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Shear-wave velocity as an indicator for rheological changes in clay materials: Lessons from laboratory experiments

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[1] Clay-rich geological formations are responsible for many landslides, the dynamics of which are still poorly understood and intensely debated. Analysis of landslide motion shows that slow clayey slope movements can suddenly accelerate and fluidize as a result of sudden loading or heavy rainfall. This solid-fluid transition, which involves disorganization of the particle network, is accompanied by a loss in rigidity that could potentially be monitored by S-wave velocity (*Vs*) variations. To investigate this hypothesis, two types of laboratory experiments were performed on clay samples originating from an area affected by numerous landslides (Trièves, French Alps). First, creep and oscillatory rheometric tests revealed the thixotropic behavior of the clay with a highly pronounced viscosity bifurcation at a critical stress τ_c. In relation with this reduction in apparent viscosity, a significant drop in *Vs* is also observed over τ_c. Second, at zero stress, acoustic surface wave propagation experiments showed a rapid linear *Vs* decrease with the gravimetric water content (*w*) in the plastic domain, and a much lower decay in the liquid domain. The geotechnically-defined liquid limit then appears as a break in the *Vs-w* curve. For water contents in the liquid domain in particular, both experiments gave consistent results. These laboratory results demonstrate that rheological changes in clay can be revealed through Vs variations, offering the possibility of monitoring solid-to-fluid transitions in the field.
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1. Introduction

[2] Clay landslides are widespread throughout the world and pose serious problems for land management, because the slide can exhibit a dramatic increase in velocity (from a few cm/y to more than one m/s) [*Van Asch and Malet*, 2009]. These acceleration phases, which generally occur during or after heavy and sustained rainfall, are regularly associated with a change in rheology, from a solid to a fluid-like behavior [e.g., *Angeli et al.*, 2000; *Picarelli et al.*, 2005; *Eilertsen et al.*, 2007]. The solid-fluid transition has aroused considerable interest in physics and soil mechanics and has been the object of significant research efforts [e.g., *Coussot et al.*, 2005; *Van Asch and Malet*, 2009]. In soil mechanics, fine-grained soils are usually classified using the so-called Atterberg limits (plastic limit *PL* and liquid limit *LL*), which are the water contents separating the three main states (solid, plastic and liquid) and measured experimentally using standard tests (for details, see *Cornforth* [2005, chap. 8]). Although the physical interpretation of these empirically-derived limits is still poorly understood, they are widely used in geotechnical engineering and frequently correlated to other engineering properties [*Cornforth*, 2005]. However, if the Atterberg limits constitute good indicators of the macroscopic behavior of clay sediments, these parameters are not sufficient to fully understand the initiation and dynamics of landslides.

[3] To gain a deeper insight into the constitutive law of such materials, i.e., the relationship between stress, strain, and strain rate, rheological tests are necessary. The rheological behavior of earthflows and debris flows has been the subject of intense research and debate in the scientific community, with the confrontation between elastoplastic and viscoplastic models [*Iverson et al.*, 1997; *Ancey*, 2007]. In elastoplastic models, fluidization is related to the observed increase in pore water pressure, resulting from water infiltration or internal stress variations [*Iverson*, 2005]. In contrast, numerous laboratory experiments performed on water-clay dispersions demonstrated the potential of viscoplastic models for homogenized fine-grained materials, whereas, for poorly sorted materials, the bulk rheology can obey either elastoplastic or viscoplastic models [*Ancey*, 2007]. In clays, rheology is thus usually described by a viscoplastic law (e.g., the Herschel-Bulkley model) in which the solid-to-fluid transition is characterized by a critical, yield stress τ_c [*Huang and García*, 1998]. However, in some clays like bentonite, *Coussot et al.* [2002] showed that this transition can be more complex, and occurs with a viscosity bifurcation. Below the critical stress, the viscosity increases with time and the initial creep eventually stops, while for a slightly higher stress the fluid abruptly starts to flow with finite viscosity. This thixotropic behavior, which results from the competition between aging and shear rejuvenation, was also observed in quick clays by *Khaldoun et al.* [2009], who found that the viscosity decreased dramatically during flow, which may explain the unexpected large runout distances of clayey mass slides.

[4] Unfortunately, viscoplastic parameters for fine-grained soils can only be determined in the laboratory [*Ancey*, 2007] and no in-situ monitoring of these properties is possible at the present time. An alternative is to continuously measure changes in the geophysical parameters characterizing the

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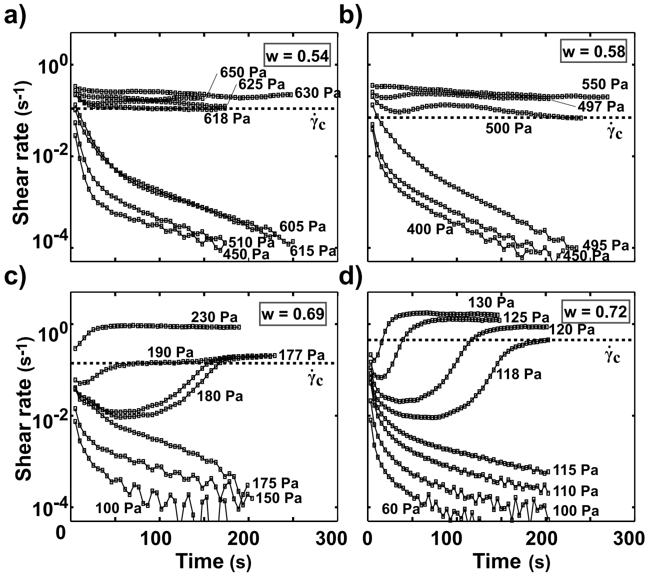

Figure 1. Creep tests: time-dependent variation in the strain rate for different imposed values of shear stress (indicated in legend). All tests show a bifurcation in viscosity with values of critical stress τ_c and critical strain rate $\dot{\gamma}_c$ (dashed horizontal lines) varying with water content. (a) w = 0.54, τ_c = 617 Pa,. (b) w = 0.58, τ_c = 492 Pa, (c) w = 0.69. τ_c = 173 Pa, (d) w = 0.72, τ_c = 116 Pa. Each curve corresponds to a different sample and the pre-shear period is not shown. Oscillations at low strain rate are due to sensor accuracy limit.

sliding material behavior. In this respect, recent field and laboratory studies [*Jongmans et al.*, 2009; *Renalier et al.*, 2010] have shown that the shear wave velocity (*Vs*) is very sensitive to clay deconsolidation (and the corresponding increase in porosity). In case of clay liquefaction, *Vs* should tend to zero. Recently, a significant drop in *Vs* (from 360 m/s to 200 m/s) was measured at the base of a small active clayey landslide (Pont Bourquin, Switzerland), several days before the triggering of an earthslide-earthflow of a few hundred m^3 [*Mainsant et al.*, 2012]. This result opens up promising perspectives in relating geophysical and rheological parameters for landslide prediction.

[5] This paper aims to investigate through laboratory tests the potentiality of *Vs* as an indicator for rheological changes and the solid-fluid transition in clay. The tested clay was sampled in the Trièves plateau (Western Alps, France), at the southern limit of the large Avignonet landslide [*Bièvre et al.*, 2011]. Atterberg limits were measured on 3 samples, yielding a mean value of $LL = 0.44 \pm 0.03$, with a plasticity index of about 0.2. First, parallel-plate rheometric tests were performed at different water contents w in order to determine the viscoplastic behavior of the Avignonet clay. In parallel, the dynamic shear modulus under loading was measured by applying harmonic shear stress variations, in order to be able to relate *Vs* values to rheological parameters. In a second step, *Vs* values at zero stress were measured in saturated clay, with water content ranging from the plasticity limit to over the liquidity limit. *Vs* values wereobtained by studying the propagation of surface waves in a clay-filled box. Combining the two series of tests, the *Vs*-*w* curve was drawn, showing the pertinence of *Vs* for monitoring the clay state over a wide range of porosity values.

2. Rheometric Tests

[6] Rheological measurements on Trièves clay were performed using a 60 mm diameter Bohlin-CVOR rotational rheometer, with a parallel-plate geometry. Before each test, the samples were pre-sheared at a strain rate of 50 s^{-1} for 10 s, and then left at rest for 5 s, to ensure a reproducible initial state. The temperature in the rheometer was fixed at 18°C. As several phenomena might hinder the repeatability of the rheometric results [*Coussot*, 2005], tests were systematically duplicated to quantify uncertainty. Creep tests, which consist in subjecting the sample to a steady shear stress and monitoring the strain rate induced versus time, were conducted for 8 different water contents (from w = 0.54 to w = 0.72) over the liquid limit LL = 0.44. Tests for w < 0.54 were not possible due to the development of heterogeneous deformation and cracking in the samples. Figure 1 shows the creep curves measured at constant stress for four values of w. For w = 0.54 (Figure 1a), a clear transition in the mechanical response is observed at a critical shear stress $\tau_c \approx 617$ Pa. Below τ_c, the strain rate systematically decreases (i.e., the apparent viscosity increases) with time and progressively tends to zero (solid behavior). Conversely, above this critical stress, a constant, finite strain rate value is reached after a short time, indicating that the clay undergoes flow. Notably, the asymptotic strain rate displays a marked discontinuity at the transition, jumping from zero to a critical value ($\dot{\gamma}_c \approx 0.11$ s^{-1}). Such an abrupt solid-fluid transition was already observed in other clayey materials and was referred to as a viscosity bifurcation [*Coussot et al.*, 2002; *Khaldoun et al.*, 2009]. For a higher water content (w = 0.72, Figure 1d), the solid-fluid transition and associated viscosity bifurcation are obtained for a lower critical shear stress τ_c=116–117 Pa, with a critical strain rate slightly higher ($\dot{\gamma}_c \approx 0.45$ s^{-1}). In addition, creep curves for values of shear stress slightly above τ_c exhibit a peculiar behavior: the strain rate first decreases for a short time, before abruptly increasing and reaching its asymptotic level close to $\dot{\gamma}_c$. Hence, the fluidization is delayed, indicating that the disruption 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 thixotropic behavior [*Roussel et al.*, 2004] in the vicinity of the critical stress. This time-dependent behavior was clearly observed for samples with w greater than 0.58 (Figure 1).

[7] For a few w values, a periodic oscillating shear stress (at a given frequency, from 0.1 to 10 Hz) was imposed to samples already subjected to a constant, base level of shear stress (hereafter denoted steady stress), and the resulting strain was measured. These tests were aimed at assessing the linear viscoelastic shear modulus $G^\star$ of the material, with a sufficiently low stress oscillation amplitude so that the response remains in the linear regime. The complex viscoelastic modulus $G^\star$, defined as the ratio between the stress and strain in the Fourier domain, is classically broken down into $G^\star = G' + iG''$, where the real and imaginary parts G' and G'' correspond to the elastic and viscous responses respectively [*Oswald*, 2009]. As shown in Figure 2a (for two different samples at w = 0.54 and 0.69), the value of G' increases with the imposed oscillation frequency, and tends

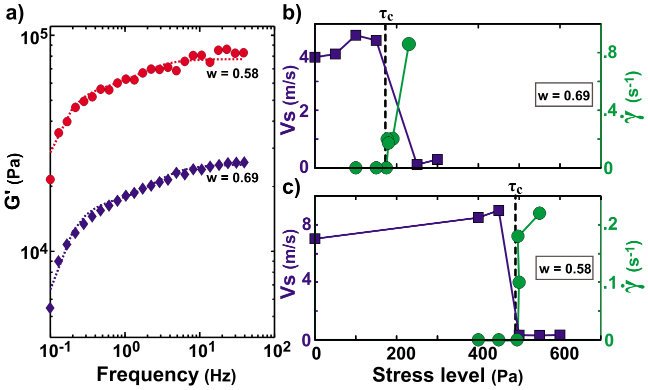

Figure 2. (a) Real part of the viscoelastic modulus (G') as a function of frequency for two samples at different water contents $w = 0.58$ (red circles) and $w = 0.69$ (blue lozenges) and at steady stress = 0 Pa. (b and c) Values of Vs (squares, oscillatory tests) and steady-state strain rate (circles, creep tests) as a function of imposed stress for the same water contents.

towards a constant value for high frequencies. Consistent with most classical viscoelastic models (e.g., the Maxwell model [*Oswald*, 2009]), the high-frequency limit of G' can be considered to be representative of the elastic shear modulus G of the material. Ultimately, oscillatory tests thus enabled the shear modulus of the clay to be estimated for different water contents and levels of steady stress. From G, the shear wave velocity Vs can easily be derived using $Vs = \sqrt{G/\rho}$, where ρ is the density.

[8] Vs and steady-state strain rate values versus imposed stress are plotted together for two values of w in Figures 2b and 2c, where the critical shear stress determined by creep tests is also shown by a vertical dotted black line. In both graphs, the strain rate increases above τ_c, resulting from the solid-fluid transition already highlighted in Figure 1. Concomitantly, the Vs curve shows a dramatic drop above tc, from 4 to 8 m/s to less than 1 m/s. These results show that the solid-fluid transition in the clay samples, which was highlighted through a viscosity bifurcation, is also accompanied by a significant decrease in Vs.

3. Acoustic Surface Wave Tests

[9] Acoustic tests were performed in order to measure Vs at zero stress for w values ranging from the plastic to the liquid domains. Surface wave experiments were conducted in a 15 cm deep box (42 cm wide, 64 cm long) filled with saturated clay, using two different layouts in order to measure Vs during natural drying of the clay. In the first layout (Figure 3a) a Brüel&Kjære laser Doppler vibrometer was used as a unique receiver. In this setup, the 15 mm-diameter piezoelectric source was manually moved from 30 to 5 cm towards the receiver, as shown in Figure 3a. The source generates a 1.6 s long sweep with frequencies linearly ranging from 400 Hz to 2000 Hz. For high water contents (w over the liquid limit LL), the frequency range was lowered (100–850 Hz) because of the severe wave attenuation. A second series of experiments (layout 2) was conducted with the same piezoelectric source, using a linear array of five accelerometers and a spacing of 3 cm. The closest accelerometer was 5 cm from the source. Because accelerometers sink and rotate in the high water content clay, all measurements with this layout were taken in the plastic domain. By combining the two layouts it was possible to measure Vs over a wide water content range from $w = 0.27$ to 0.68, with an overlap below $LL = 0.44$. For both layouts, the box was filled with homogenized saturated clay with high water content ($w = 0.68$ for layout 1, and close to LL for layout 2). The change in surface wave velocity with w was monitored during the natural drying of the clay.

[10] The porosity ϕ and gravimetric water content w were regularly measured on soil samples. The acquired signals were correlated with the source signal to reconstruct the wave propagation, similarly to *Larose et al.* [2007]. Figures 3b and 3d show the signals after correlation for $w = 0.60$ and $w = 0.27$ respectively. The main propagating wave is the Rayleigh wave, the frequency content of which decreases with increase in the water content (Figures 3c and 3e). The Rayleigh wave group velocity (U_R) was measured by picking the times of the maximum of the Hilbert envelope of the signals (Figures 3b and 3d). Over the whole w range, U_R was

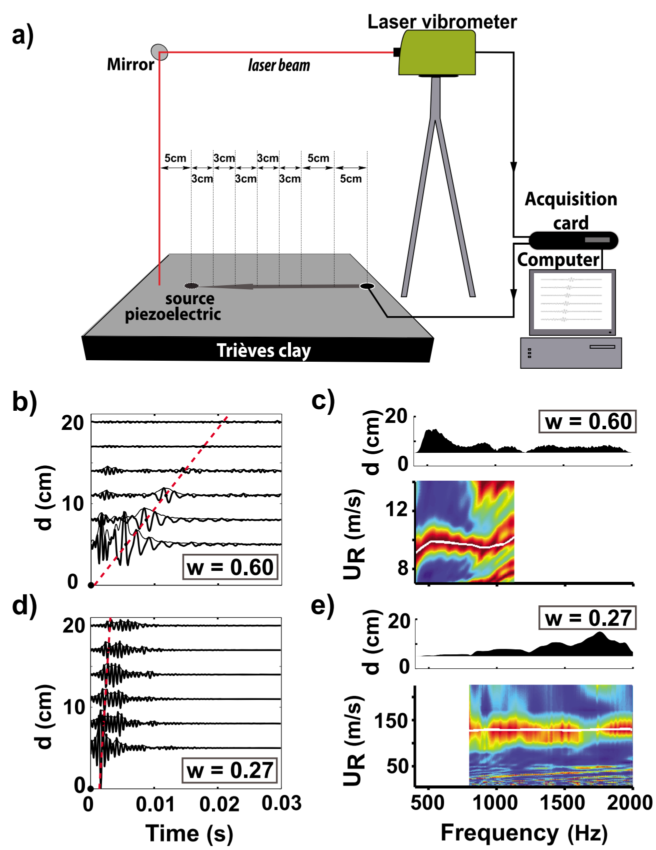

Figure 3. Acoustic surface wave experiments conducted in a clay-box. (a) Layout 1 with a moving piezoelectric source and a fixed laser Doppler vibrometer. (b and d) Signals measured with a laser vibrometer for water contents $w = 0.6$ and 0.27 respectively. (c and e) Corresponding Rayleigh wave dispersion curves (group velocity U_R) and normalized Fourier spectrum for the signal located 5 cm from the source. In Figures 3b and 3d the mean group velocity for Rayleigh wave U_R is given by the dashed line joining the times of the maximum of the signal Hilbert envelope $U_R = 9.9$ m/s (Figure 3b); $U_R = 121.1$ m/s (Figure 3d).

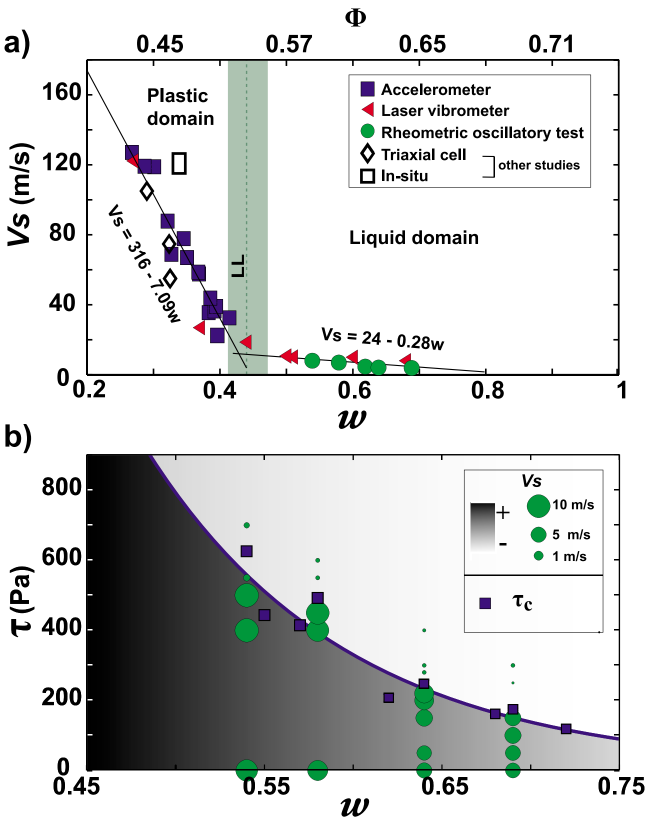

Figure 4. (a) Vs as a function of water content w and corresponding porosity ϕ at zero stress for the five types of experiment (see text for detail). The liquid limit LL is shown with its uncertainty by a shaded bar. Linear regression lines are drawn for the two domains (plastic and liquid). (b) Critical stress τ_c (blue squares) as a function of w. The blue line is the exponential law fitting the τ_c data. Vs values measured at specific water content for different shear stress values are shown with green circles, the diameter of which increases with Vs magnitude. The darker the shadowing the higher the Vs value, qualitatively.

found to decay with w, from 121 m/s for w = 0.27 to less than 10 m/s for w = 0.68. At high water content, the measured P-wave velocity was close to 1500 m/s. In these experiments the clay layer was assumed to be a homogeneous half-space. As clay drying progresses from the surface to the bottom of the box, it was possible for an inverse vertical seismic wave velocity gradient to develop, generating dispersion of the Rayleigh wave and invalidating the clay homogeneity assumption. Dispersion curves for the two signals displayed in Figures 3b and 3d were computed using the f-k method implemented in the Sesarray package [*Wathelet et al.*, 2004] (www.geopsy.org). In the higher energy range of the spectra, dispersion curves (Figures 3c and 3e) exhibit a nearly constant phase velocity, which indicates the absence of dispersion in the frequency band of interest. Phase velocity values of 10 m/s and 120 m/s were determined for water contents of 0.60 and 0.27 respectively. These phase velocities agree with the group velocity values determined from the envelope maxima (Figures 3b and 3d), supporting the non-dispersive characteristic of these waves. The clay half-space hypothesis also requires that the surface wave propagation not be influenced by the box bottom boundary. Considering the rule of thumb that Rayleigh waves are mostly sensitive to the mechanical properties of the material down to a depth of one-third of the wavelength, the penetration for the signals shown in Figure 3 was estimated to be 0.6 cm (w = 0.60) and 5.0 cm (w = 0.27). These values are far below the clay thickness (15 cm), thereby ensuring that the waves propagate within the clay only.

[11] For consistency, the Rayleigh wave group velocity U_R was determined in a given narrow wavelength range in order to investigate the same clay thickness. Signals were band-pass filtered with a central frequency chosen so as to obtain a common wavelength of about 5 cm over the whole w range (0.27–0.60). The S-wave velocity (Vs) was then deduced from U_R using the approximate relation proposed by *Viktorov* [1967]:

$$Vs = U_R \frac{1+\nu}{1.12\nu + 0.87} \tag{1}$$

where the Poisson coefficient ν is given by the equation

$$\nu = \frac{\left(\frac{Vp}{Vs}\right)^2 - 2}{2\left[\left(\frac{Vp}{Vs}\right)^2 - 1\right]} \tag{2}$$

As Vs appears in both equations, an iterative process with an initial value of 0.49 for the Poisson coefficient was used to determine Vs.

4. Discussion

[12] Vs measurements obtained at zero stress from all experiments are merged in Figure 4, which also shows three Vs values previously measured by *Renalier et al.* [2010] in a triaxial cell at zero stress, using bender elements in the same clay. Although four independent sets of data (acoustic tests with two types of receiver, rheometric oscillatory tests and Vs measurements in triaxial cells) have been used for building the curve, all Vs values are consistent. In particular, data obtained with the laser vibrometer, which span the whole investigated range of w, are in good agreement with the measurements coming from other techniques. Data obey two linear laws: in the plastic domain, a strong decrease in Vs with w is observed from w = 0.27 to about 0.43, followed by a lower decay in the liquid domain (from w = 0.43 to 0.69). The slope break between these two linear regimes occurs for w = 0.43, which is in the range of the LL (0.44 ± 0.03) defined by geotechnical tests. Linear regression models were fitted on the two parts of the curve, yielding Vs decrease rates of 7.09 and 0.28 in the plastic and liquid domains respectively. In particular, the laboratory-determined Vs values in the plastic domain are also consistent with in-situ shallow measurements (Vs = 120 m/s for w =0.33) performed in the Avignonet landslide [*Renalier et al.*, 2010].

[13] In the liquid domain ($w > LL$), effective fluidization of the material occurs only above a critical stress, as clearly revealed by creep tests. As shown in Figure 4b, the value of critical stress τ_c regularly decreases with w, approximately according to an exponential law, as previously proposed by *Coussot and Boyer* [1995]. Vs values measured by oscillatory tests are shown in the same figure. They exhibit both a regular decrease with w, consistent with Figure 4a, and a

sharp decrease above the critical stress τ_c, when the clay undergoes flow. These results demonstrate that *Vs* significantly varies with rheological changes in the clay, presumably resulting from the disorganization of the particle network. First, the liquid limit *LL*, which is empirically determined through standard laboratory tests, corresponds to a dramatic change in the *Vs* decay rate with *w*. Second, the clay fluidization occurring above a critical shear stress is associated with a significant drop in *Vs*. Hence, these results suggest that rheological changes in clayey landslides could be tracked by monitoring *Vs*, provided that the transition mechanism observed in rheometric tests also occurs under real confining conditions. Indeed, in-situ experiments conducted in the Avignonet landslide showed a significant *Vs* increase with depth (and confining pressure), from 120 m/s at the surface to about 400 m/s at 40 m depth. Viscoplastic rheology models, such as the Herschel-Bulkley law, imply that the clay flows once the critical yield stress has been exceeded at the base of a plug layer, the thickness of which is controlled by the clay properties and the slope [*Huang and García*, 1998]. However, although no specific laboratory tests were performed to investigate the solid-fluid transition in confined conditions, it is likely that this phenomenon also generates a decrease in *Vs* in the fluidized layer. This assumption is supported by recent seismic measurements conducted in the clayey landslide of Pont Bourquin, Switzerland [*Mainsant et al.*, 2012], which was equipped with continuously recording seismic sensors during spring and summer 2010. An earthslide-earthflow, which occurred in mid-August 2010, was preceded a few days before by a significant decrease in *Vs* (from 360 m/s to 200 m/s) in a 2 m thick layer located at the identified earthslide base (10 m depth). This result suggests that the time-dependent variation in this parameter could effectively be a valuable precursor for earthflows.

5. Conclusions

[14] The solid-fluid transition in the Avignonet clay was studied using rheometric tests during which the shear wave velocity *Vs* was monitored through oscillatory tests. A dramatic rheological change, associated with a viscosity bifurcation, was observed at critical shear stress values varying with the water content. This change was shown to be accompanied by a severe drop in *Vs* above the critical shear stress. These laboratory results, which link rheological and seismic velocity changes, highlight the potential benefits of *Vs* for monitoring the solid-fluid transition in clay, as recently shown in the Pont Bourquin landslide. The study of the variation in *Vs* with water content *w* at zero stress also suggests that the so-called liquid limit *LL*, experimentally defined in geotechnical engineering for separating the plastic and liquid domains, corresponds to a dramatic change in the decay rate of *Vs*. All the laboratory tests performed in this study have shown that *Vs* is a pertinent parameter for monitoring the clay mechanical state changes, opening up prospects for monitoring clayey slope fluidization. Given that a long observation time could be required before an earthflow occurrence, solid-fluid transitions will be studied during flume tests in order to better understand the *Vs* variations precluding this rheological change.

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