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The solid-to-liquid transition in the Trièves clay: the lessons from rheometric and seismic tests

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ABSTRACT: The Trièves clay (Western French Alps) is a thick Quaternary formation affected by numerous slow earthslides (slide velocity of a few cm/year to a few dm/year). Under extreme meteorological conditions (heavy rain falls, quick melting of the snow cover), these slides can turn into devastating earthflows. In order to study this solid-to-liquid transition, identification, rheometric and seismic laboratory studies were performed on clay samples collected at the border between the Avignonet and Harmalière landslides. Identification tests showed the wide range of liquid limits characterizing the Trièves clay. Rheometric creep tests were performed on two samples with different gravimetric water content. The clay material behaves as a thixotropic yield stress fluid and is characterized by a marked viscosity bifurcation. This rheological behavior could be a key point explaining the solid-to-liquid behavior of this material. The seismic study aims at characterizing the clay in different moisture conditions and to test our capacity to measure Rayleigh wave velocity (V_R) variations in clay from the liquid limit to a drier state. V_R values ranging from 22m/s to 120m/s were successfully measured for a gravimetric water content decreasing from 40% to 26%, respectively. These results show that V_R (and indirectly the shear-wave velocity) is very sensitive to a change in the clay physical state and could be used as a monitoring parameter.

1 INTRODUCTION

Earthslides in clayey material are widely spread and regularly threaten people and infrastructures, posing serious problems for land management. In the French Alps, the Trièves plateau (south of Grenoble), exhibits numerous large and slow moving landslides, which affect a 200 meters thick Quaternary clay layer which was deposited in a glacially dammed lake during the Würm period (Monjuvent, 1973; Fig. 1). Under extreme meteorological conditions (heavy rain fall, quick melting of the snow cover), these slides can turn into devastating mudflows (e.g., Harmalière in 1981, La Salle en Beaumont in 1994).

The Trièves clay is characterized by a strong vertical anisotropy created by an alternately layering of silts (light material) and clay (dark material; Giraud et al. 1991, Vuillermet et al. 1994). This anisotropy explains the difference in permeability between perpendicular bedding planes (10^{-10} m/s) and parallel to those (10^{-8} m/s), as well as variations in material cohesion (1-5 kPa along the laminae and 13-23 kPa normal to them). Previous studies have also shown that the so-called Trièves clay is a complex of clays, silts and sands, whose facies could vary both vertically and laterally. Clay mineralogical investigation at three different sites (Giraud et al. 1991) showed differences in mineral content, related to lithological variations in the surrounding relief. In the Sinard sector, the predominant clay minerals are Illite (42-47%), Chlorite (14-16%) and Montmorillonite (0-5%). Among non-clayey minerals, Calcite (15-20%), Quartz (14-16%), and Feldspar (5-10%) were identified.

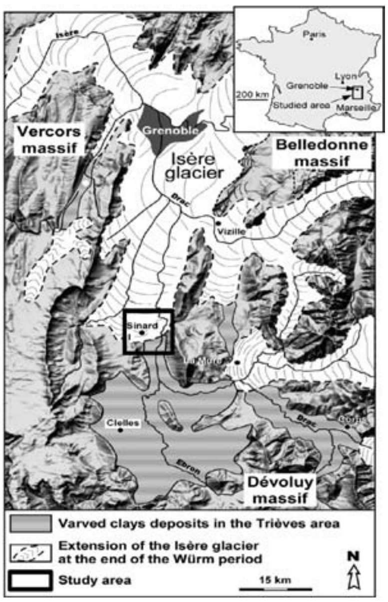

Figure 1: Location of the study area (box) and palaeogeographical map at the end of the Würm age (adapted from Monjuvent, 1973).

Recent laboratory and field work studies have shown that the shear wave velocity (Vs) is very sensitive to clay deconsolidation (and the corresponding augmentation in porosity) and significantly decreases with the landslide activity, with a division by a factor 2 to 3 between the zones unaffected and strongly deformed by the landslide. Therefore, if a slide evolves into a flow, the shear wave velocity should tend to zero in the zones behaving as a fluid (Jongmans et al. 2009).

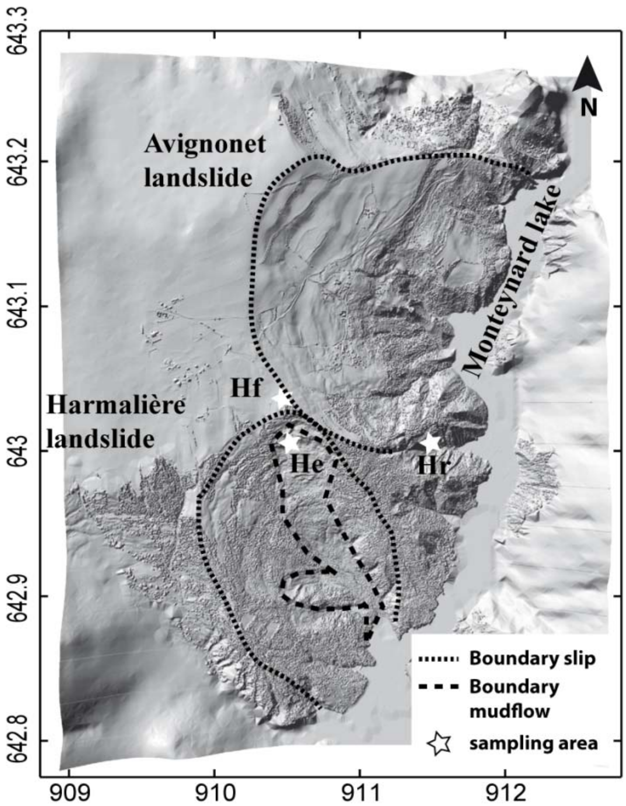

Figure 2. Aerial LiDAR DEM of both landslides (Harmalière and Avignonet) and sampling locations of the three clays: *Hf*, *He* and *Hr* (modified from Bièvre & al., in press)

From a rheological perspective, it is well known that clayey materials above the liquid limit, behave as yield stress fluids (Coussot, 2005). Moreover, recent studies evidenced that the existence of a yield stress can be associated to a phenomenon of viscosity bifurcation, namely a dramatic drop of the apparent viscosity of the material when the critical stress is reached (Coussot et al. 2004). Such materials are then characterized by both a critical shear stress and a critical shear rate, which corresponds to the shear rate below which no stable flow can be observed. Hence, the larger the critical shear rate, the more dramatic the observed fluidization at the critical stress. Moreover, this viscosity bifurcation is also generally associated to a strong thixotropic behavior, i.e. strong variations of the rheological properties with the current state of the material (the degree of jamming). Interestingly, Coussot et al. (2002), using inclined plane experiments, reported that Trièves clay presents clear thixotropic properties. If associated to a viscosity bifurcation, such properties could play a major on the fluidization of landslides.

The present study aims at investigating the solid-to-fluid transition in the Trièves clay through rheometric and laboratory seismic tests. Clay samples were taken at three sites (Fig. 2) in the zone affected by the Avignonet and Harmalière landslides. First, the physical identification and mineral composition of these clay samples (3 samples per site) were performed and compared with previous studies. Second, rheometric parallel-plane tests were performed on samples of the Trièves clay with different water content to determine the existence of a viscosity bifurcation and, if existing, the associated values of critical shear stress and critical shear rate. Finally, we performed seismic experiments in a box filled with clay saturated with different gravimetric water contents (from 30 to 40%) created by the natural drying of the clay in order to test our capacity to measure V_R (Rayleigh wave velocity) at the liquid limit.

2 CLAY IDENTIFICATION

Clay samples were collected at three sites: in a borehole (5 m depth) drilled at the top of landslides (*Hf*), into the Harmalière mudslide (*He*) and in a gully located at the boundary of the Avignonet landslide (*Hr*; see Fig. 2 for location). Laboratory measurements (grain size distribution, X-Ray diffractometry and Atterberg limits determination) were performed in order to test the variability of soil characteristics in this area.

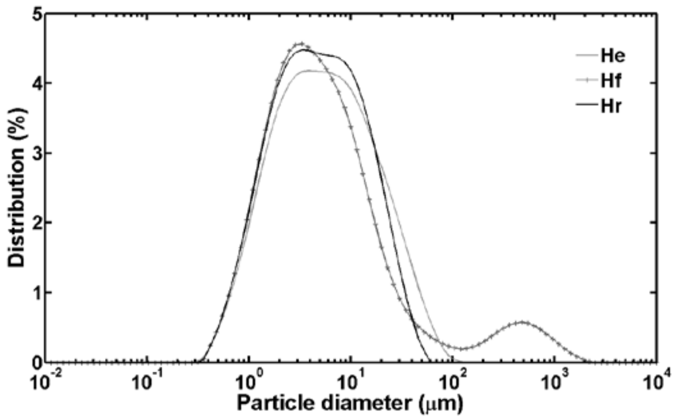

Figure 3. Grain size distribution curves for the 3 sites: Hr, Hf and He. Each curve is an average of three measurements.

Figure 3 shows the mean grain size distribution curves for the three investigated sites. Particles have a size less than two millimeters and the size of 40% of particles is less than 2µm (clay), showing the presence of both clay and silt. At site *Hf*, a small proportion of sand particles was evidenced, probably resulting from the drilling through upper sandy layers. Grain size results are similar to those obtained on laminated clay samples taken in the southern part of the Avignonet landslide (Bièvre, 2010).

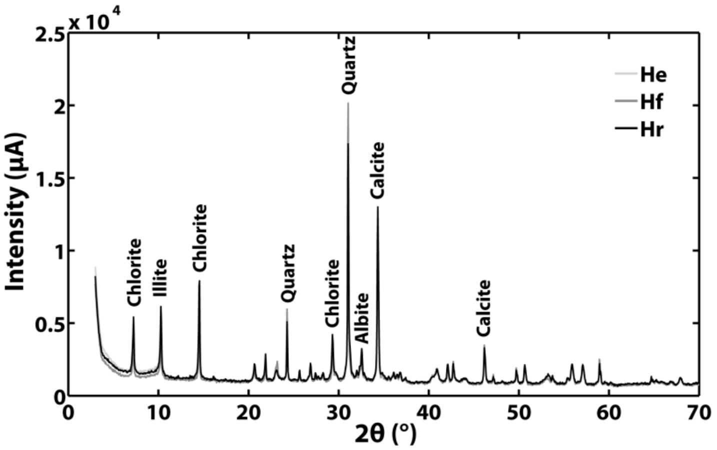

Figure 4. Comparison of the diffractograms of Hr, He and Hf samples crushed <80µm.

XRD (X-Ray Diffraction) analysis was conducted on the three-site samples crushed at 80µm. Results indicate a mineral composition similar for the three samples (Fig. 4) and show the presence of the main minerals identified in previous studies. For clay minerals we find predominantly Cchlorite and Illite, while a predominance of Quartz and Calcite is observed for non-clay minerals. The first three peaks associated with clays are higher at *Hr* suggesting a larger clay quantity at that site. However some minerals might not be detectable with XRD method if they are not well crystallized or in quantities too small to be detected (<1%).

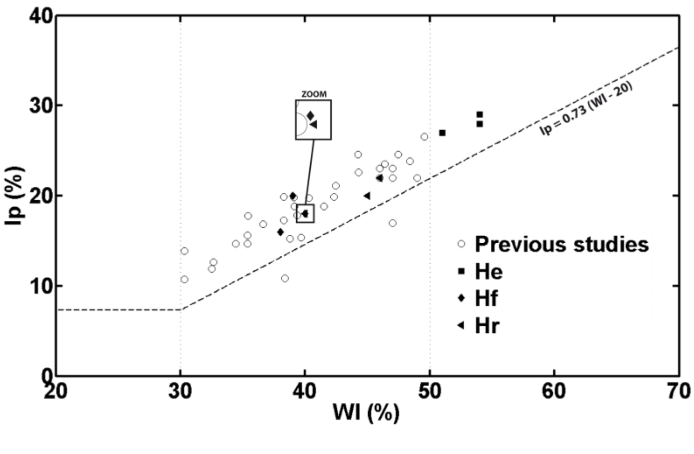

Figure 5. Plasticity diagram showing the Atterberg limits obtained for the 9 samples (3 samples per site He, Hf and Hr), as well as the comparison with previous results (Giraud & al., 1991).

Figure 5 shows the identification results (in the plasticity diagram) for the 9 samples. Wl is the limit liquid limit, i.e. the water content which separates the state liquid and the plastic state. Ip is the plasticity index, i.e. the difference between the liquid limit (Wl) and the plasticity limit Wp (the amount of water that separates the plastic state and solid state). This index gives an indication of the extent of the plastic range. Atterberg limits at *Hf* and *Hr* are in a range similar to the one obtained during previous studies at different locations (Giraud et al. 1991), with a relatively low plasticity index (10-25%). Consequently, the liquid limit can be easily reached, explaining the triggering of mudflows following heavy rainfall and/or quick snowmelt. The lower value of plasticity index at *Hf* (between 38% and 40%) may result from the presence of sand particles. On the other hand, the higher value of the plasticity index at *He* indicates that these highly reworked clays are sensitive to swelling and shrinking phenomena. Together with a liquid limit above 50%, these reworked clays can be classified as plastic clays.

3 PRELIMINARY RESULT OF RHEOLOGICAL BEHAVIOR OF HARMALIERE CLAY

A previous study showed the thixotropic behavior of Sinard Clay (on the Trièves Plateau) using inclined plane tests (Coussot et al. 2002). We performed laboratory tests to confirm this behavior with a shear stress rheometer and to determine the critical stress and critical shear rate defining the liquid-solid transition for two different water content samples of *Hr* clay used creep tests.

3.1 Protocol

The material used was prepared with clay from the-Harmalière gully (*Hr*) mixed with water coming from an Avignonet piezometer for the time necessary to have a smooth and homogeneous clay. This water was already in chemical equilibrium with the clay. Two samples with different water contents were prepared: *Hr1* with a gravimetric water content of 68% and *Hr2* with a gravimetric water content of 57%. Rheological measurements were performed using a *Bohlin-CVOR* rotational rheometer in the *Cemagref* Laboratory. We used a parallel-plate geometry with 2mm gap. Before each test, the samples were presheared at a rate of $50s^{-1}$ during 10s, and then left at rest during 5s. The samples were then submitted to constant levels of applied shear stress, and the resulting shear rate was monitored as a function of time (creep tests).

Performing rheometrical tests on Trièves clay samples turned out to be relatively delicate because of the rapid drying of the samples and the tendency of the free surface to undergo rapid distorsion during shear. As a consequence, our results should be considered as preliminary.

3.2 Results

Figure 6a shows the response of sample *Hr1* for 9 imposed levels of shear stress between 130 Pa and 180 Pa. We observe a clear transition in the mechanical response at a critical value of shear stress around 159-160Pa. Below this value, the shear rate systematically decreases (i.e., the apparent viscosity increases) and progressively tends to zero. Above this critical level, on the contrary, the shear stress rate tends towards a constant value, indicating that the material undergoes flows. Moreover, we note the material displays a pronounced viscosity bifurcation since the critical value of shear rate, below which no flow is monitored, is relatively high: . For values of shear stress above , we also observe that at short times, the apparent viscosity generally increases, before abruptly decreasing and reaching its asymptotic level. Hence, the fluidization of the material is delayed, meaning that the destructuration of the material depends not only on the applied shear stress but also on the time during which this stress is applied. This is a clear indication of a thixotropic behavior.

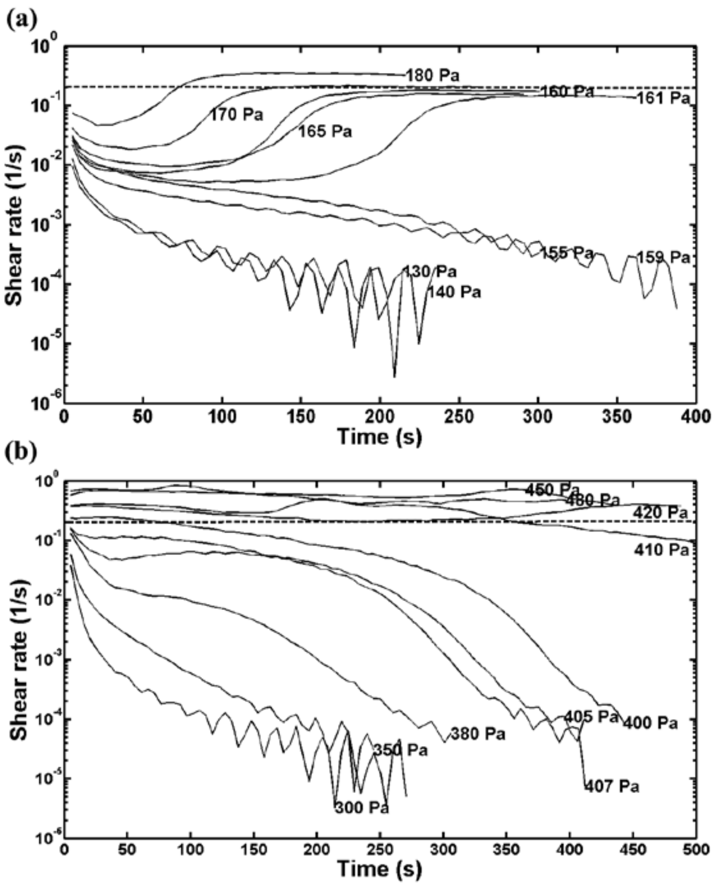

Figure 6. Results of creep tests on *Hr* Trièves clay. (a) for a gravimetric water content at 68% and (b) for a water gravimetric content at 57%.

Similar experiments were performed with *Hr2* sample using stress levels varying between 300Pa and 480Pa (Fig. 6b). Generally, the noise level is higher and the experimental artifacts are more problematic than with the *Hr1* sample. Nevertheless, we clearly observe a similar phenomenon of viscosity bifurcation occurring for at a critical stress between 407Pa and 410Pa. The critical shear rate appears, within the resolution of or data, to be identical to that observed for *Hr1* sample: . Hence, unlike the critical shear stress, the critical shear rate seems to be independent of the water content.

In both studies, the critical stress is not obvious to define. For creep tests on *Hr1*, Figure 6a shows that the critical stress is closer to 161Pa than to 160Pa. This uncertainty is more pronounced with *Hr2* curves (Fig. 6b): shear stresses at 405Pa and 407Pa mark a bifurcation faster than at 410Pa. These errors can be explained by several experimental factors. First, the clay samples dry slightly between several tests, making it more viscous. Second, a widening more or less important can occur between the two plates which varied the real applied stress.

The results of these two experiments show that Trièves clay behaves as a thixotropic yield stress fluid, and is characterized by a pronounced viscosity bifurcation. This property can result in a catastrophic fluidization of the material when the critical shear stress is reached, and could thus play a key role in the dynamics of Trièves clay landslides.

4 RAYLEIGH WAVE VELOCITY IN A BOX OF CLAY

As stated in the introduction, S- wave velocity (Vs) values in saturated clay are very sensitive to void ratio (or porosity) variations and could be used as a tool for assessing the clay deconsolidation state. Here we develop an experimental protocol to estimate Vs in a clay box from Rayleigh wave study.

4.1 Protocol

A 42 cm wide, 64 cm long and 15 cm deep box was filled with homogenized saturated clay (from the site *Hr*) with water content close to or higher than the liquid limit. A superficial piezometric source placed in the middle of the box generated a chirp signal in the 400-2000 Hz range. The signals were recorded by a linear array of five vertical component accelerometers placed at 5, 8, 11, 14 and 17 cm from the source. All channels were connected to waveform conditioning amplifiers. Signals were regularly measured during 36 days to study the natural drying of the clay. A chirp signal was sent every 40 minutes during the first 16 days of the experiment, then every two hours for the last twenty days. Two temperature probes were installed: one at the surface and the second one at 4 cm depth in the clay. All sensors were directly connected to a 16-bit acquisition card. Moreover, a TDR (Time Domain

Reflectometer) probe with a 12 cm waveguide was fixed to monitor the average volumetric water content over the box thickness. Figure 7 shows a sketch of the experiment. The clay water content and density were directly measured on soil samples, using cylindrical samplers (3 cm in height and 12 cm^3 in volume). Collected clay samples were dried during 30 hours at 105 °C and weighted before and after drying (called after GWC method). Notably this standard protocol is not perfect for clay whose porosity is multiscale (Guillot et al. 2002). It is however accurate enough to study macrostructural phenomena. Also, the natural drying is not totally uniform over the box surface and three samples were systematically taken at the same time at three different places. The standard deviation was about 2%.

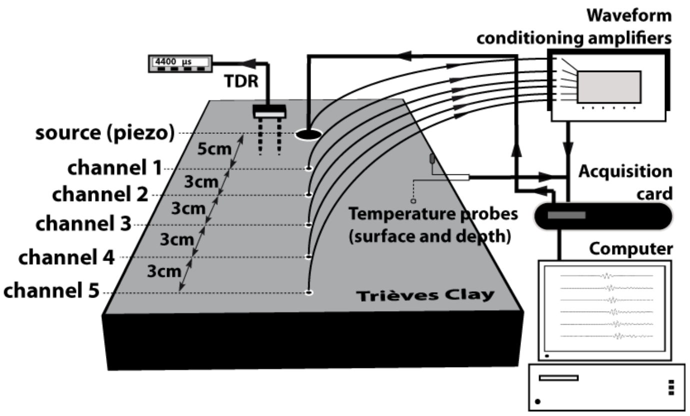

Figure 7. Sketch of the laboratory seismic experiment in a clay box. The TDR measurements (electomagnetic wave travel times) are taken manually.

The Rayleigh wave group velocity was measured by the time-lag of the Hilbert envelopes of correlations between the source signal and each accelerogram. Then the five Rayleigh wave velocities (V_R) were averaged and the evolution of V_R with time was fitted by a polynomial law in the least squares sense.

4.2 Results

Figure 8 shows the V_R, water content and temperature values measured during the one-month experiment (from July 24 to August 30, 2010). The Rayleigh wave velocity (Fig. 8a) shows a rapid V_R increase of 9 m/s during the first day, before reaching a gradient of about 3m/s to 4m/s per day until the end of experiment. At the beginning of the experiment, both GWC and TDR methods give a gravimetric water content of about 40% (Fig. 8b), close to the liquid limit calculated for a sample from site *Hr* (see Fig. 5). The corresponding Rayleigh wave velocity is about 22 m/s. We observe an anti-correlation relationship between V_R and the moisture content. The drier the clay, the higher the wave velocity and the greater penetration depth were. From the GWC variations from 40% to 26%, the bulk density increased from 1,28 to 1,59.

The relationship between water content and Rayleigh wave velocity is erratic at the beginning of the experiment. This probably results from the discrepancy between the short wavelength (at low velocity) and the 3-cm height of the sampler.

The GWC curve shows two outliers values on August 6 and 9, with values greater than the initial state, while TDR values regularly decreased during this period.

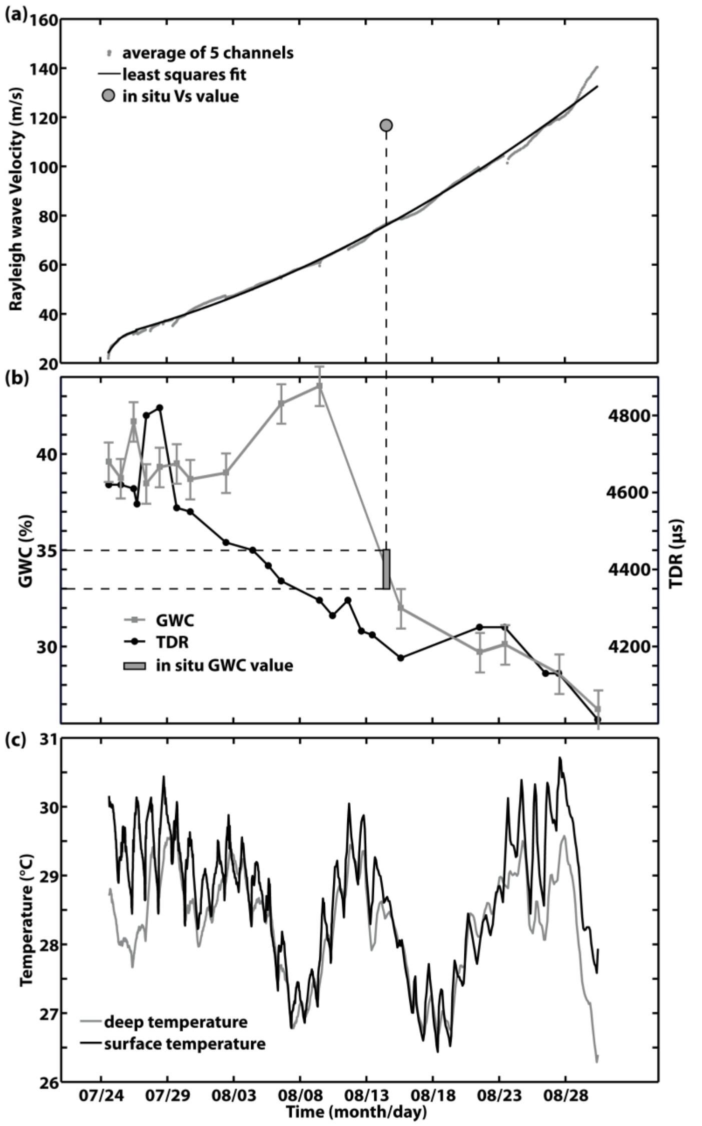

Figure 8. Laboratory results of the seismic experiment in the Trièves clay (Hr). (a) Variation of Rayleigh wave velocity over time. (b) Soil moisture evolution using the gravimetric water content (GWC) method and the TDR method. (c) Temperature variations in time at the surface and at 4 cm depth. Vs and GWC values obtained in situ by Renalier et al. (in press) have been added in Figure 8a and b.

In an homogeneous halfspace, the Rayleigh wave velocity V_R is very close to the shear wave velocity Vs (difference between of about 4% for a high Poisson's ratio close to 0.5) (Puech et al. 2004). So to first order, we can assimilate V_S to V_R , and compare our laboratory values to the S-wave velocities measured at the Avignonet landslide by Renalier et al. (in press). At 5 m depth, they obtained V_S= 120m/s for a gravimetric water content between 33% and 35% (Figure 8a and 8b). This Vs value is about 50m/s higher than those measured in our laboratory experiment for the same water content range. This discrepancy probably results from the difference in consolidation state (influence of the mean effective stress) between the field and laboratory conditions.

Temperature curves at the surface and at 4 cm depth (Figure 8c) are relatively similar (except at the beginning and at the end of the experiment) and exhibit slight variations, with a maximal range of 4°C. No significant relation appears between temperature and water content variations. The difference between the two curves at the beginning of the experiment could be to a contrast in temperature between the water mixed with clay and the air.

5 CONCLUSION & PERSPECTIVE

Three different laboratory investigations were conducted on clay samples collected at the border between the Avignonet and Harmalière landslides. The clay mineralogical composition determined by X-ray diffraction is similar and consistent with previous studies, pointing out illite and chlorite as the predominant clay minerals. On the contrary, the, the Atterberg limits vary dramatically with location, as it was also shown by previous studies. No significant change in grain size distribution and in mineral composition was found to explain this variation. Rheometer measurements have revealed the thixotropic behavior of the clay, associated with a strong viscosity bifurcation. This change in rheological properties could play a key role in the solid-to-liquid transition observed in the Trièves clay. Finally, we successfully generated the propagation of high-frequency Rayleigh waves in a box filled with saturated clay at a water content close to its liquid limit. During a one-month natural drying experiment, the velocity gradually increased from 22 m/s to 120m/s, showing the high sensitivity of V_R (and V_S) to the clay consolidation state, whose water content decreased from 40% to 26%. In the future, flume laboratory tests are planned to study the solid-to-liquid transition, using V_R as a parameter to characterize the solid state of the clay.

6 ACKNOWLEDGMENTS

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