The Effect of Dynamic Loading on the Shear Strength of Pyroclastic Ash Deposits and Implications for Landslide Hazard: The Case of Pudahuel Ignimbrite, Chile

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Abstract

The co-seismic and post-seismic behaviour of pyroclastic ash deposits and its influence on slope stability remains as a challenging subject in engineering geology. Case studies in volcanic areas of the world suggest that soil structural changes caused by seismic shaking results in landslide activity. It is critical to constrain how this kind of soil behaves during coseismic ground shaking, as well as the effects of dynamic loading on shear strength parameters after shaking. Direct shear tests carried out on cineritic volcanic materials from the Pudahuel Ignimbrite Formation in central Chile show a direct effect of cyclic loading on the shear strength and in a minor extent on the rheology. A high apparent cohesion found in monotonic shear tests, likely attributed to suction and cementation, is destroyed by dynamic loading. At the same time, the internal friction angle rises. This defines a differential post-dynamic behaviour depending on normal effective stress conditions, which favour the occurrence of shallow landslides. These results show how the use of shear strength parameters obtained from standard monotonic direct shear tests may produce misleading results when analyzing seismic slope stability in this type of soils.

1. Introduction

Pyroclastic ash deposits are widely distributed in volcanic regions, presenting complex and differential geotechnical behaviour during earthquakes. While they tend to be competent foundation soils in aseismic conditions, their behaviour during seismically-induced dynamic loading can be problematic. For example, in central Chile Pleistocene, volcanic deposits are widespread and were associated with higher levels of damage in buildings during the 1985 (Mw 7.8) Valparaiso and the 2010 (Mw 8.8) megathrust earthquakes (Leyton et al., 2011, 2013). Studies of the geotechnical behaviour of these types of soils have shown that they are characterized by high shear strengths (cohesion up to 90 kPa and friction angles of 35º-40º in unsaturated samples), with an important component of cohesion due to the presence of weak cements and/or negative pore pressures (i.e. apparent cohesion), which may be destroyed by saturation or seismic shaking (e.g. Bommer et al., 2002; Rolo et al., 2004 and references therein). In addition, when saturated they can be susceptible to liquefaction (e.g. Gratchev and Towhata, 2010). Such soils have proved to be highly prone to earthquake-induced landslides, with documented examples from a variety of locations, including Central America (Evans and Bent, 2002), Japan (Gratchev and Towhata, 2010; Chigira et al., 2013) and Patagonia (Sepúlveda et al. 2010).

Given the widespread occurrence in different seismogenic settings and susceptibility to failure of pyroclastic hillslope deposits, it is critical to constrain how they behave during coseismic ground shaking, as well as the effects of dynamic loading on soil structural change and hence shear strength parameters due to precursory seismic events. However, this has been challenging due to the difficulties in generating representative dynamic stress conditions under laboratory conditions (e.g. Bray and Travasarou, 2007; Wasowski et al., 2011). In a slope, seismic loading generates both dynamic normal and shear stresses, which has conventionally proven to be difficult to reproduce experimentally. However, recent technological advances and experimental work have led to significant advances in our understanding of coseismic strain accumulation in hillslopes (e.g. Schulz and Wang, 2014; Brain et al., 2015).

In this paper we present the results of a programme of geotechnical tests undertaken to analyse the dynamic and post-dynamic behaviour of pyroclastic ash deposits from the Pudahuel Ignimbrite Formation in central Chile (Fig. 1). This formation was observed to be associated with both local site effects and earthquake-induced landslides during large subduction earthquakes in 1985 and 2010 (Leyton et al., 2011; Sepúlveda et al., 2015). In this study we have utilised a dynamic back pressured shear box (DynBPS) that is able to replicate dynamic normal and shear stress states in slopes under laboratory test conditions.

2. Materials & Methods

2.1 The Pudahuel Ignimbrite deposits

The Pudahuel Ignimbrite is an Upper Pleistocene stratigraphic unit mainly composed of pyroclastic ash deposits, widely distributed in the valleys of Maipo and Cachapoal rivers in central Chile (Fig. 1) as well as the Yaucha and Papagayos rivers in Argentina. It corresponds to deposits interpreted to originate from a single huge, violent eruption, or a series of closely spaced eruptions dated at 450,000 ± 60,000 years B.P. (Stern et al., 1984), from the Maipo volcanic complex (Diamante Caldera, Fig. 1) located on the border of Chile and Argentina at 34°S 10´W. The unit is defined in the district of Pudahuel in western Santiago (Maipo valley, Fig. 1), where rhyolitic pumice and ash tuff deposits are found in the upper 10 to 40 m (Wall et al., 1999; Wall, 2000; Rebolledo et al., 2006). The deposits have been described as a basal ash fall layer overlain by a thick (>30 m) pyroclastic ash flow and a <5 m thick uppermost pyroclastic surge (Rebolledo et al., 2006). The water table in Pudahuel is found at c. 14 m depth, indicating that part of the deposit is saturated. Petrographic and geochemical analyses by Stern et al. (1984) showed that similar deposits in a hilly area known as Tierras Blancas ("white land") near the town of Machalí in the Cachapoal valley (Fig. 1) and other places downstream correspond to the same deposit. The total volume for the pyroclastic flows was estimated to be 450 km^3 (Stern et al., 1984).

2.2 Sample collection and lithological characterisation

In this study, undisturbed block samples (e.g. ASTM D7015) were collected from Machalí (Tierras Blancas) and Pudahuel deposits (Fig. 1) in Chile and transported to UK for testing in appropriate protected conditions to prevent disturbance and desiccation. Both samples can be described as whitish volcanic ash with pumice fragments and occasional lithics. The soil in-situ is dry, with moisture contents below 5 %. The soil bulk density at natural moisture content is close to 1 g/cm^3. Whilst it is able to form stable steep cuts and even unsupported caves and small tunnels in Machalí (Fig. 1), it shows very friable behaviour. Grain size analyses undertaken by sieving and laser granulometry (Fig. 2) show that in both cases the dominant grain size is sand, with 10 - 20% of silt and very little clay (< 1%). The soil is slightly coarser at Pudahuel, but in both cases the amount of gravel is less than 5%, mainly resulting from the presence of gravel-sized pumice fragments.

2.3 Testing Equipment

Direct shear strength tests were carried out at the Laithwaite Landslide Laboratory at Durham University in the UK. In this study we use two direct shear testing machines, both manufactured by GDS Instruments in the UK. Firstly, to undertake standard monotonic direct shear tests, we used a Back-Pressured Shear Box (BPS). Secondly, to assess dynamic behaviour we used the new Dynamic

Back-Pressured Shear Box (DynBPS). The machines are located in a climate-controlled laboratory that regulates both temperature (± 1°C) and relative humidity (± 1%). Both machines subject samples with plan dimensions of 100 × 100 mm and a height of 20 mm to direct shear, which we consider to be the most representative of landslide rupture in our field settings. Experiments can be undertaken in either a dry or a saturated state. The sample is situated in a water bath within a sealed pressure vessel. If the test is to be undertaken in dry conditions the water bath is left dry. If the test is to be undertaken under saturated conditions the water bath is filled and pressurised, allowing the pore water pressure to be measured and controlled via a pressure controller.

In the BPS, as with a conventional direct shear machine, the normal stress is applied via a vertical ram acting on the full cross-section of the sample. In this case the applied force, which is applied via a piston regulated by a pressure controller, is measured with a load cell. Deformation is measured via LVDT. The apparatus permits deformation under stress (or load), or strain (displacement) control. In conjunction with the pressure controller for the water bath and a pore pressure transducer, it is possible to control effective normal stress. Shear stress is applied as per a conventional direct shear machine, in this case via a stepper motor. The applied load is measured with a load cell, permitting control of stress, load, displacement or strain. The maximum allowed shear displacement is 20 mm.

In the DynBPS machine, both vertical and shear stress can be applied under dynamic conditions up to 5 Hz. Dynamic load can be controlled in terms of displacement or stress; the dynamic vertical and horizontal loads are applied separately. More details on the testing equipment are provided by Brain et al. (2015).

2.3 Laboratory Testing Programme

In this series of experiments, the undisturbed block samples were carefully sub-sampled to the dimensions of the testing cell in preparation for laboratory testing. Samples with gravel-size pumice fragments were excluded for testing. The majority of tests for Machalí samples were undertaken in an unsaturated state, replicating the observed conditions at the site. In contrast, for the Pudahuel samples, and a small number of the Machalí samples, saturated tests were undertaken.

A total of 21 experiments on undisturbed samples, and 12 experiments on remoulded samples, were undertaken (Tables 1 and 2, Figs. 3, 4 and 5). In the case of the Machalí undisturbed samples, these consisted of ten monotonic and five dynamic tests. For the Pudahel samples, three monotonic and three dynamic tests were performed on undisturbed samples. In addition, a series of three monotonic and three dynamic tests on remoulded samples were undertaken for each site. The results can be compared with shear strength tests that had been previously undertaken by Lagos (2003) and Rebolledo et al. (2006) on the same material, including several monotonic direct shear tests on remoulded samples from a range of sites and one consolidated isotropic undrained (CIU) triaxial test series in an undisturbed sample from Pudahuel.

To obtain the shear strength failure envelopes, a series of monotonic direct shear tests were undertaken on undisturbed and remoulded samples from Machalí under both unsaturated and saturated conditions, and under saturated conditions for the Pudahuel samples, according to local site conditions (Table 1). In these tests the samples were consolidated to a predetermined normal total (and, in the case of the saturated samples, effective) stress, and then sheared at a constant displacement rate of 0.1 mm/min in fully drained conditions. During testing, measurements were made of normal stress and strain, and shear stress and strain. In the case of the saturated tests, the pore water pressure was also recorded to permit calculation of normal effective stress.

The aim of the dynamic tests was not to generate failure under dynamic conditions. The imposed stresses during the dynamic phases of the tests were designed to keep the stress path below the static failure envelope. In each case the aim was to investigate whether dynamic testing that did not cause sample failure had an impact on monotonic behaviour. Thus, after dynamic loading the samples were taken under monotonic loading conditions (i.e. through conventional direct shear) until displacement reached full travel. As such these experiments allow studying the role of dynamic loading in preparing slopes for failure rather than inducing failure itself during dynamic loading.

The dynamic tests (see Table 2) were undertaken in four stages:

- In Stage 1, the samples were consolidated to predetermined normal effective stresses, replicating the depth range of potential shear surfaces in Machalí estimated from field observations (1 to 20 m). The normal effective stresses applied for the Machalí samples were of 50, 100, 150 and 200 kPa. For the Pudahuel test series we opted to investigate the influence of different dynamic loads at the same normal stress. In this case, all dynamic tests were carried out at an effective normal stress of 150 kPa to represent stress conditions below the water table in Pudahuel.
- Stage 2 consisted of the application of a monotonic shear stress at a displacement rate of 0.1 mm/min until a predetermined shear stress of 50 % the normal stress was achieved (Table 2), which replicated the stress state encountered in typical slopes at the Machalí site. The same stress conditions were applied to the Pudahuel samples to allow comparison.
- In Stage 3 cyclic stresses were applied for 30 cycles at a frequency of 2 Hz. This is the dominating natural frequency measured using H/V or Nakamura's method (Leyton et al. 2011) at a site at Pudahuel. For simplicity, in-phase horizontal and normal loads were applied, with maximum horizontal stress amplitude (Kh) being double the vertical stress (Kv). During the 2010 earthquake, the only record for these soils (Maipú seismic station in Pudahuel deposits) recorded peak accelerations of 0.54 g (horizontal) and 0.23 g (vertical) (Saragoni & Ruiz, 2012). For the Machalí test series on unsaturated samples, the loads were selected such that the horizontal load was around 50 % of the shear strength at the applied normal stress. The peak horizontal cyclic shear stresses applied were of 52, 75, 98 and 120 kPa, respectively. For the tests on saturated samples from the Pudahuel site, all taken at a normal effective stress of 150 kPa and an initial shear stress of 75 kPa, the applied peak

horizontal shear stresses were of 50, 100 and 200 kPa, with an in-phase vertical load half the horizontal load (Table 2). For comparison, a similar test on a saturated sample from Machalí was carried out at the same stress state, with a peak cyclic horizontal stress of 100 kPa.

- The fourth and last stage was carried out after the cyclic loading had been completed. Then, the sample was loaded monotonically to full travel at the initial normal effective stress, allowing recording of post-dynamic peak and residual strength and obtaining the corresponding failure envelopes.

3. Test Results

3.1 Monotonic tests

The results of monotonic tests are summarized in Table 1. The Machalí undisturbed samples show a high cohesion of slightly over 60 kPa under unsaturated conditions, which is reduced to 17 kPa when the sample is saturated, suggesting that this is predominantly an apparent cohesion effect. The peak friction angle varies between 39° and 51°, being higher for saturated samples, suggesting a sample densification caused by cohesion loss. The monotonic tests on remoulded samples show smaller cohesion values (c. 8 kPa) but similar friction angles (47°) to the undisturbed samples. Residual strength is generally similar to peak strength in relation to the friction angle, but in the remoulded samples all cohesion is lost.

While the (apparent) cohesion is quite variable from one site to another and it is dependent on the saturation conditions, the friction angle is comparable with those obtained from standard direct shear tests in both unsaturated and saturated samples from different sites by Rebolledo et al. (2006), which range from 38° to 47°. The peak cohesion obtained by these authors varied from 7 to 20 kPa.

The undisturbed, unsaturated samples tend to show a semi-ductile rheology (Fig. 3), while the undisturbed-saturated and remoulded-unsaturated samples show a more variable behaviour from brittle-ductile to semi-ductile curves.

3.2 Dynamic test results

3.2.1 Machalí

Results of dynamic tests on unsaturated, undisturbed Machalí samples are summarized in Fig. 4. In all cases the dynamic stresses did not cause the stress path to cross the monotonic failure envelope. During the cyclic loading shear displacements between 2.8 and 4.5 mm were recorded, most of which registered during the first ten cycles (Fig. 4). At the same time, the shear stresses increased with each cycle (Fig. 3b), suggesting a strain-hardening response during cyclic loading.

In most cases the samples showed a clear post-dynamic peak strength with a post-peak strain-softening to semi-ductile behaviour (Fig. 3b), with residual values between 80 % and 95 % of the peak value. If linear envelopes are traced through the peak and residual values (Fig. 4), the resulting post-dynamic strength parameters are zero cohesion and friction angles of 55° (peak) and 51° (residual). The experiment was repeated on remoulded samples under the same loading conditions. In this case the results were essentially identical, with no cohesion and friction angles of 56° (peak) and 52° (residual) for the post-dynamic failure envelopes.

3.2.2 Pudahuel

In this series of tests on saturated samples, the effect of changes on the cyclic load amplitude was investigated. In all cases except one (the remoulded sample with a 200 kPa peak horizontal stress) the dynamic stresses did not cross the monotonic failure envelope. Similarly as for the other tests, monotonic shear under displacement control was applied afterwards until the apparatus reached full travel.

In these tests, excess pore water pressures developed during the dynamic phase, although these were less than 10% of the back pressure and quickly dissipated. The post-dynamic peak shear strengths were all 'above' the monotonic failure envelope observed for the saturated Pudahuel samples, showing an increase in strength with higher loading amplitude for undisturbed samples, and a more variable behaviour for the remoulded samples (Fig. 4c). The strength of the Pudahuel sample is higher than the undisturbed, saturated Machalí sample tested under the same loading conditions, which is consistent with the monotonic test results. In turn, the Machalí saturated sample shows a slightly higher strength than the unsaturated test at the same dynamic loading conditions.

4. Discussion

Figure 5 presents the dynamic and static failure envelopes measured for the Machalí series of tests. The monotonic unsaturated failure envelope displays a high level of cohesion, which we interpret as cohesion generated by suction (i.e. apparent cohesion) and inter-particle bonding. When tested under saturated, monotonic conditions the samples lose almost all of their cohesion but display a higher level of internal friction than for unsaturated conditions. Remoulded samples tested under unsaturated conditions show essentially identical strength parameters to the saturated undisturbed samples (Fig. 5), suggesting that the behaviour of the undisturbed unsaturated samples, characterized by high cohesion, is dominated by the effects of suction. There is still some cohesion in saturated samples that can be attributed to weak cements, which are destroyed during cyclic loading. Preliminary X-ray diffraction analyses carried out at the University of Chile (Morata, pers.

comm., 2014) show the presence of clay minerals and silica polymorphs. Cementation due to chemical weathering producing clay and silica viscous agents is likely in the Pudahuel Ignimbrite soils. The effect of loss of suction and/or destruction of cementation in pyroclastic materials has been proposed as mechanism of strength loss in seismically-induced landslides in volcanic soils (Evans et al., 2002). As found in similar volcanic soils elsewhere (Rolo et al. 2002 and references therein), the effect of such cements and suction may explain the metastable behaviour of these soils that can sustain steep slopes and caves in static conditions but tend to fail during heavy rainfall or seismic shaking, or show poor behaviour as foundation soil during earthquakes (Leyton et al. 2011).

The samples subject to dynamic testing show no cohesion, but have a higher angle of internal friction (Fig. 5). It appears that the dynamic loading cause a restructuring of the sample that destroys (apparent) cohesion (i.e. results in a loss of suction and cementation) but increases the angle of internal friction, perhaps due to some densification or strain hardening effect. Additionally, the rheology tends to be more brittle, or displaying evidence of strain softening, after shaking. The results from the Pudahuel site also show an increase in shearing resistance for higher shear stresses (Fig. 4).

Given the nature of the climate in the study area, it is likely that seismic shaking usually occurs when slopes are in an unsaturated state. Thus, the loss of cohesion as a result of dynamic loading is an important effect. In studied soils, for potential shallow landslides, this loss of cohesion will increase the potential for instability, and these effects will not be compensated by the higher angle of internal friction. For deeper landslides (shear surfaces with normal stress over c. 100 kPa, where the failure envelopes in Fig. 5 intersect) the loss of cohesion is likely to be less important, with shear strength being dominated by the higher angle of internal friction (Fig. 5).

For example, a simple stability analysis of a theoretical 2D, unsaturated soil slope of 30 degrees using the infinite slope method (e.g. Das, 1998) with the shear strength parameters of the undisturbed, unsaturated Machalí samples for both monotonic and post-dynamic conditions show how for shallow slides the loss of cohesion reduces the static factor of safety in over 40%, while for deeper slides, where the increase of friction angle dominates the behaviour, the static factor of safety may even increase despite the cohesion loss (Table 3). Thus, the behaviour observed in this test series suggests that in these materials seismic shaking is likely to promote shallow rather than deep-seated landslides, which is in accordance with observed behaviour during the 2010 earthquake (Sepúlveda et al. 2012, 2015).

The results illustrate the effects of dynamic loading during earthquakes on pyroclastic ash soils and hence possible changes in shear strength parameters due to precursory seismic events that may modify the stability conditions of slopes. The effect of loading frequencies or horizontal to vertical stress ratios in such changes need to be further investigated, as well the role of liquefaction on slope failures in these types of soil.

5. Conclusions

Direct shear tests carried out on pyroclastic materials from the Pudahuel Ignimbrite Formation in central Chile show a direct effect of cyclic loading on the shear strength, and in a minor extent on the rheology. A high apparent cohesion found in monotonic shear tests, likely attributed to suction and cementation, is destroyed by dynamic loading. At the same time, the internal friction angle rises. This defines a differential behaviour with a post-dynamic shear strength lower than the static strength at normal effective stresses below 100 kPa, due to loss of cohesion, while for higher normal stresses the effect of frictional resistance results in higher strength. Additionally, if higher shear stresses are applied for a given normal stress, the peak strength increases. The results are consistent with observations of differential behaviour as foundation soils and shallow landsliding in slopes of the Pudahuel Ignimbrite Formation during recent strong earthquakes in the region. We conclude that seismic shaking in this kind of cineritic soils induce changes in shear strength leading to shallow slope failures and that the use of shear strength from monotonic direct shear tests may produce quite misleading results when studying seismic slope stability in this type of soils.

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TABLES

Table 1. Monotonic shear tests settings and resulting shear strength parameters (peak and residual strength) on Machalí and Pudahuel sites.

Site	**Sample Condition**	**Saturation**	**Normal Effective Stresses (kPa)**	**Peak Cohesion (kPa)**	**Peak Friction Angle (°)**	**Residual Cohesion (kPa)**	**Residual Friction Angle (°)**
Machalí	Undisturbed	Unsaturated	50, 100, 150, 200, 350	64.2	39.4	62.7	37.3
Machalí	Undisturbed	Saturated	35, 70, 100, 140, 200	17.0	46.4	6.1	47.0
Machalí	Remoulded	Unsaturated	50, 150, 200	8.6	47.4	0.0	44.2
Pudahuel	Undisturbed	Saturated	70, 150, 250	13.7	51.3	12.1	44.8
Pudahuel	Remoulded	Saturated	70, 150, 250	0.0	50.9	0.0	51.6

Table 2. Summary of dynamic test settings for Machalí and Pudahuel samples.

Sample Site	**Sample condition**	**Saturation**	**Normal Effective Stress (kPa)**	**Initial Shear Stress (kPa)**	**Max. Horizontal Cyclic Stress, Kh (kPa)**	**Max. Vertical Cyclic Stress, Kv (kPa)**
Machalí	Undisturbed	Unsaturated	50	25	52	26
Machalí	Undisturbed	Unsaturated	100	50	75	37
Machalí	Undisturbed	Unsaturated	150	75	98	49
Machalí	Undisturbed	Unsaturated	200	100	120	60
Machalí	Undisturbed	Saturated	150	75	100	50
Machalí	Remoulded	Unsaturated	50	25	75	37
Machalí	Remoulded	Unsaturated	150	75	98	49
Machalí	Remoulded	Unsaturated	200	100	120	60
Pudahuel	Undisturbed	Saturated	150	75	50	25
Pudahuel	Undisturbed	Saturated	150	75	100	50
Pudahuel	Undisturbed	Saturated	150	75	200	100
Pudahuel	Remoulded	Saturated	150	75	50	25
Pudahuel	Remoulded	Saturated	150	75	100	50
Pudahuel	Remoulded	Saturated	150	75	200	100

Table 3. Results of static slope stability analyses using the infinite slope method for unsaturated soils without seepage using monotonic and post-dynamic strength parameters for Machalí undisturbed samples. A slope angle of 30 degrees is assumed.

Strength parameters	***Factor of Safety, depth 5 m***	***Factor of Safety, depth 30 m***
Monotonic (c=64kPa, ϕ=39º)	4.3	1.9
Post-dynamic (c=0kPa, ϕ=55º)	2.5	2.5

FIGURES

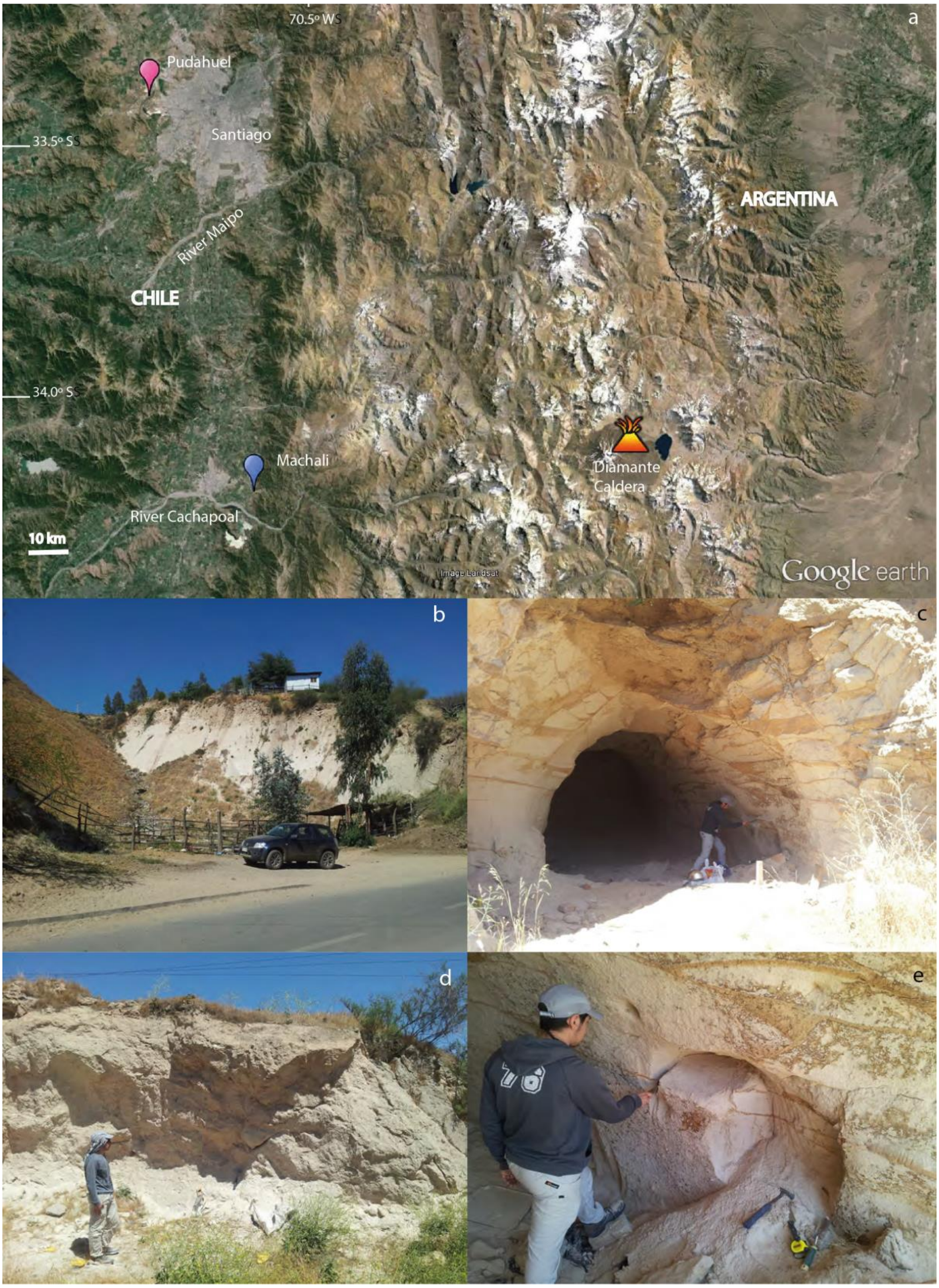


Figure 1. a) Landsat-Google Earth image indicating the location of Pudahuel ignimbrite sampling sites of Pudahuel (pink symbol) and Machali (blue symbol) and Diamante Caldera; b) Shallow landslide in Machalí; c) Machali samples site in unsupported cave; d) Pudahuel samples site; e) Detail of sample carving process.

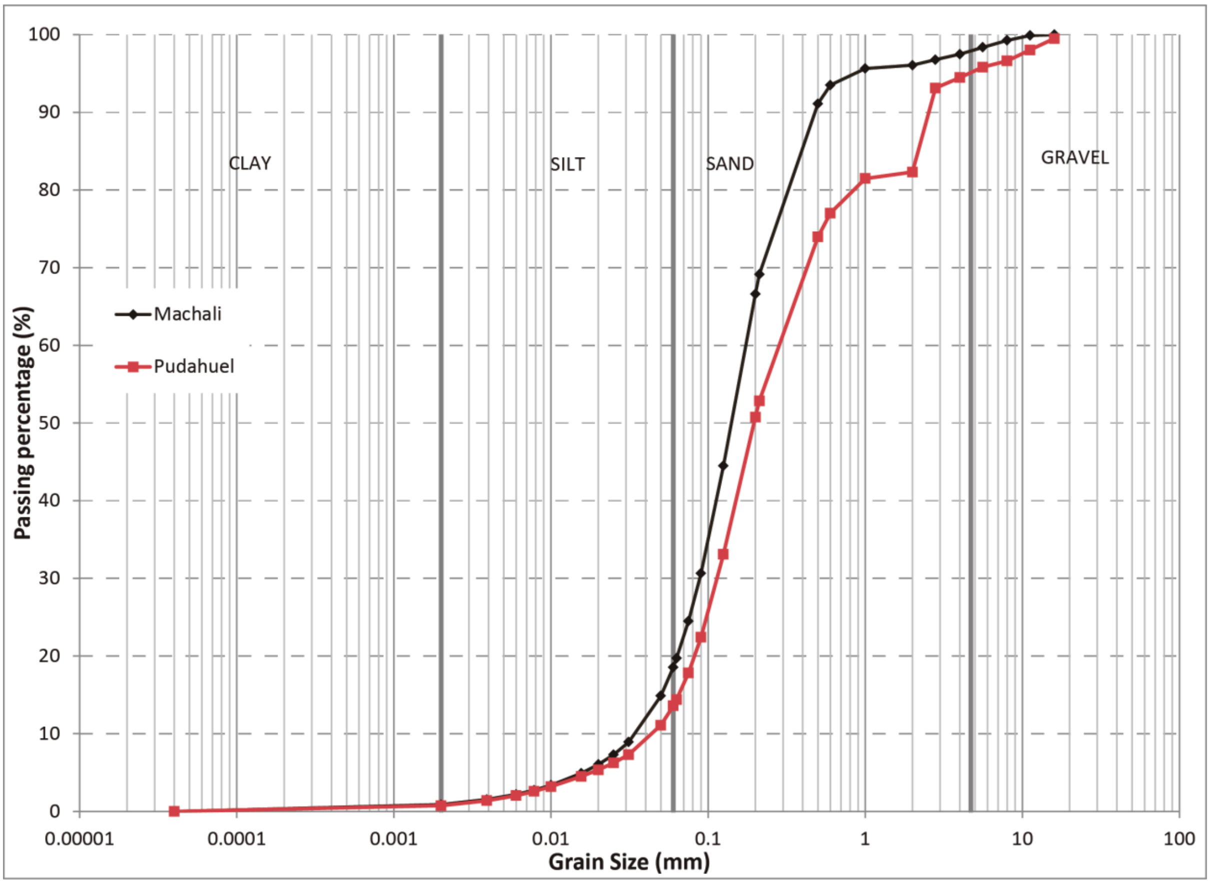


Figure 2. Cumulative grain size distribution of the Machalí and Pudahuel samples.

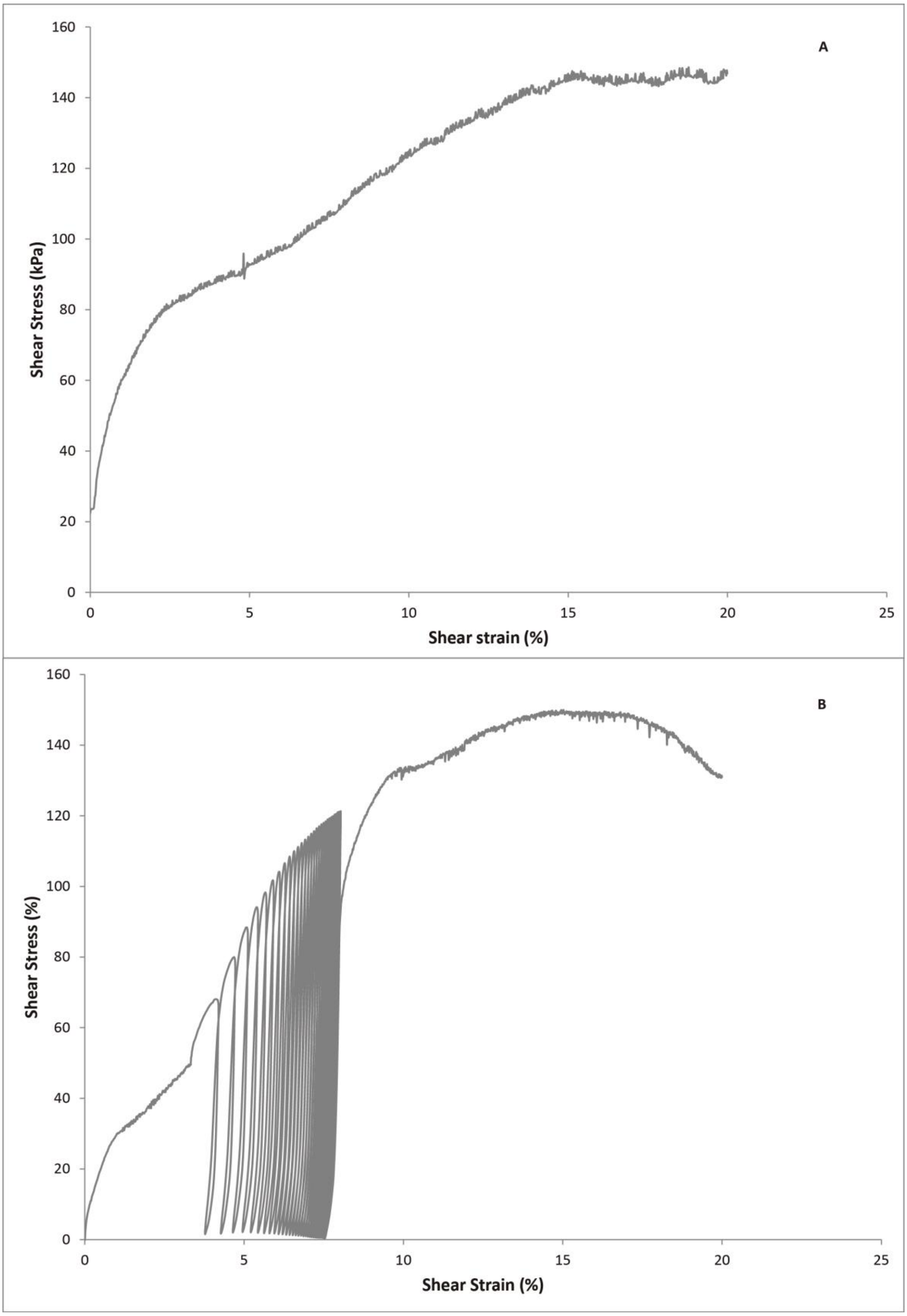


Figure 3. Examples of shear stress-shear strain charts of a) monotonic and b) dynamic shear tests on Machalí unsaturated samples at normal stress of 100 kPa.

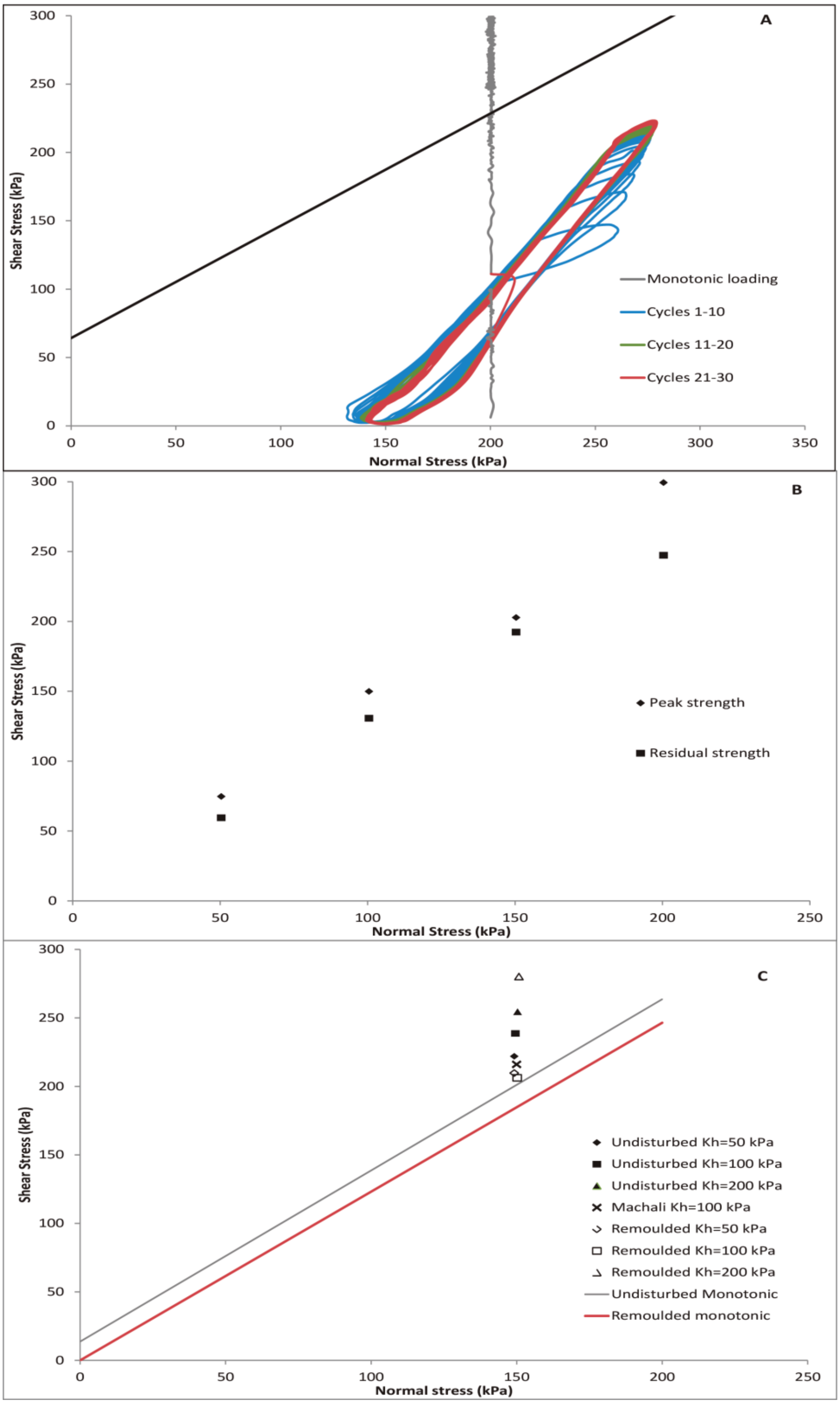
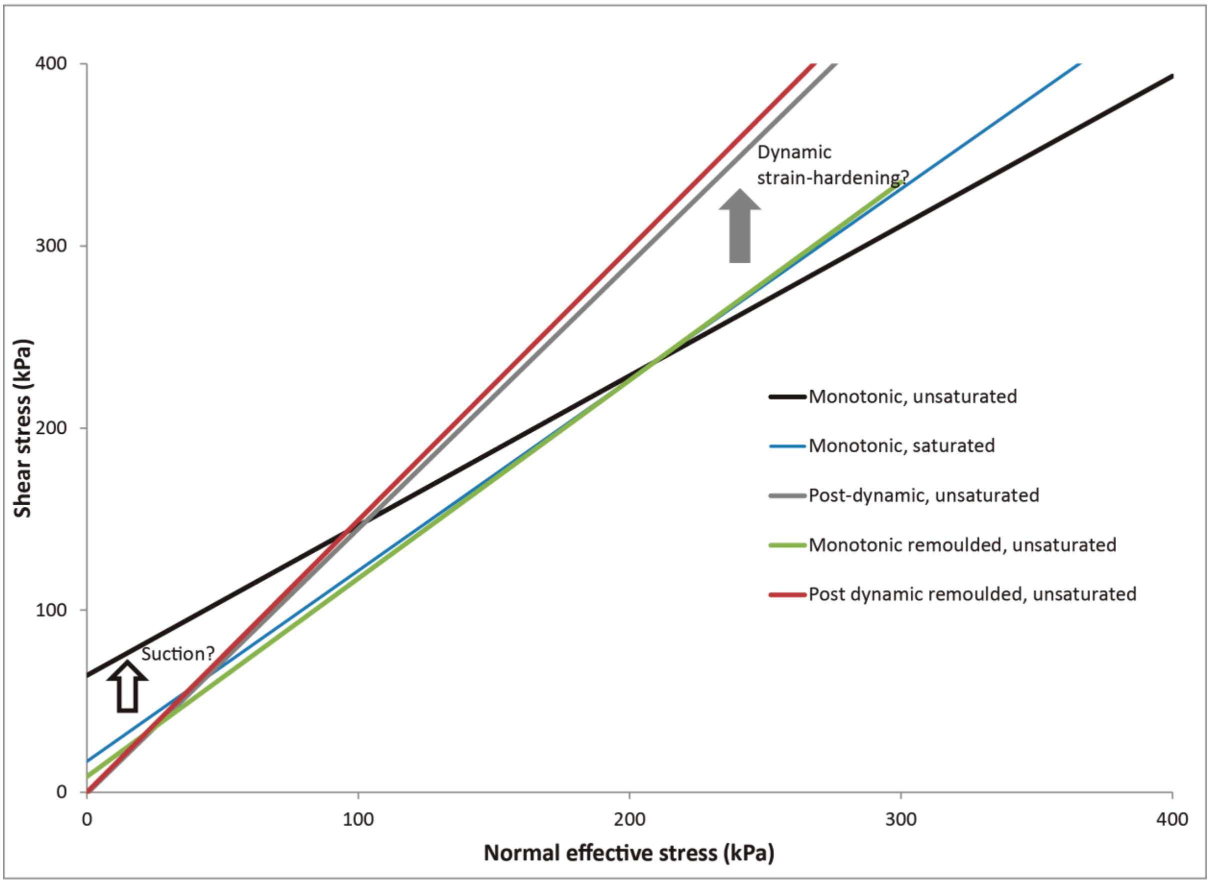


Figure 4. Dynamic tests results: a) Example of stress conditions in plot of shear stress vs normal effective stress during a test on Machalí, undisturbed, unsaturated sample at baseline condition of 200 kPa normal stress. b) Peak and residual strength data for Machalí undisturbed, unsaturated samples. c) Pudahuel saturated tests post-dynamic peak shear strength for different dynamic loadings (Kh: horizontal stress amplitude) on both undisturbed and remoulded samples. The monotonic failure envelopes and one equivalent saturated test of a Machalí undisturbed sample are also presented for comparison.



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419 Figure 5. Monotonic and post-dynamic peak strength failure envelopes for the Machalí tests.