information was insufficient for having an exhaustive idea of the lateral extension of the process. Nevertheless, the boreholes were used to compare and valid the results deduced from geophysical survey.

GEOLOGICAL AND GEOTECHNICAL SETTINGS

General framework

Located to the South of Grenoble (French Alps), the studied zone, the Saint-Guillaume (SG) landslide, is characterized by a small and slow landslide typical of this region (Fig. 1A). The basement of the area is composed of marly limestone of the Oxfordian (Quaternary age). The sedimentary fill is composed of varved clay (called Trièves clay) indicating a glacio-lacustrin environment (Fig. 1B). The deposit sequences are the results of the presence of glaciar lakes that were created during the last Würmian age (from -100000 to -20 000 years), which were blocked to the North by the Isère’s glacier. These quaternary

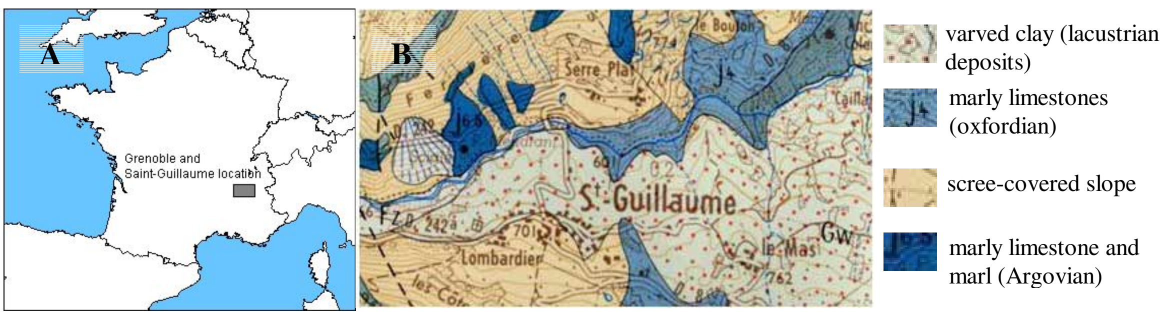

Figure 1: Location of the Saint-Guillaume landslide to the South of Grenoble in the French Alps (A) and simplified geological map centered on the Saint-Guillaume town (B).

deposits are made of sandy-silty lacustrine clay formations (Antoine [1]), characterized by low density, high compressibility and low strength. Their characteristics make them potentially collapsible, as observed in all Trièves region where the topographic surface is favorable to the activation of sliding. The SG landslide is limited to the South by a scree-covered slope, as consequences of the presence of limestones cliffs. An umbilical zone of limestone is also visible to the East, which divides the clay formation in two parts, one to the West and the other one to the East, also confirmed to the North, by the shape of the clay/limestone transition to the opposite site of the valley (Fig. 1B).

Geotechnical description of the SG landslide

Since 1984, many buildings falling in the SG landslide have been moderately damaged. Started in 1984, a traditional geomorphological-geotechnical survey has been deployed on the site (Fig. 2), composed of height topographic control points and three instrumental measurements in borehole by inclinometer type. The slope deformation monitoring, added to recent in-situ and stereoscopic aerial photos examination, has allowed an assessment of an average value of displacement rate that is about 1cm/year and 3cm/year in planimetry, at the southern and the northern part of the Saint-Guillaume area, respectively. The direction of the movement, which is consistent with in-situ observations, let us suppose a large and extended sliding subdivided into small differential movement.

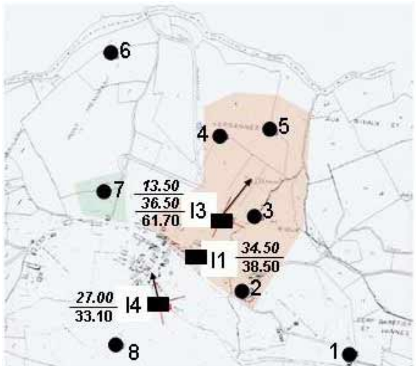

Figure 2: Geotechnical survey in the Saint-Guillaume landslide. (black full-circle: height topographic control points – black full-square: instrumented borehole by inclinometer, the upper number in italic corresponds to the slip surface depth and the below number to the varved clay/marly limestone transition depth – the black arrows indicate the main direction of the slip measured with inclinometer)

The borehole drilled in the studied area have pointed out the existence of a varved clay/marly limestone transition zone located 38.50m, 61.7m and 33.10m depths at I1, I3 and I4 boreholes, respectively. The instrumental measurements in borehole have also detected the existence of slip surfaces, all of them inside the clay layer. These movements let us affirm the SG landslide fits the simplest model of landslides that considers the moving part as a deformable block sliding over a circular surface, dividing the sedimentary formation. At the I1 borehole, the sliding surface was detected at a depth of 34.50m, this borehole being out of service since 1996 after the cutting of the inclinometer tube. At I4, the existence of the sliding surface was observed at 27m deep, toward the N10°W direction. The I3 borehole has pointed out the existence of two major surfaces of sliding: the first one at 13.5m of depth while the second was between 33 and 37m of depth, with the maximum displacement rate at 36.50m deep.

GEOPHYSICAL AND SEISMOLOGICAL SURVEY

H/V spectral ratio

The H/V spectral ratio using seismic noise measurement is a widely used method. In 1989, Nakamura[2] first proposed to record the seismic noise (or ambient noise) to provide useful information for local amplification estimates in order to evaluate the seismic site effects due to the topmost sedimentary layer. The process consists in computing the spectral ratio between horizontal and vertical ground motion recorded simultaneously at the surface of soil. Since the explanation formulated by Nakamura on the efficiency of the method, many experimental (e.g. Lermo[3]; Field[4]; Duval[5]) and theoretical analysis (Lachet[6]) have confirmed the effectiveness of this method, by comparing the evaluation of site effects using the H/V spectral ratio, the receiver functions (Langston[7]) and the Standard Spectral Ratio (Borchedt[8]). A close relation exists between H/V spectral ratio and the ellipticity of the contributing Rayleigh waves, which dominate the seismic noise (Lachet[6]; Scherbaum[9]). In case of a layered sedimentary profile with an impedance contrast large enough, the ellipticity of Rayleigh waves vanishes and becomes polarized only on the horizontal direction for the frequency corresponding to the fundamental frequency of the surface layer response. The shape of the ellipticity is found to be subject to a strong trade-off between layer thickness and average layer velocity. Scherbaum[9] have made this observation by combining the inversion schemes for dispersion curves and ellipticities such that the velocity-depth dependence is essentially constrained by the dispersion curves while the layer thickness is constrained by the ellipticities. In the case of a very simple soil profile composed of a soft layer resting on a stiffer bedrock, the amplified frequency f_o may be easily estimated by the well-known relation linking the thickness H and the shear wave velocity α of the topmost layer ($f=\alpha/4H$). An European project (SESAME, http://sesame-fp5.obs.ujf-grenoble.fr) is undergoing which includes a theoretical and numerical part to better understand the nature of seismic noise, and experimental and data processing investigations to clearly assess the stability, robustness, reliability and physical meaning of the H/V spectral ratio.

In practice, the H/V spectral ratio experiment consists in recording seismic noise with a 3D velocimeter put on the ground. For the SG landslide, we used the user-friendly CitySharkTM II acquisition station developed for noise measurement (Chatelain[10]). This multi-channel station allows connecting 6 3D sensors for simultaneously recording of seismic noise with 18 channels. Several profiles were done on the field and each sensor was separated from the other by about 20m, in order to obtain a continuous evaluation of lateral variations of the clay layer response, that underlines the shear wave velocity or depth variation. Six 3D Lennartz (5secondes) were used and about 70 points of noise recordings were done on the SG landslides.

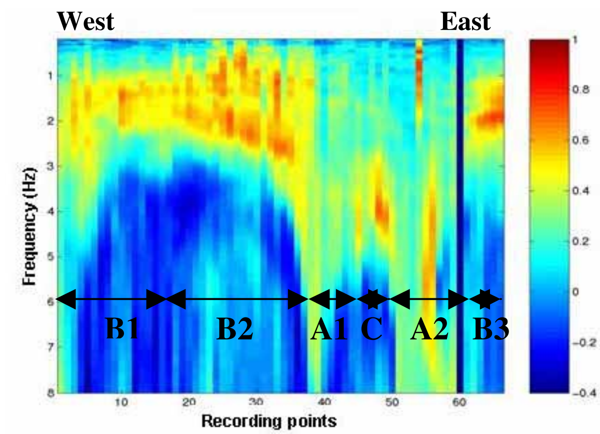

Figure 3: H/V spectral ratio using seismic noise done along the West-East Saint Guillaume profile crossing the landslide. The amplitude of the spectral ratio is given as logarithmic scale.

Figure 3 shows the value of the H/V spectral ratio computed along the profile crossing the SG landslide from the West to the East. Strong lateral variations are observed that indicates strong variabilities of the topmost layer. To the East (zone B1), the H/V spectral ratio clearly show amplified frequencies close to 2Hz, decreasing up to 1.3Hz at point 20. Then, two amplified frequencies appear (zone B2): the first one varies from 1.5Hz up to 3HZ and the frequency starts to vanish at point 36; the second one decreases up to less than 1Hz and vanishes also at point 36. It is important to note that the I1 inclinometer borehole falls in the two amplified frequencies zone, and it pointed out a slip surface at 34.50m of depth and the clay/limestone transition at 38.50m. Between points 36 and 47 (zone A1), no amplified frequencies can be observed but after point 47, high values of spectral amplitude appear again around 4Hz up to point 50 (zone C) that indicates the presence of a spatially limited clay layer. After point 50 (zone A2), the H/V spectral ratio does not show amplified frequencies that fits the presence of the umbilical marly limestone zone (Fig. 1B), without clay. Finally, at the eastern part of the profile (zone B3), the 2Hz frequency appears again that is in conformity with the presence of the varved clay formation shows on Fig. 1B.

Because the fundamental frequency of a simple bi-layer model depends on the thickness and the shear-waves velocity, we can not conclude at this point on the *fo* values variation. Nevertheless, as before-mentioned from the boreholes analysis, the depth of the clay/limestone transition varies from one to each other while the properties of the Trièves varved clays are known to be very uniforms (Antoine[1]). This let us suppose a strong relation between the *fo* value and the thickness of the clay layer or with the sliding superficial soils.

Geophysical survey

Complementary geophysical methods have been applied to the eastern part of the study area. These methods were planned in order to estimate the shear wave velocity into the clay layer and the underlying bedrock, and to define the clay/limestone transition depth.

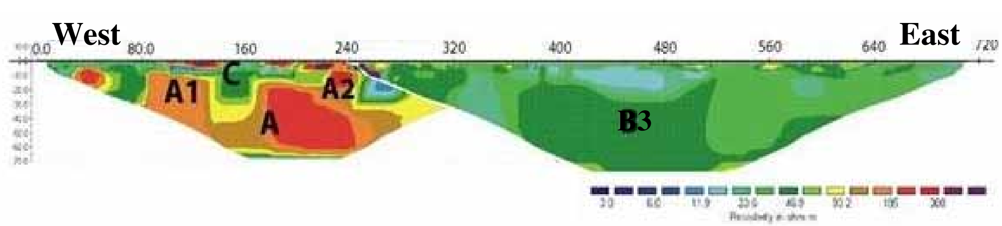

Figure 4: Electric West-East profile crossing the Saint-Guillaume landslide.

Two electrical tomography (Fig. 4) performed to the eastern part of the studied area (zones B3) shows low resistivity values (less than 50 Ohm.m) corresponding to the resistivity usually observed for the clays. A very thick layer of clay is detected, up to 70m of depth, without any apparent horizontal discontinuities. Nevertheless, the S-wave refraction profile (zone B3) gives a three layers model (Fig. 5A): (1) the very topmost layer of 2 meters thick with a shear wave velocity of about 180m/s; (2) a 30 meters thick layer characterized by 256m/s of shear wave velocity; (3) a deeper layer with 689m/s of shear wave velocity. Since un-identified with the electrical method, these three layers may be composed of the same sedimentary formation, i.e. varved clay, but the S wave variations underline the changing of strength properties, large enough to give an impedance contrast of 2 corresponding to the deeper transition zone. Applied to the zone characterized by the two amplified frequencies (zone B1), the shear wave profile gives a theoretical 1D transfer function (Kenneth[11]) at the I1 inclinometer borehole (Fig. 5B) with a large frequency peak, falling in the 1-to-2Hz frequency band observed on the experimental H/V spectral ratio. At I1 borehole, the limit at 34.50m of depth corresponds to the sliding surface that confirms the variation of strength properties between the upper deformed block of clay, sliding over an underformed clay block.
The electric profile points out also the limestone zone (zone A2) observed on the geological map that gives precise constraints on the resistivity value of the SG limestone to around 200 Ohm.m. Then, it is a rise of the underlying marly limestone which may be observed in the center part of the electric profile (zone A1) that confirms the vanishing of the amplified frequency showed by the experimental H/V spectral ratio (Fig. 3). The rise of the bedrock is also confirmed by the P wave refraction profile conducted on this zone. Between A1 and A2 zones characterized by the sub-surface limestone, a laterally limited zone composed of clay is detected by the electric and P wave profiles that correspond to the highest amplified values of the H/V spectral ratio (zone C).

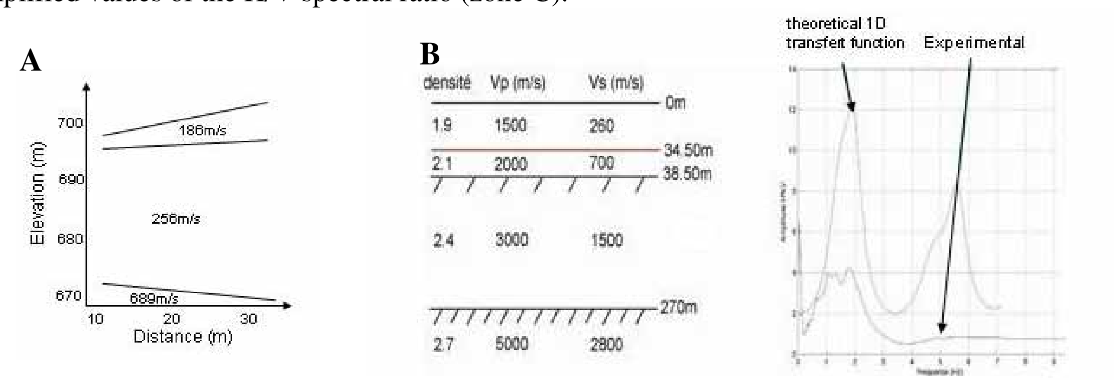

Figure 5: (A) Shear wave velocity profile at the B3 zone; (B) cross section at the I1 borehole (zone B1) and its theoretical 1D transfer function compared to the experimental H/V spectral ratio.

DISCUSSIONS AND CONCLUSIONS

The H/V spectral ratio was used in order to check its efficiency and limitation to define the lateral variations of a very surficial layer characterized by a sliding motion. There is no doubt that the H/V spectral ratio is rather limited to define all the mechanical properties of such geotechnical formation. Nevertheless, a very good correlation has been found between the classical geophysical method and the H/V spectral ratio, also confirmed by the geotechnical borehole drilled in order to survey the sliding surface.
First, the H/V spectral ratio method computed along linear profiles gives a very good representation of the lateral variabilities of the clay/limestone transition depth. This was also confirmed by a very good correlation with the electric profile and the P wave refraction profile. The unsuspected rise of the bedrock to the surface is detected, characterized by the vanishing of the amplified frequency.

Then, the H/V spectral ratio allows defining the position of the slip surface at the I1 borehole that should be confirmed at the I3 and I4 boreholes. But the double amplified frequency is a consequence of the presence of a very thin layer in depth, with an impedance contrast high enough to be detected by this method.

Finally, the spectral ratio computed along profiles can be use for mapping the sub-surface variabilities. In case of homogeneous geotechnical properties (i.e., shear waves velocity), this method is very useful and can be applied in addition to classical geotechnical survey to have a continue evaluation of the topmost layer topography, that gives a good evaluation of the volume of soil being able to slip.

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