Geological and geotechnical characteristics of the Pudahuel ignimbrite, Santiago, Chile

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Abstract: Chile, located in a geotectonic active margin, is frequently affected by strong earthquakes, with a seismic event of magnitude greater than 7 every 10 years. Santiago, the capital city, is home to 40% of the total population, nearly 6 million people. The city is mainly built on alluvial deposits of Maipo and Mapocho rivers, fine sediments and volcanic ash. The last material, deposited during an important volcanic eruption dated at 450,000 years B.P., controlled an unexpected high level of damage during the 1985 (M=7.8) earthquake. This deposit has been assigned to a geological unit named Pudahuel Volcanic Ash.

The relevant damage of buildings founded in this unit encouraged an interdisciplinary study aimed at determining the geological and geotechnical parameters that would control the behaviour of volcanic ash during seismic events.

The Pudahuel Volcanic Ash unit has a thickness of 40m. Most of the deposit corresponds to a pyroclastic ash flow, 33-37 m in thickness. Underlying the flow there is a 2m thick volcanic ash layer; overlying the flow there is a pyroclastic surge of 2-5 m in thickness.

Laboratory tests, the description of 34 m of drill core, a downhole drilling test measure and two refraction profiles allowed characterisation of the material's geotechnical properties and the velocity of shear and compressive waves. Former borehole core descriptions were used to define the continuity of ash strata in different sectors.

The pyroclastic flow deposit has a density between 1.14 and 1.17 Mg/m3, a friction angle of between 27º and 33º, and almost zero cohesion. For different confining pressures, shear wave velocities between 175 and 375 m/s were measured. Shear modules calculated from seismic velocities, are relatively low, comparable with clays. This indicates a high deformation for low stress and therefore high levels of seismic waves amplification due to the deformation of the ground.

This study concludes that the material under the pyroclastic flow determines the seismic response. The lowest seismic intensity was registered where coarse material underlies the ash flow; meanwhile, highest seismic intensities were registered in places where a thick stratum of fine soil underlies it.

Résumé: Le Chili, localisé sur une marge géotectonique active, est généralement touché par de puissants tremblements de terre et tous les 10 ans, par un évènement sismique de puissance supérieure à 7. Santiago, la capitale, rassemble 40% de la population totale du pays avec presque 6 millions d'habitants. La ville est construite sur des dépôts alluvionnaires des rivières Maipo et Mapocho, constitués de fins sédiments et de cendres volcaniques. Ces dernières, déposées durant une importante éruption volcanique datée à 450 000 ans ont joué un rôle inattendu dans les dégâts importants occasionnés par le tremblement de terre de 1985 (M=7.8). Ce dépôt est assigné à l'unité géologique appelée Ignimbrite de Pudahuel.

Les dommages subits par les édifices ont encouragé la mise en place d'une étude pluridisciplinaire permettant de déterminer les paramètres géologiques et géotechniques qui contrôlent le comportement de l'Ignimbrite de Pudahuel durant un évènement sismique.

L'unité d'Ignimbrite de Pudahuel a une épaisseur de 40m. La plus grande partie du dépôt correspond à un flux de cendres pyroclastiques, d'épaisseur variant de 33 à 37m. Sous ce flux, repose un niveau de 2m d'épaisseur de cendres volcaniques alors que dessus, se trouve un épanchement pyroclastique de 2 à 5m d'épaisseur.

Des tests de laboratoire, la description d'une carotte longue de 34m et des mesures à l'intérieur du trou de sondage ont permis de déterminer les propriétés géotechniques des matériaux et les vitesses des ondes de cisaillement et de compression. Des descriptions de carottes préexistantes ont été utilisées pour définir la continuité des couches de cendres dans différents secteurs.

Le dépôt de flux pyroclastique a une densité sèche comprise entre 1.06 et 1.27 Mg/m3, un angle de friction résiduel compris entre 37 et 42º (test de cisaillement) et presque zéro cohésion. L'angle de friction résiduel obtenu avec le test Triaxial est de 30° et zéro cohésion. Pour des pressions de confinement différentes, les vitesses mesurées des ondes de cisaillement varient entre 175 et 375 m/s. Les modules de cisaillement, calculés à partir des vitesses sismiques sont relativement bas et comparables aux argiles. Ceci indique une déformation importante associée à une faible contrainte et donc une amplification des ondes sismiques provoquée par la déformation du sol.

Cette étude conclue que le matériel présent sous le flux pyroclastique détermine la réponse sismique. L'intensité sismique la plus basse a été enregistrée quand des matériaux grossiers se trouvent sous les cendres alors que les plus hautes intensités sismiques ont été enregistrées à des endroits où les cendres se trouvent sur une couche épaisse de sol fin.

Keywords: environmental geology, geology of cities, seismic response, seismic risk, planning, earthquakes.

INTRODUCTION

Chile, frequently affected by strong earthquakes, with a seismic event of magnitude greater than 7 every 10 years, is located along the western coast of South America, to the east of the trench zone where the oceanic Nazca Plate is being subducted beneath the continental South American Plate, at rates of 8- 9 cm/yr. This tectonic configuration has dominated from at least Lower Jurassic when the subduction system was activated, marking the beginning of the Andean Cycle (Thomas, 1958; Piracés, 1976).

South of 33ºS, Chile is characterized by the existence of 3 parallel morphostructural units of north-south trend. These units are, from east to west the Andes Main Cordillera, the Intermediate or Central Depression and the Coastal Cordillera. This configuration would have been generated during a maximum compression phase during Upper Oligocene – Middle Pliocene (Thiele, 1980).

The Intermediate Depression is a basin refilled mainly by alluvial sediments and, in a smaller proportion, by material associated with volcanic activity. Santiago, the capital city of Chile, with a population of nearly 6 million, is located almost entirely in this morphological unit, surrounded to the east by the western border of the Andes Main Cordillera mountain range. This boundary apparently remains active today.

The basement of Santiago basin corresponds to volcanic rocks assigned to Upper Oligocene – Lower Miocene (Charrier and Munizaga, 1979) Abanico Formation. The bottom of the basin is indirectly known through gravimetric studies (Araneda *et. al*., 2000). It corresponds to a very irregular surface where buried hill chains are recognized. Santiago basin has an approximate surface area of 2360 km^2 (Araneda et al., 2000). Its sedimentary infill, which in some areas exceeds 500 m of thickness, has been assessed directly (by drilling) only to approximately 120 m depth. The uppermost meters of the filling correspond mainly to alluvio-fluvial sediments and volcanic ash deposits included in a unit named Pudahuel Ignimbrite, deposited during an important volcanic eruption dated as 450,000 years B.P.

The unexpected high level of damage during 1985 earthquake (M=7.8) in structures built on Pudahuel Ignimbrite deposits encouraged an interdisciplinary study aimed at determining the geological and geotechnical parameters that would control the behaviour of Pudahuel Ignimbrite during seismic events.

PUDAHUEL IGNIMBRITE

Background

Stern *et al*. (1984), suggest that the Pudahuel Ignimbrite deposits were the result of an eruption or a series of closely spaced eruptions from the same volcanic centre occurred 450,000 ± 60,000 years ago. The author inferred that this centre was the Maipo Volcanic Complex, located 120 km SE of Santiago in the Main Cordillera, and calculated the volume of the pyroclastic flows as 450 km^3 (Figure 1). Wall *et al*. (1999) describe the Pudahuel Ignimbrite as a deposit of a massive pyroclastic flow that covers alluvial deposits and it is covered by fluvial deposits. The observed thickness of this deposit reaches 10 m, although geophysical studies indicate a maximum thickness of 40 m in the zone of Pudahuel. The deposit consists of a rhyolitic pumice and ash tuff with a low percentage of biotite. The pumice fragments can have diameters up to 15 cm. Accidental lithic fragments and carbonized wood rests are suspended in the matrix. Locally, it has been reworked fluvially.

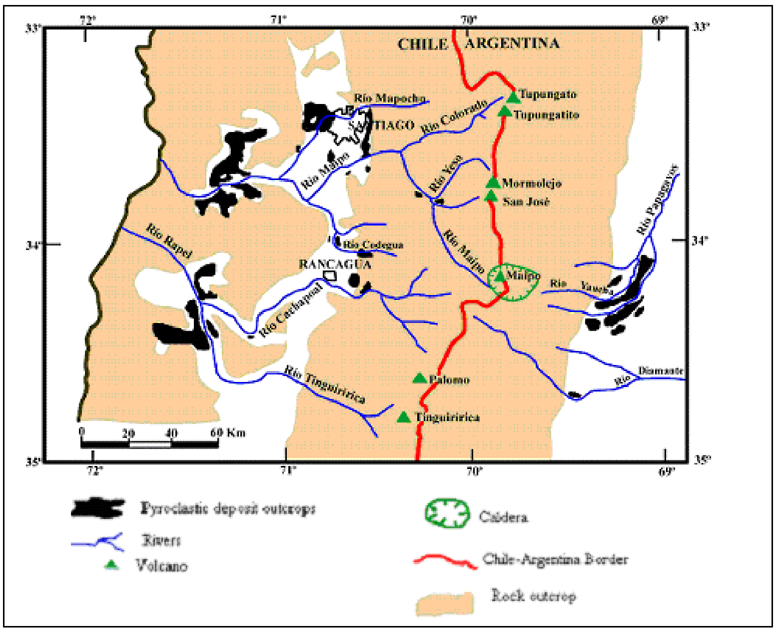
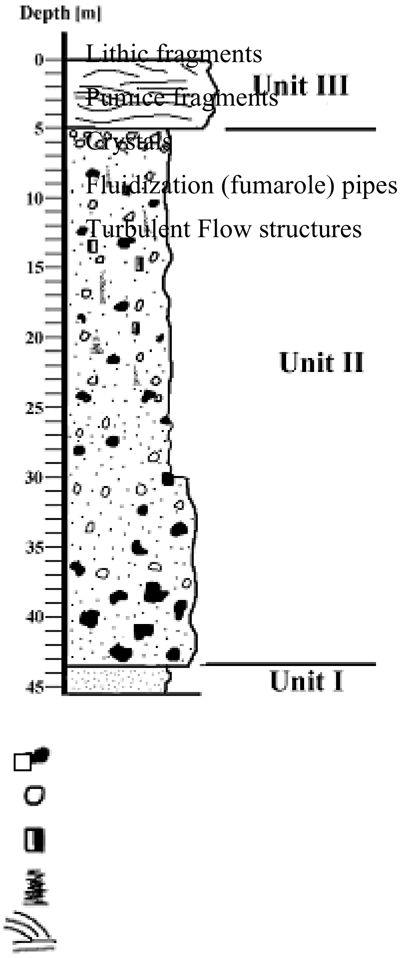


Figure 1. a) Areal Distribution of Pyroclastic Flow deposits. (Modified from Stern, 1984).

Lithology

The Pudahuel Ignimbrite (Figure 2) has a thickness of 40m; most of the deposit corresponding to a pyroclastic ash flow (Unit II), 33-37 m in thickness. Underlying the flow there is a 2 m thick volcanic ash fall layer (Unit I); overlying the flow there is a pyroclastic surge of 2-5 m in thickness (Unit III).



Unit III
40-70% glassy fine ash matrix with 5% plagioclase and 10% biotite crystals. 5% lithics. 60-30% pyroclasts: 20% block sized and 80% lapilli: 55% of pumice and 35% andesitic lithics. The volcanic glass of the matrix is welded. This unit has sedimentation structures.

Unit II
60% volcanic ash matrix composed of: 15% of vesicular pumice fragments, 45% of angular glass shards, 20% of plagioclase crystals and 5% of laminar biotite crystals, 12% of angular lithic fragments and 3% of lithic fragments altered to epidote and chlorite.
40% of tephra, 32 % blocks and 8% lapilli: 40% of vesicular pumice fragments, 5% of crystals (70% plagioclase, 30% of hexagonal laminar biotite; 55% of lithic fragments (5% vesicular juvenile fragments, 80% of andesitic accessory lithics (lapilli to block sized), 15% of accidental lithics (80% intrusive rock fragments and 20% of altered rock fragments).

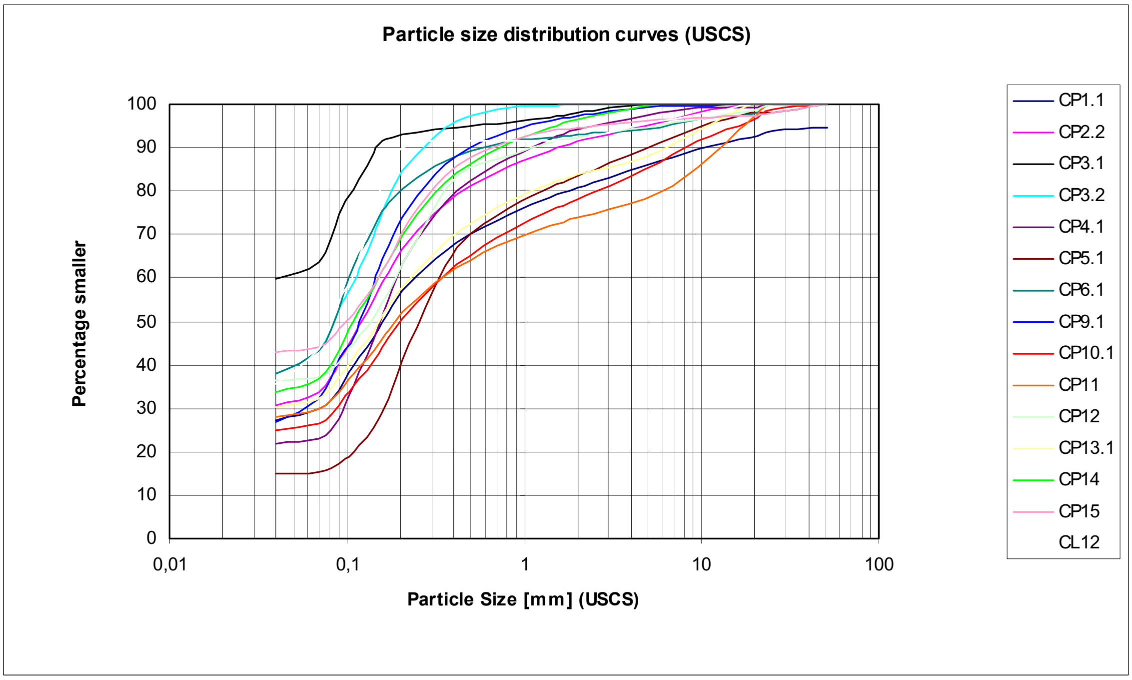
Unit I
Fine ash (<0.06 mm), 90% of volcanic glass.

Figure 2. Stratigrafic Column of Pudahuel Ignimbrite

Geotechnical characteristics of Unit II

In all sectors where Pudahuel Ignimbrite outcrops the Unit II prevails. In general, Unit III has been eroded and/or altered and Unit I is thin and/or it does not outcrop.

Grain size analyses to samples of different sectors allowed classifying the material that constitutes the Unit II as a silty sand (SM) with non plastic fines (Figure 3). They contain between 16 and 36% of fines (passing sieve # 200), which are mainly small angular volcanic glass particles (shards).



CP1.1 Pudahuel. Unit II; CP2.2 Lo Aguirre. Unit II; CP3.1 Lo Aguirre Unit I; CP3.2 Lo Aguirre. Unit I; CP4.1 El Manzano east. Unit II; CP5.1 El Manzano east. Unit II; CP6.1 El Manzano west. Reworked; CP9.1 Rinconada de Maipú. Unit II; CP10.1 Rinconada de Maipú. Unit II; CP11 Melipilla, matrix of conglomerate. Unit II; CP12 Melipilla. Reworked; CP13.1 Melipilla Rapel Unidad II, CP14 Apoquindo Unit I; CP15 Quebrada Macul ash interbedded with alluvial deposits in faulted terrace (Qt); CL12 Maipo Argentina.

Figure 3. Granulometry of Pudahuel Ignimbrite: Unit I, Unit II and reworked

Laboratory tests in remoulded samples of the Unit II taken in Pudahuel returned a permeability of 10^{-4} cm/s (constant head) and 10^{-5} cm/s (falling-head).

The specific gravity varies between 2.3 and 2.4 (Table1).

Table 1. Specific Gravity. ASTM method.

Sample	CP1.1a	CP1.1	CP9.1	CP2.2	CP20*
Specific Gravity (Gs)	2,29	2,32	2,33	2,42	2,35

*Ruta 5; 78 km south of Santiago

Direct shear tests

Table 2 shows the determination methods and the density used in the tests. The relative density (Dr) suggests they correspond in general to moderately dense soil (60-80%). Results of direct shear tests made in Unit II samples are shown in Table 3. The dry and saturated behaviour for samples 4.1 and 9.1 are shown in Figure 4.

Table 2. Densities of the samples and determination methods

Sample	$\rho_{natural}$	**Method**	ω	ρ_d	D_r
CP2.2	1,145	Undisturbed sample	4%	1,1	57%
CP4.1		Undisturbed sample		1,17	52%
CP9.1	1,12	Sand cone: in situ density	5%	1,06	84%
CP10.1	1,17	Undisturbed sample	2%	1,15	60%
CP13.1	1,28	Undisturbed sample	11%	1,16	61%
CP1.1		Undisturbed sample		1,17	52%
CP1.1	1,37	Sand cone: in situ density	8%	1,27	80%

Table 3. Test results of direct shear tests in Unit II

			Cohesión* C [kPa]		Φ [°]		
Sample	**Box Size**	**Particle size**	**Peak**	**Residual**	**Peak**	**Residual**	**Type test**
CP2.2	5x5	Under sieve ASTM #8	12	6	41	38	Unsaturated (w=4%)
CP4.1	5x5		12	3	39	39	Unsaturated (w=0%)
CP9.1	5x5		9	8	48	38	Unsaturated (w=5%)
CP10.1	5x5		10	5	39	38	Unsaturated (w=2%)
CP13.1	5x5		18	6	38	38	Unsaturated (w=0%)
CP4.1	5x5		7	7	40	39	Saturated
CP9.1	5x5		20	9	47	38	Saturated
CP1.1	30x30	**Whole soil**	9	9	38	38	Saturated

**All the samples tested in 5x5 box show dilatancy during the tests.

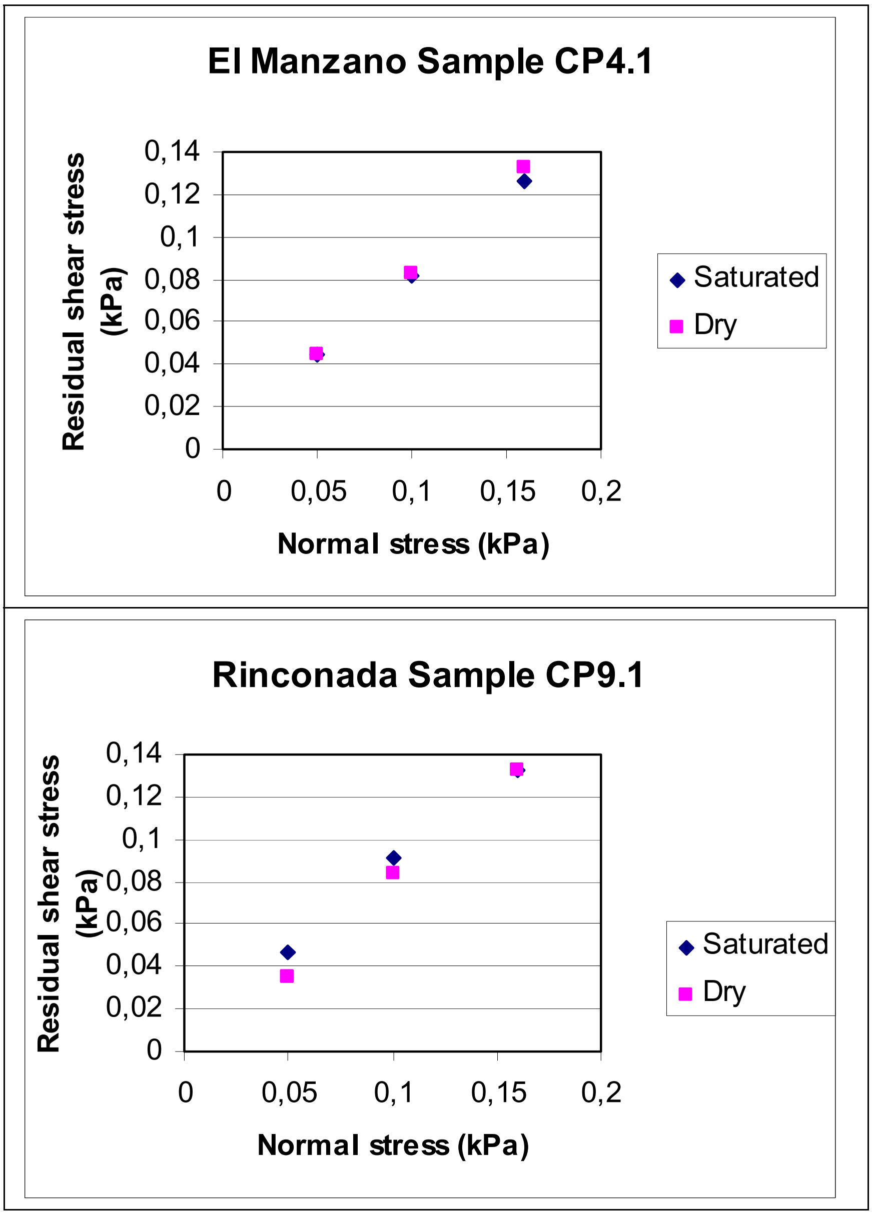


Figure 4. Test behaviour in dry and saturated samples

CIU Triaxial tests

From triaxial tests carried out in undisturbed samples of Unit II an angle of shearing resistance of 30º and a null cohesion were obtained (Table 4, Figure 5). In most soils it is possible to recognize a variation between the angles of shearing resistance obtained from triaxial and direct shear tests. In the Pudahuel Ignimbrite this difference is at least of 10º.

Table 4. Triaxial (CIU) test results. Undisturbed samples Unit II Pudahuel Ignimbrite

σ_c [kg/cm^2]	γd [gr/cm^3]	p_{max} [kg/cm^2]	$q_{último}$ [kg/cm^2]
0,5	1,17	3,72	2,04
1,0	1,18	2,91	1,5
2,0	1,16	4,19	2,15

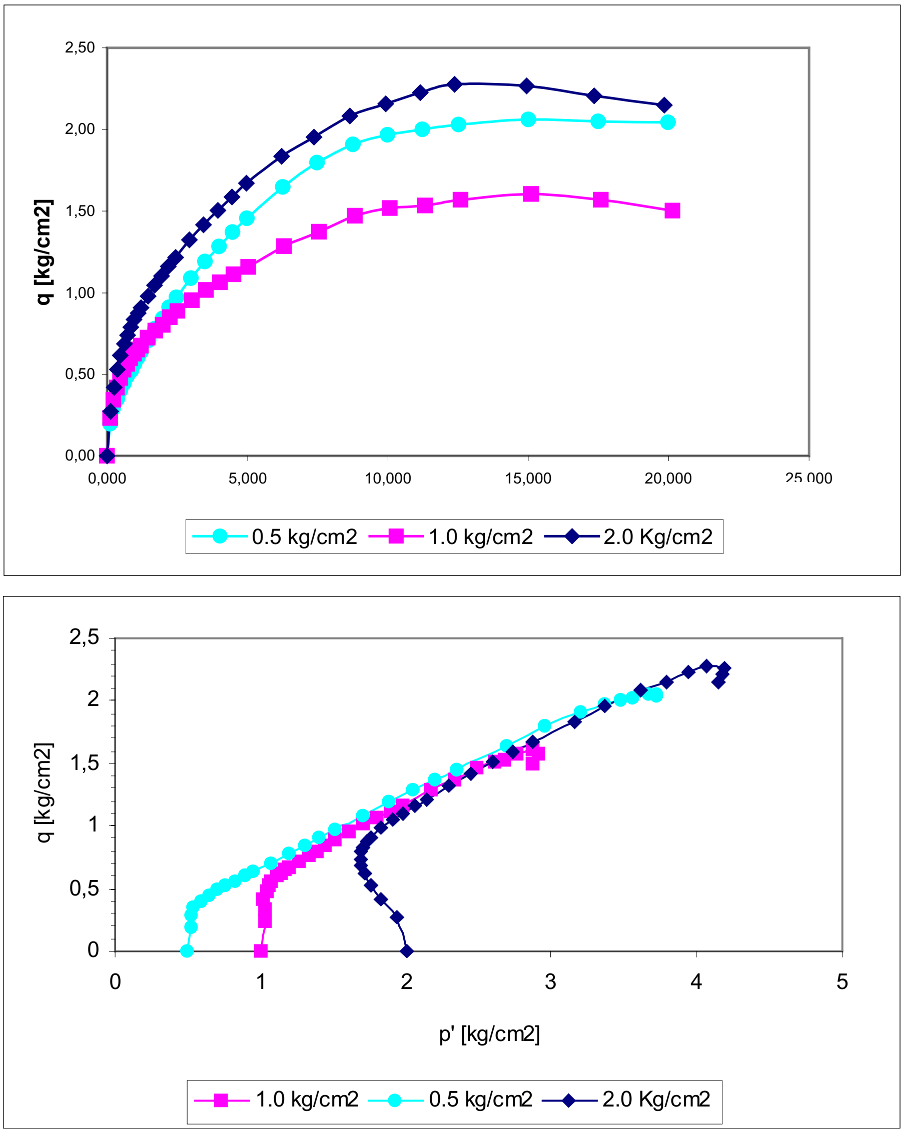


Figure 5. Triaxial test result. Pudahuel Ignimbrite Unit II.

Shear wave velocities

Two measurements of shear wave velocities in undisturbed saturated samples of Unit II were made using Bender Element. The tests had loading and unloading stages, reaching a maximum confining pressure of 7 kg/cm^2 (Figure 6).

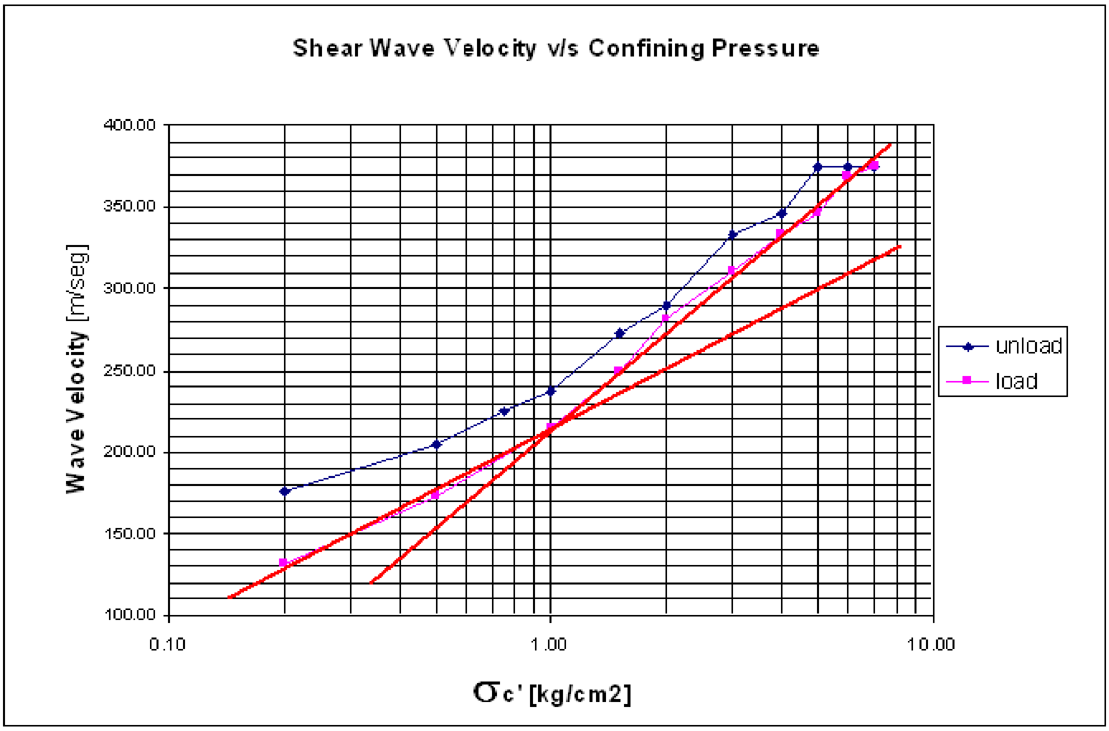


Figure 6. Shear wave velocity v/s confining pressure.

For Unit II, shear wave velocities of 175 and 375 m/s were obtained for confining pressures of 0.2 and 7 kg/cm^2. From Figure 6 it is possible to see that this soil is not sensitive to wave velocity changes with preconsolidation and also that there is a variation in the wave velocity at 1 kg/cm^2, which suggests a change in the soil structure from that load. This is already suggested from the triaxial tests results.

A load of 2.34 kg/cm^2 was considered to represent an average value of Vs for the Pudahuel Ignimbrite. This load occurs at 20 m depth if the upper layer has an average density of 1.17 gr/cm^3. For this load Vs is 290 m/s and the Shear Modulus (from equation 1) is 98.4 MN/m^2.

1)

$$G = \rho \times V_s^2$$

Where: G = Shear Modulus, ρ = Density, V_s = Shear wave velocity =290 m/s

Down Hole

The Down Hole test was carried out in Pudahuel. The borehole log in Figure 7 shows that at the site it is possible to recognize three layers: a) the upper, which corresponds to alluvial sediments (gravels and sands), 11 m thick; b) an intermediate layer consisting of the Unit II of the Pudahuel Ignimbrite, 31 m thick, and c) the lower layer, composed of silt.

Wave velocities were measured to 40 m depth. However the existence of the water table at 14 m depth altered the results and therefore the shear wave velocities below this level were invalidated for the analysis.

The shear wave velocities obtained for the Pudahuel Ignimbrite between 11 and 14 m are similar to these obtained using Bender Element. The velocities Vp (around 624 m/s) measured for the upper layer are lower than those expected for this type of soil. This is related mainly to the low compaction of these recent fluvial deposits.

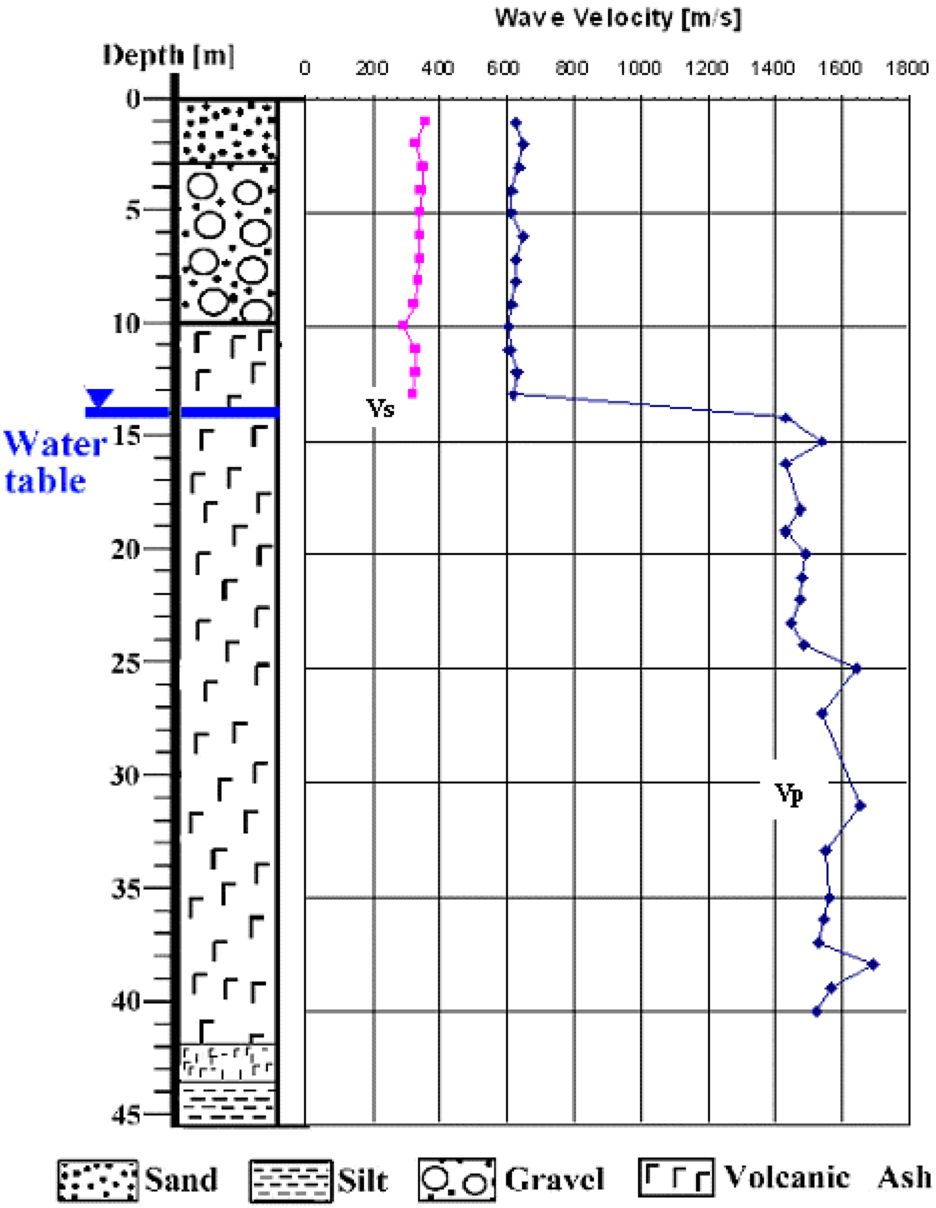


Figure 7. Stratigraphic column and Down hole results.

SEISMIC RESPONSE OF THE PUDAHUEL IGNIMBRITE DEPOSITS

Seismic Intensity during the 1985 Earthquake

The earthquake that occurred in March 1985 was one of the more destructive earthquakes to affected Chilean territory. One unexpected effect of this event was the high intensity registered in constructions built on the Pudahuel Ignimbrite deposits.

Menéndez (1991), from comparison of intensities in rocks for the 1985 earthquake with the intensities obtained in different soils, proposed that in gravel deposits the intensity increases between 0.5 and 1.0 degree compared to the rock, in the colluvial deposits it increases 1.0 to 2.0 degrees, in the Pudahuel Ignimbrite deposits it increases 1.5 to 2.0 degrees and in fine grained deposits it increases 2.0 to 2.5 degrees.

The soil seismic response during the 1985 earthquake indicates that in the places where the Pudahel Ignimbrite deposits are on fine grained sediments (silts and clays) the intensity was 7.75 to 8.25; in the sectors where the foundation soil corresponds to gravel and sands the obtained intensities vary between 6.0 and 7.25 (Lagos, 2003; Figure 8).

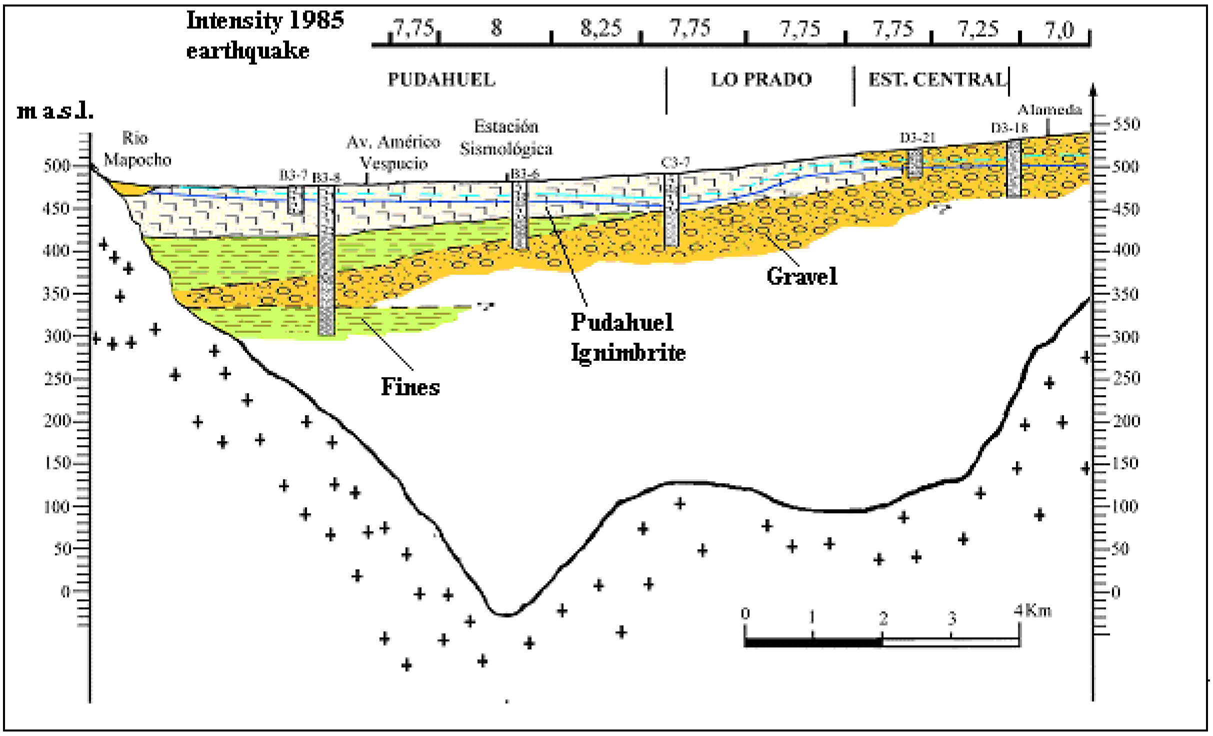


Figure 8. Profile A-A´. (After Lagos, 2003)

Accelerations

Acceleration data of two seismic events registered in a seismological station located in Pudahuel are compared with those registered in a reference seismological station located in Cerro Santa Lucía (Siebert, 2005). This station is on a good quality rock mass. The data for the analysis, taken from the Chilean Seismological Service registries, are in Tables 5 and 6.

Table 5. Earthquakes considered for the acceleration analysis.

Date	Hour UTC	Magnitude (M_L)	Depth (km)	Type	Epicentre
27/9/2004	22:58:24.6	5.3	32.9	Interplate	-32º 41' 16" S 71º 44' 34" W
13/3/2005	20:39:0.6	5.2	10.8	Continental Intraplate	-32º 43' 51" S 71º 43' 4" W

Table 6. Acceleration data for seismic response

Earthquake	Stations	Acceleration in z [m/s^2]	Acceleration in EW [m/s^2]	Acceleration in NS [m/s^2]
27/09/2004 Magnitude 5.3, Quintero	Pudahuel	0,118	0,087	0,117
	Sta. Lucía	0,016	0,014	0,029
13/03/2005 Magnitude 5.2, Quintero	Pudahuel	0,042	0,051	0,066
	Sta. Lucía	0,012	0,010	0,014

Figure 9 shows that the acceleration in Pudahuel is higher than the one in Santa Lucia for the analysed earthquakes. Although the events had similar magnitude and were measured at the same distance from the seismic source, the seismic response was different in the two stations. This might be related to the depth of the seismic source: a deeper earthquake should cause greater accelerations than shallow events. Nevertheless an inverse response on proximity to the focus is expected, that is to say, a shallow earthquake should produce greater accelerations than a deeper one.

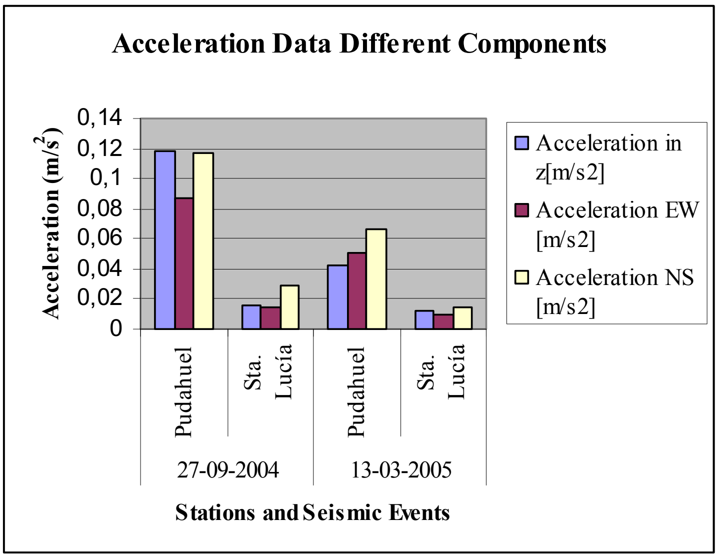


Figure 9. Acceleration Data for two seismic events

PRELIMINARY CONCLUSIONS

The pyroclastic flow deposits which constitute Unit II of the Pudahuel Ignimbrite have a dry density between 1.06 and 1.27 Mg/m3, a residual friction angle between 37 and 42º (shear test), and almost zero cohesion. The residual friction angle obtained by Triaxial test was 30º and null cohesion. For different confining pressures shear wave velocities between 175 and 375 m/s were measured (Bender Element).

Shear modulus calculated from seismic velocities, are relatively low, comparable with clays. This indicates a high deformation for low stress and therefore high levels of seismic wave amplification due to the deformation of the ground. This may be related with the seismic records that demonstrate an important amplification in the seismic acceleration of Pudahuel Ignimbrite deposits compared to the surrounding rock.

From the geological profiles it is possible to propose that one of the main factors influencing the seismic response is the type of soil that exists under the Pudahuel Ignimbrite. Studies designed to determine the shear modulus of this material and the influence of the sediment thickness in the seismic response is being currently developed.

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