Singularities of Geotechnical Properties of Complex Soils in Seismic Regions

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Abstract: Volcanic activity results in a wide range of soil types with very unusual characteristics, the most remarkable of which are volcanic ash clays containing the clay minerals allophane and imogolite. In addition to these soils, volcanic activity often produces the special environmental conditions that result in the formation of diatomaceous soils, namely, water rich in dissolved silica. These soils consist of individual particles containing intraparticle voids filled with water, resulting in a very unique porous particle morphology that is quite different than stereotypical sedimentary soils. This paper presents a series of careful laboratory tests on samples of both materials found in Chile. These tests demonstrate that soils weathered from volcanic ash develop yield pressures that are similar to the preconsolidation pressure of sedimentary soils. This type of soil also shows a dramatic change in properties due to drying. In addition, diatomaceous soils and those containing allophane have very low densities, in spite of which they develop remarkably high shear strength. The need for their properties to be properly understood and taken into account in geotechnical design, especially seismic design, is emphasized, since the location of these soils generally coincides with earthquake activity, which, like volcanic activity, arises from tectonic plate interaction.

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Introduction

Plate tectonics are recognized as the main cause of earthquakes around the world, and they should similarly be recognized as the main source of volcanic activity. For example, along the so-called circum-Pacific belt, there is clear correspondence between the presence of volcanoes and seismic activity. Volcanic activity generates a specific spectrum of soil deposits, all of which have distinctive characteristics, the most remarkable of which are volcanic ash deposits containing the clay mineral allophane. In addition, areas influenced by volcanic activity often have the specific environmental conditions favorable to the formation of diatomaceous soil deposits, namely, water rich in dissolved silica. In contrast to common sedimentary soils, volcanic ash clays and diatomaceous soils consist of porous individual particles of unusual shape, making possible a particle morphology that is quite unique. In describing their microscopic features, it is important to be clear about the terminology used here; the term fabric refers to the arrangement of particles, particle groups, and pore spaces in a soil, while the term structure refers to the combined effects of fabric, composition, and interparticle forces. With this understanding, soil structure reflects all facets of the soil composition, namely, history, present state, and environment (Mitchell and Soga 2005). Individual forms of particle interaction, particle assemblages defining units that interact with other units, and pore spaces within and between these units are part of the microfabric component of the soil structure (Collins and McGown 1974). As a consequence of this, the intraparticle voids existing in volcanic ash clays and diatoms are likely to be associated with very unusual microfabric.

With sedimentary soils, it can be shown that soil fabric is mainly controlled by the environmental characteristics existing during the deposition of soil particles, or genesis of the soil, and subsequent loading, whereas soil structure is only developed with time and it is controlled by both particle mineralogy and geological processes. In this context, the weathering process, through solution and reprecipitation that creates a more porous material and the formation of clay and other secondary minerals, is one of the most important geological influences in the creation of the soil structure. Soils produced directly by such weathering can, therefore, be expected to show quite different behavior than common sedimentary soils (Zhang et al. 2004). Additionally, weathering may produce bonds between particles and induce the formation of new units or aggregates. At the same time, it is recognized that the development of aggregates also takes place in sedimentary soils, where the interaggregate and intraaggregate pore spaces have been identified as the two common types of pore spaces for describing clayey sedimentary soils (Delage and Lefebvre 1984). In the case of volcanic ash, the weathering process leads to both a complex structure and unusual particle morphology, with the result that the soil shows very unique and very interesting behavior. With the above factors in mind, this paper gives an account of the properties of two soil groups having very distinctive geotechnical properties arising from the volcanic environment associated with their formation, namely, volcanic ash clays and diatomaceous soils.

Overview of Volcanic Ash Soils

Volcanic ash is normally made up of significant quantities of volcanic glass, which is likely to be one of the minerals most rapidly

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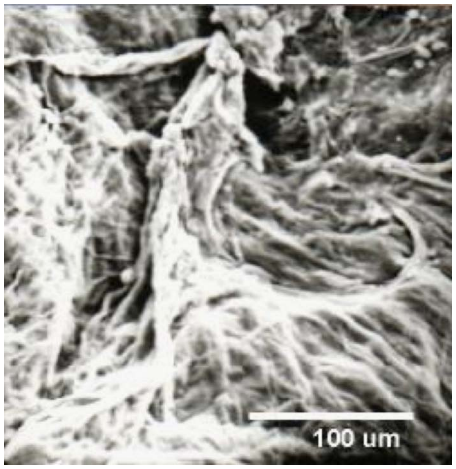

Fig. 1. Electron-microscope photograph of imogolite particles

weathered by the action of water. As well as glass, volcanic ash also contains more stable minerals, such as feldspars, quartz, apatite, biotites, and possibly others. Percolation of water through the soil thus very quickly alters the particles of volcanic glass, followed by other minerals, generating in this way a soil structure developed through weathering. Due to this rapid chemical weathering, even young ash deposits show some degree of in situ alteration at their place of origin, and, accordingly, they are commonly classified as residual soils. As the weathering progresses, it is believed to induce the following sequence of transformation of minerals: Volcanic ash—allophane and imogolite—halloysite—kaolinite—sesquioxides—laterite (Wesley 1973). The amorphous or poorly crystalline structure of volcanic glass weathers first to other poorly crystalline minerals named allophane and imogolite. The term allophane has been used in the past for any noncrystalline aluminosilicate, or amorphous clay-sized material, but more recently its use has been restricted to describe aluminosilicates associated with the weathering of volcanic glass (Wada 1989). Allophane consists of hollow, irregular spherical particles, with outer diameters between 3 to 5 nm, which means three orders of magnitude below the limit for colloidal size. Due to its minute size, the surface area of allophane is estimated to be in the order of 1,000 m^2/gr. The walls of these irregular spheres are 0.7 to 1 nm thick, and have openings that permit the passing of water molecules to the inner portion of the spheres. The hollow spherical shapes together with the high surface area and the defects of the noncrystalline structure produce a tremendous attraction for water inside and outside the particles, which results in a great amount of adsorbed water (Besoain 1985; Wada and Wada 1977).

Hand in hand with allophane, a mineral called imogolite is usually found. This is identified as a paracrystalline mineral, which means that it crystallizes only in one direction. As a result, these minerals form long threads consisting of a hollow "nanotube," with a length from several hundred to some thousand nm and with inner and outer diameters in the order of 1 and 2 nm, respectively. These unitary tubes often form bundles of many tubes creating a coarser thread. An electron-microscope photograph of a group of imogolites of a Chilean soil is shown in Fig. 1. The tube wall consists of a single curved gibbsite-like sheet where orthosilicate groups (SiOH) face the inner side while the outer sheet contains gibbsite units (AlOH) (Cradwick et al. 1972). Allophane and imogolite minerals usually coexist, generating a very unusual particle arrangement where long threads of imogolite tend to surround particles of allophane, resulting in a highly hydrated gel. Classical concepts of solid soil particles do not fit well with this hydrated gel, and the behavior of these soils can be expected to differ from that associated with normal sedimentary soils.

Overview of Diatomaceous Soils

Diatomaceous earth or diatomite is a sedimentary material resulting from the accumulation of skeletons left by microscopic unicellular aquatic plants named diatoms. These single-celled algae have been adapted to marine as well as freshwater aquatic environments, requiring for their life and reproduction sufficient light, because they are photosynthetic, and a continuous supply of nutrients such as phosphate, nitrate, and soluble silica. These plants take the available dissolved silica from the water and transform it into the amorphous silica of which their shells or frustules are made. Depending upon the local environmental conditions, the diatomaceous soil deposits vary from almost pure diatom to highly contaminated mixtures of diatom shells with other sediments and organic matter. It is interesting to note that although silica is the second most abundant element in the crust of the earth, only a few algae groups utilize silica in their biological processes, and all of them do it only to transform the available dissolved silica in order to build their skeletons (Brownlee and Taylor 2002). The essential requirement for the growth of diatoms is the availability, in the aquatic environment, of dissolved silica, which is most commonly found near areas of volcanic activity. Diatomaceous soils are, therefore, likely to occur in volcanic regions, which are in turn associated with active tectonic plate boundaries, especially those of a subductive nature. For example, many important commercial deposits are regularly encountered along the Pacific Rim, from Chile to British Columbia (Antonides 1997). Although the existence of more than 10,000 species of extinct and living diatoms occurring worldwide is accepted, the fundamental configuration of the fossilized skeleton is similar in all of them, and basically consists of two siliceous shells (frustules) interlocked by several connected bands. The shapes of these skeletons have a broad variety of delicate lace-like assemblies, highly sculptured and intricate, that go from disks and spheres to ladders, feathers, and needles. However, based on their symmetry, they are simply classified into two large groups as centric (radial or circular) and pennate (axial or elongate). In general, marine environments are more favorable for centric diatoms, while in fluvial continental environments, pennate diatoms are more common. Depending on the species, nutritional conditions, and other environmental factors, the diatom skeletons vary from colloidal size to frustules of more than 1 mm in diameter. Most typically, their size ranges from 10 to 200 μm (microns). The unique intricate morphology of the diatom skeleton is characterized by a primary series of inner pores, which are associated with the voids formed by external walls. In addition, a secondary network of pores is present in the shell itself, creating in this way a porous particle.

Experimental Program

Testing programs for both materials, diatomite and volcanic ash, were defined in order to investigate the geotechnical properties of each of these soils. "Undisturbed" block samples of two different volcanic ash soils were retrieved from the south of Chile and identified as Santa Barbara and Chillán (Paredes 2005), and "undisturbed" block samples of a diatomaceous soil were retrieved from a commercial site located in the vicinity of Arica, in the north of Chile. The site of this diatomaceous soil is very dry and under this condition the material is hard, similar to a very soft rock. All the block samples were retrieved by meticulously carving a block from the natural soil at each location. The blocks were covered with several layers of plastic wrap and transported to the laboratory in individual boxes carefully protected. In this way, high quality samples were obtained. Laboratory tests were carried out on both materials, consisting of classification, modified Proctor, unconfined compression, consolidation, shear wave velocity (using bender elements installed in a triaxial cell), and consolidated-undrained (CIU) triaxial tests. Additionally, undrained cyclic triaxial tests were performed on the volcanic ashes. For the two volcanic soils, the Atterberg limit tests using the Casagrande apparatus were performed with the material initially dried under different conditions. Thin layers of soil were spread on the surface of square pieces of glass and subjected to different drying conditions; these were: At room temperature (approximately at 24°C) for a period of about one week, directly under the sun (temperature at midday was approximately 30°C) for a period of one week, and in the oven at 60°C for 48 h. The tests were also performed with the soils initially at their natural water contents, and drying the materials during the test with a spatula. Similar drying procedures were adopted for the modified Proctor tests.

The dimensions of the consolidation metal rings were 3 cm in height and 5 cm in inner diam. The initial dimensions of the specimens tested in the triaxial cell (static, cyclic, and bender element tests) were 10 cm high and 5 cm in diam. The same dimensions were adopted for the unconfined compression tests. Triaxial specimens (CIU triaxial tests and shear wave velocity measurements) were saturated by first passing CO_2 gas through them, followed by percolation of approximately half a liter of deaired water. Back pressure was then applied until saturation of the samples was achieved, which was considered acceptable when the measured B-values were equal to or greater than 0.96. For the reconstituted samples, the procedure adopted for sample preparation was wet tamping, using five layers of identical height and weight. In the case of the diatom samples, an initial water content of 45% was adopted, which permitted appropriate sample handling. In the case of the volcanic ashes, the natural water content of the undisturbed samples was reproduced.

Experimental Results of Volcanic Ash Soils

The grain size distribution curves are presented in Fig. 2. The finer part of the curves for the Santa Barbara and Chillán soils was not determined because of the difficulty of separating the individual particles of allophane and imogolite. The allophane contents of Chillán and Santa Barbara are 36 and 16%, respectively. The liquid limit (LL) and plasticity index (PI) obtained with different drying procedures are presented in Fig. 3, where the dramatic changes caused by drying are easily seen. The greater the temperature used for drying the soils, the greater the reduction in LL and PI. In addition, part of the oven dried Chillán sample was resaturated for one week under distilled water and the Atterberg limit tests carried out again. The result shown in Fig. 3 indicates that only a modest recovery of plasticity takes place, suggesting that in these soils oven drying produces a permanent change in the plasticity. The results of compaction tests with soil batches initially dried under different conditions are presented in Fig. 4. These results also confirm the drastic and permanent change of the soil properties caused by drying, especially by oven drying. The higher the temperature used in drying, the greater the change and the increase of the Proctor density. This confirms previous results reported by Wesley (1973) and shows the same trend as in volcanic soils from other regions. In addition, it is interesting to note that for the soil without drying, the maximum dry density achieved by the modified Proctor is unusually low, less than 7.75 kN/m^3 (0.79 t/m^3). The optimum water content is approximately 70 and 81%, for Santa Barbara and Chillán, respectively. The fracture of imogolite tubes caused by temperature has been reported by MacKenzie et al. (1989). The process of drying, thus, seems to collapse both the allophane spheres and the imogolite tubes, allowing the inner adsorbed water to be liberated.

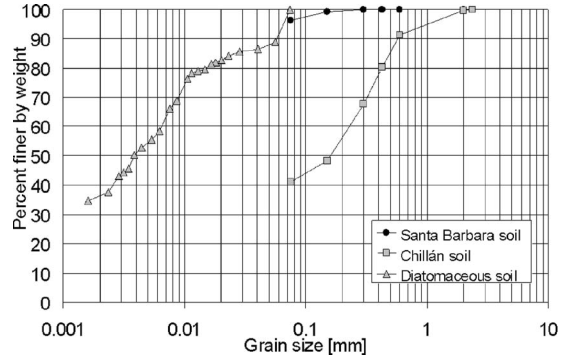

Fig. 2. Grain size distribution curves of tested soils

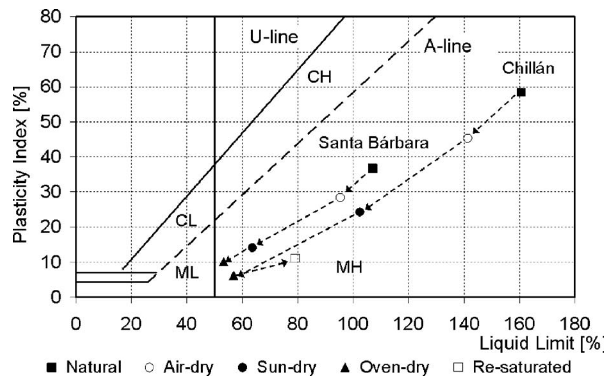

Fig. 3. Plasticity chart. Effect of drying on Santa Barbara and Chillán volcanic soils

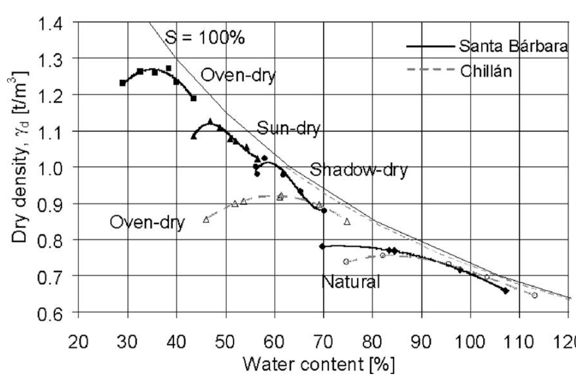

Fig. 4. Effect of drying on the Proctor compaction test

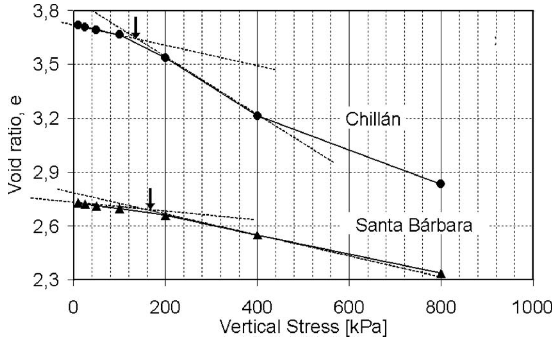

Fig. 5. Consolidation test results on undisturbed samples

Thereafter, it appears that the spheres and the tubes do not recover their hollow shape, and the inner adsorbed water cannot be restored. Hence, one practical outcome obtained from this experimental evidence is that soils containing allophane should never be dried before performing geotechnical tests.

Consolidation tests on "undisturbed" samples of Santa Barbara and Chillán soil were carried out, and the results are presented in Fig. 5. Following the recommendation of Wesley (1994), the results are plotted using an arithmetic scale for pressure. The existence of a pressure in the vicinity of 150 kPa where the compressibility suddenly increases is seen in the arithmetic plot for both Santa Barbara and Chillán soils. According to the available geological information for the area, these values of preconsolidation pressures are definitely not associated with geological stress history. Desiccation can be an explanation for this "preconsolidation," but in this case it is rejected because the soils in their natural condition were close to saturation and the Atterberg limits of the natural materials were higher than those obtained from samples dried at room temperature. The observed preconsolidation pressure, thus, has to be the result of the physical and chemical weathering process that has occurred in the soil, which has also been hypothesized by other researchers (Wallace 1973; Wesley 1994; Wesley 2002). At the same time, because weathering involves processes of leaching and solution that generate a more porous material, a reduction of density with unloading of the soil mass is to be expected. Weathering can, therefore, generate a preconsolidation resulting from the combined effect of unloading and chemical changes of the soil. Consequently, it is better to refer to this preconsolidation pressure as yield pressure, thus, distinguishing it from the established preconsolidation pressure caused by geological stresses or desiccation (Wesley 1994). The values of the compression index C_c (computed from e-log σ_v plot), and for rebound (or swelling) C_r are summarized in Table 1. Table 1 also shows values of the factor $\alpha = C_c/(1+e_o)$ for both soils; these are close to 0.3. It is important to realize that in any practical calculation of vertical ground deformation of fine-grained soils, the factor α is controlling the computed settlement, and not the value of C_c alone. Therefore, although the compression index of volcanic soils is unusually high, the in situ void ratio in these soils is also quite large, resulting in a value of α slightly larger than common sedimentary soft clays, which have values in the range of 0.1 to 0.2. Thus, when the materials tested here are subjected to stresses beyond the yield pressure, their actual compressibility is not significantly higher than common normally consolidated sedimentary soft clays. Under stresses below the yield pressure, the compressibility is low, and therefore, shallow foundations on these soils perform well with limited settlements when the stresses are restricted to less than the yield pressure.

Table 1. Compressibility of Allophane and Diatomaceous Soils

Soil	e_o	C_c	$C_c/(1+e_o)$	C_r
Santa Barbara	2.750	1.23	0.33	0.050
Chillán	3.730	1.53	0.32	0.050
Diatom—sample A	2.236	1.0	0.31	0.065
Diatom—sample B	1.471	0.70	0.28	0.035

Table 2. CIU Triaxial Tests on Undisturbed Samples of Volcanic Ash Soil

Test	Effective confining pressure (kPa)	Dry density, γ_d (kN/m^3)	Initial water content, w (%)
Ch1	50	5.49	97.9
Ch2	60	5.79	107.2
Ch3	100	5.39	124.2
Ch4	150	5.79	87.3
Ch5	200	5.59	124.2
Ch6	400	5.20	124.2
SB1	50	6.77	79.5
SB2	100	6.96	78.1
SB3	100	6.28	93.5
SB4	200	6.77	80.7
SB5	300	6.86	78.1
SB6	400	7.06	80.7

Note: Ch: Chillán; SB: Santa Barbara.

The soil structure developed in soils is reflected to some extent by their sensitivity. To evaluate this index property, remolded specimens were prepared with the remaining soil from the "undisturbed" specimens. The soil was strongly kneaded inside a plastic bag for a period of 30 min and then compacted to the same density as the "undisturbed" specimens. The resulting values of sensitivity were 3 and 13 for Santa Barbara and Chillán, respectively. The Chillán volcanic clay, thus, shows clear evidence of the importance of the structure created by the weathering process.

The shear strength was investigated through CIU triaxial tests using undisturbed samples. The test conditions are indicated in Table 2, and the results are presented as stress-strain, pore water pressure, and effective stress path curves in Figs. 6 and 7. All samples consolidated below the yield pressure consistently show a moderate contractive response with some dilation at large strains, whereas those samples consolidated at higher pressure drastically change to a fully contractive response, with a small drop in strength. This significant difference in behavior caused by the mechanical action of the confining pressure is similar to that observed in common mechanically preconsolidated sedimentary fine-grained soils. At stress levels below the yield pressure, a cohesive component of strength is observed, which must be a true cohesion associated with the bonds developed by weathering. The existence of this cohesion is confirmed by the regular presence of permanent, almost vertical, slopes several meters in height seen in the south of Chile where the presence of volcanic ash soils is evident. Similar conclusions regarding the existence of very substantial saturated steep slopes in these soils have been reported by Wesley (1973, 1990). It is important to note that the friction angle above the yield pressure is unusually high, 39 and 43 deg for Santa Barbara and Chillán samples, respectively. This is unusual, considering that these materials have PI greater than 35, LL greater than 100, and void ratios above 2.7. These high values

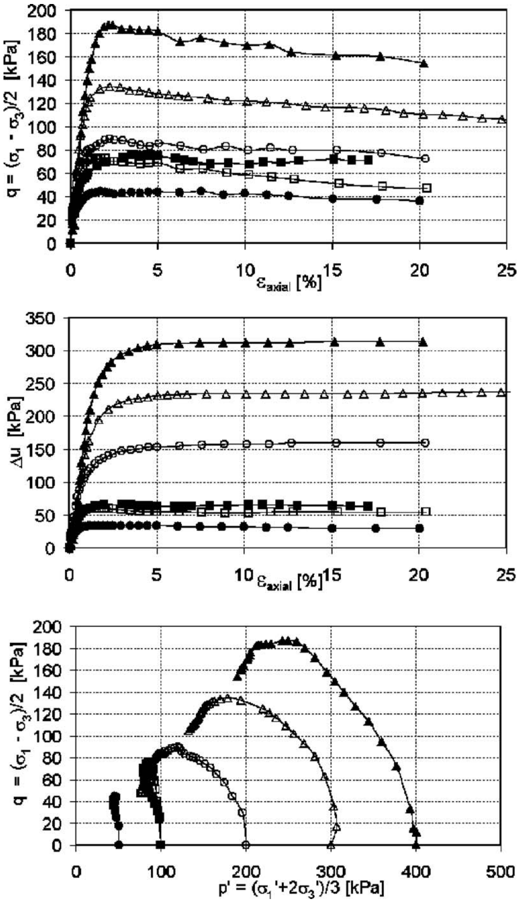

Fig. 6. Triaxial test results on undisturbed specimens of Santa Barbara volcanic ash soil

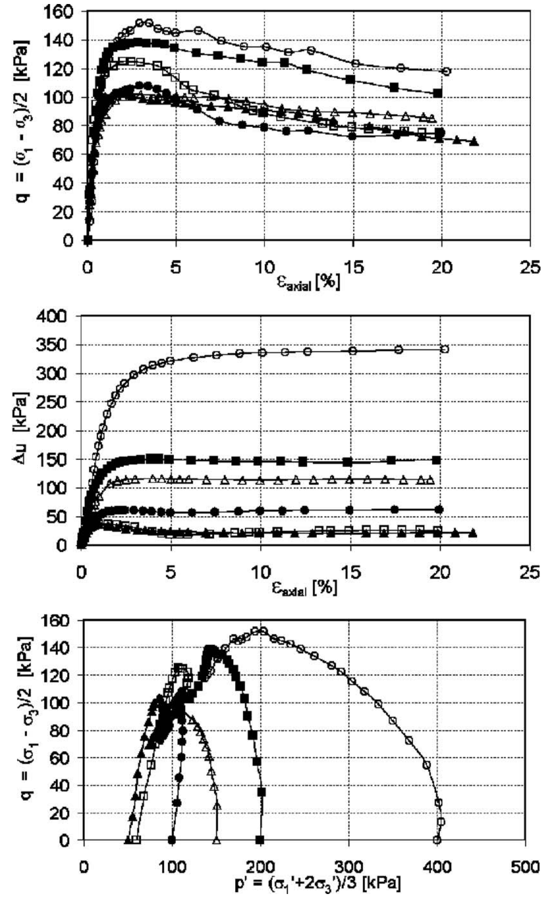

Fig. 7. Triaxial test results on undisturbed specimens of Chillán volcanic ash soil

may be caused by the "reinforcing effect" of the thread-shaped imogolite particles.

In view of the significant reduction in the static strength caused by remolding, it was decided to investigate the effect of cyclic loading on these soils. A series of undrained cyclic triaxial tests was performed at two different consolidation pressures, below and above the yield pressure. The results are presented in Fig. 8, in terms of cyclic stress ratio and number of cycles to induce 100% pore water pressure build up. The results demonstrate the dramatic effect of the confining pressure on the cyclic strength. They indicate that for initial confining pressures below the yield pressure, the cyclic strength is significantly high, and even for strong earthquakes, liquefaction would not occur. On the other hand, when these soils are subjected to confining stresses above the yield pressure, the cyclic strength is unexpectedly low and comparable with the liquefaction resistance of a medium to dense sand. The reduction of the cyclic strength as the confining pressure increases, is an effect that has been taken into account through the factor K_σ introduced by Seed (1983). For samples tested at a confining pressure of 300 kPa, and considering the cyclic strength developed at 20 cycles of loading, this factor K_σ takes values of 0.58 and 0.45 for Santa Barbara and Chillán, respectively. The reduction of cyclic strength in these materials is, thus, significantly larger than that reported by other researchers for sandy soils (Seed and Harder 1990).

To complement the geotechnical information obtained for these allophane soils, shear wave velocities in both "undisturbed" and remolded samples were measured by means of bender elements mounted in a triaxial chamber following the procedure developed at Norwegian Geotechnical Institute (NGI) (Dyvik and Madshus 1985). The measured shear wave velocities as a function of the isotropic consolidation pressure are presented in Fig. 9. The influence of soil structure is clearly reflected in the behavior of the undisturbed samples; the initial section shows a high shear wave velocity and a change of gradient at a stress approaching 150 kPa (the "yield" pressure). This change in behavior is not observed in the remolded samples, which present a linear increase of the shear wave velocity with the confining pressure on a log scale.

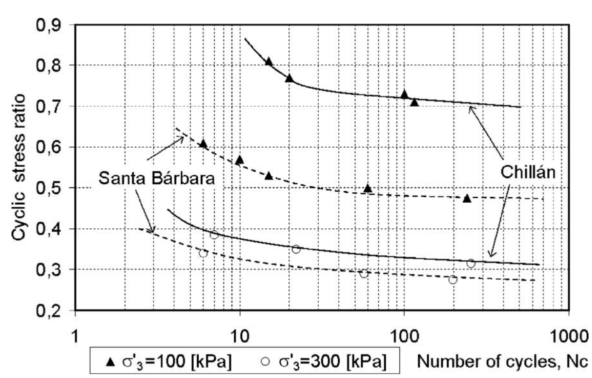

Fig. 8. Effect of confining pressure on cyclic strength of undisturbed specimens of Chillán and Santa Barbara volcanic ash soils

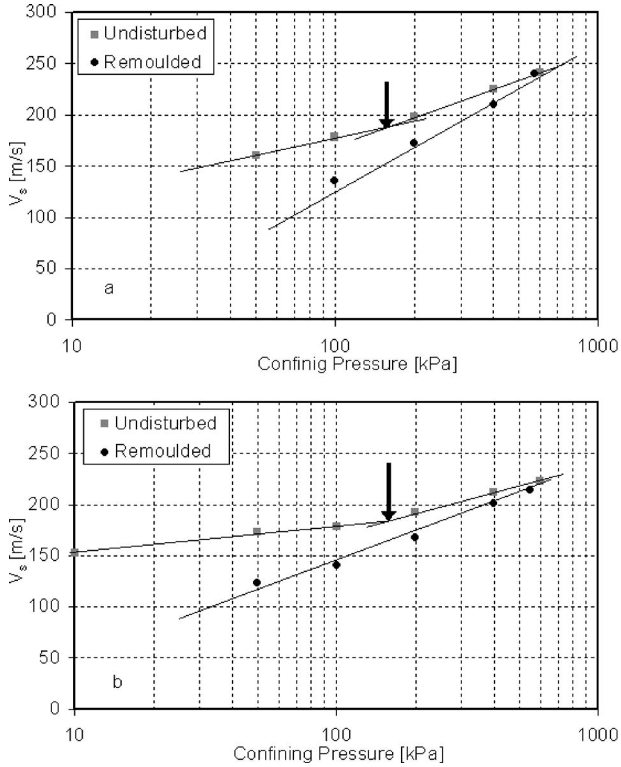

Fig. 9. Shear wave velocities measured on undisturbed and remolded samples on (a) Santa Barbara; (b) Chillán volcanic ash soils

Experimental Results of Diatomaceous Soil

The diatomite tested shows very low plasticity; average values of plastic and liquid limits of 55 and 60, respectively, were obtained. This classifies the diatomite as a silty soil of high compressibility. The particle morphology of some of the diatoms existing in the samples is shown in Fig. 10. The energy dispersive X-ray (EDX) spectrum analysis presented in Fig. 11 indicates that around 90% of the minerals in this soil consist of silica, indicating that diatoms are the main component of this soil. At the same time, it is of interest to note that other investigations have reported diatomaceous earth ranging from nonplastic (Shiwakoti et al. 2002) to clay of high plasticity (Volpi et al. 2003). This difference is attributed to the presence of clay minerals other than silica in the diatomaceous soil. Specific gravity measurements on the tested diatoms gave a value of 2.15. To evaluate the compaction behavior of the samples, a modified Proctor test was performed. A maximum dry density of 10.59 kN/m^3 (1.08 t/m^3) and an optimum water content of 42% were obtained. Similar results have been reported by Khilnani and Capik (1989). This low value of dry density is attributed to the porous particles, which are rarely found in common sedimentary soils.

The results of two consolidation tests carried out on "undisturbed" specimens are presented in Fig. 12. Regardless of the initial void ratio, both samples show a clear preconsolidation pressure at approximately 800 kPa. The resulting values of C_c and C_r are presented in Table 1. These measured values of C_c are normally associated with soils of high compressibility. However, as was observed with allophane soils, the values of the factor α are slightly larger than those of sedimentary soft clay. It is interesting to note that for Mexico clay, which contains about 20 to 30% of volcanogenic silica and 55 to 65% of diatoms, the value of α is in the range of 0.7 to 1.0 (Mesri et al. 1975). This much higher compressibility may be associated with the coexistence of allophane and diatom.

The measured high values of preconsolidation pressure can possibly be attributed to the geological history of the site. However, another possible explanation for this clear change in the compressibility at about 800 kPa is a breakdown point caused by particle crushing, considering that individual particles are likely to be weak because of their porous nature. To investigate this possibility, an additional consolidation test on a remolded specimen was carried out where no possible effect of geological history could exist. The result of this test is also presented in Fig. 12. The use of a semilog scale has been intentionally avoided because its mathematical nature may result in misinterpretation of the true behavior of the soil (Verdugo 1992; Wesley 1994). The consolidation curve of the remolded sample shows a total absence of any breakdown point, indicating that for the range of pressure used, there is no evidence of any particular level of pressure at which particle crushing can be identified. In contrast, "undisturbed" samples show a sharp change in compressibility at 800 kPa, which represents a preconsolidation pressure. This behavior suggests that in the range of pressure used in these tests, diatom particles do not present a threshold pressure associated with significant crushing.

To evaluate the shear resistance of diatoms, CIU triaxial tests were performed on "undisturbed" and remolded samples. The stress-strain curves, pore water pressure change, and effective stress paths of "undisturbed" samples are presented in Fig. 13, and in Table 3, the test conditions are indicated. For the range of confining pressures used in these tests, it is seen that although the dry density of some samples is as low as 8.83 kN/m^3 (0.9 t/m^3), the response is essentially dilative. Interpreting these results with an initial failure envelope associated with a preconsolidated stage, the resulting shear strength parameters correspond to $c'=40$ kPa and $\phi'=45$ deg. In contrast to the above, experimental results on reconstituted specimens prepared with initial dry densities of 5.10, 5.88, and 8.83 kN/m^3 (0.52, 0.60, 0.9 t/m^3) were obtained. These dry densities are related to degrees of compaction of 48, 56, and 83%, respectively. Typical results are presented in Fig. 14. It is interesting to observe that even loose samples with a dry density of 5.88 kN/m^3 (0.6 t/m^3) all show effective stress paths with an "elbow," or phase transformation point, indicating dilation from a medium level of strain. For the three densities used in these tests, angles of internal friction of 35.2, 37.8, and 49.0 deg were obtained, suggesting high resistance between particles; this is likely to be connected to the high angularity, sharpness, and hardness of the diatom particles. What is more, over the rather wide range of confining pressures used in these tests, the failure envelope is clearly not curved, indicating high mechanical strength of the diatom particles, even though they contain a significant quantity of inner pores. This suggests that the diatom particles themselves consist of a strong siliceous skeleton that keeps the inner voids stable. This suggests that when saturated, the water inside the particles is mechanically inert, and does not affect the pore water pressure generated in the interstices between particles and interaggregate. It, therefore, does not influence the effective stress.

In order to investigate the soil properties at small strains, shear wave velocities on reconstituted samples compacted at two different densities were measured, the results of which are presented in Fig. 15. It can be seen that a common bilinear relationship exists between shear wave velocity and confining pressure on a logarithmic scale. However, the values of the shear wave velocity are

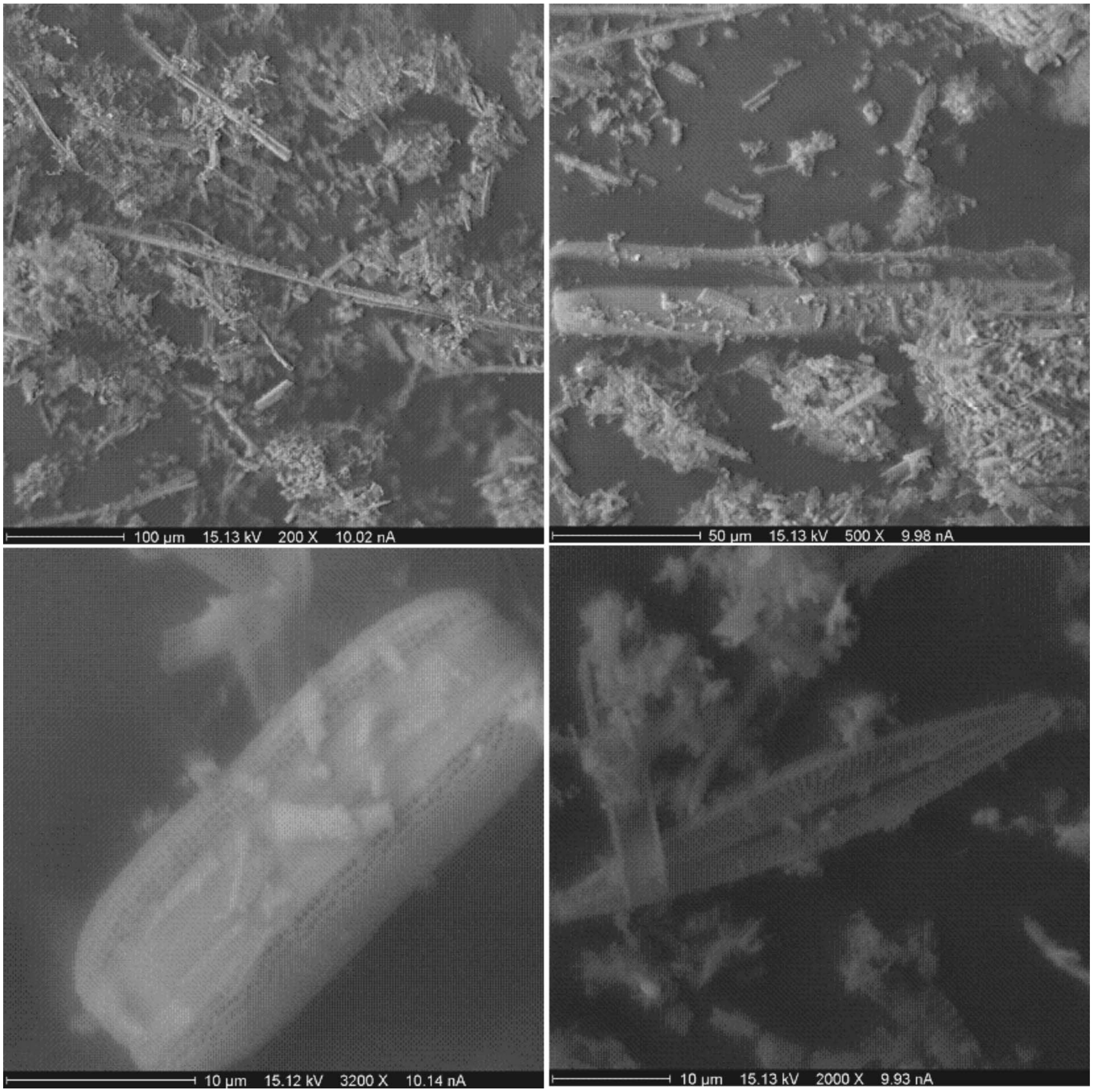

Fig. 10. Particle shape of diatomaceous soil of this study

moderately small in relation to other similar silty soils. The diatomaceous soil tested would, therefore, tend to behave, under seismic waves, with a similar stiffness to normally consolidated soft clays.

An interesting series of experimental results using mixtures of diatomite-kaolin, diatomite-Singapore clay, and Toyoura-kaolin has been reported by Shiwakoti et al. (2002), showing that the addition of diatoms greatly increases the frictional strength of the soils. Data from Japanese natural fine soils also show friction angles consistently greater than the estimation proposed by Kenney (1959) and Bjerrum and Simons (1960) for conventional clays free of diatoms. According to the data presented in this study, the increase in the friction angle of Japanese soils could be caused by the presence of either diatoms, or allophanes, or both.

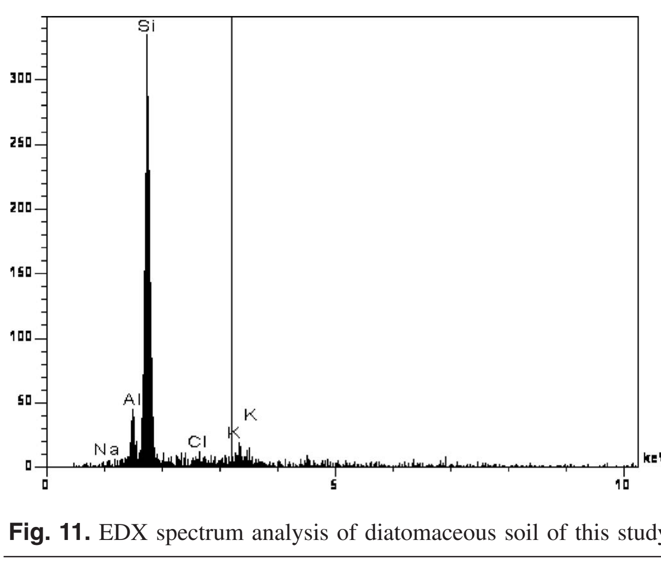

Fig. 11. EDX spectrum analysis of diatomaceous soil of this study

Natural Coexistence of Diatoms and Allophanes

In view of the fact that soils containing allophane and diatomite material originate from a common volcanic environment, it is

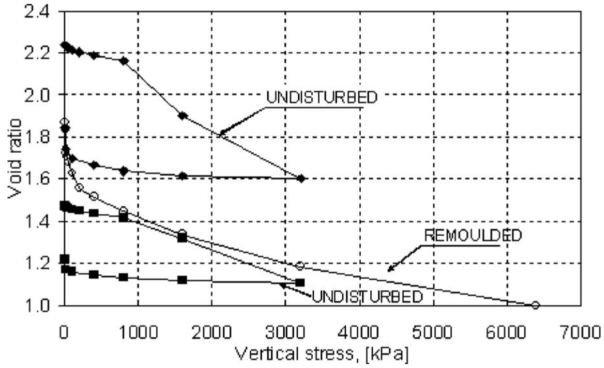

Fig. 12. Consolidation results of diatoms on undisturbed and reconstituted specimens

likely that natural soil deposits occur in which these two soil types coexist in various proportions, depending upon the different geological scenarios of deposition. Sampling and analysis of the sediments of two different lakes in the south of Chile has shown the existence of laminated clayey sediments rich in diatoms and thin tephra layers dominated by amorphous materials, consisting mainly of volcanic glass and noncrystalline clays (Bertrand et al. 2003). Another example, well known for its singular geotechnical properties is the clay of Mexico City, where the upper part comprises highly compressible volcanic silty clays of fine volcanic ash, with a large percentage of diatoms, in the range of 55 to 65% (Mesri et al. 1975; Zeevaert 1991; Diaz-Rodriguez et al. 1998). This material shows sensitivity as large as 20, natural water content up to 400%, and a drained strength controlled by friction angles in the range of 30 deg (Zeevaert 1991). Exhibiting the same behavior as the allophane soils tested in this study, Mexico City clay is described by Zeevaert (1991) as typical of clay belonging to the preconsolidated category. For shallow layers, the observed preconsolidation pressure (yield pressure) is in the range of 90 to 120 kPa.

Table 3. CIU Triaxial Tests on Undisturbed Samples of Diatomaceous Soil

Test	Effective confining pressure (kPa)	Dry density, γ_d (kN/m^3)	Initial water content, w (%)
1	50	8.92	25.0
2	100	9.12	22.7
3	150	11.67	9.45

Another important example of a soil deposit that contains a significant amount of diatomite is the Osaka Bay clay where the Kansai International Airport of Japan has been constructed. Tanaka and Locat (Tanaka and Locat 1999; Locat and Tanaka 2001) have reported a comprehensive study of this material, concluding that the presence of microfossils has a notable impact on

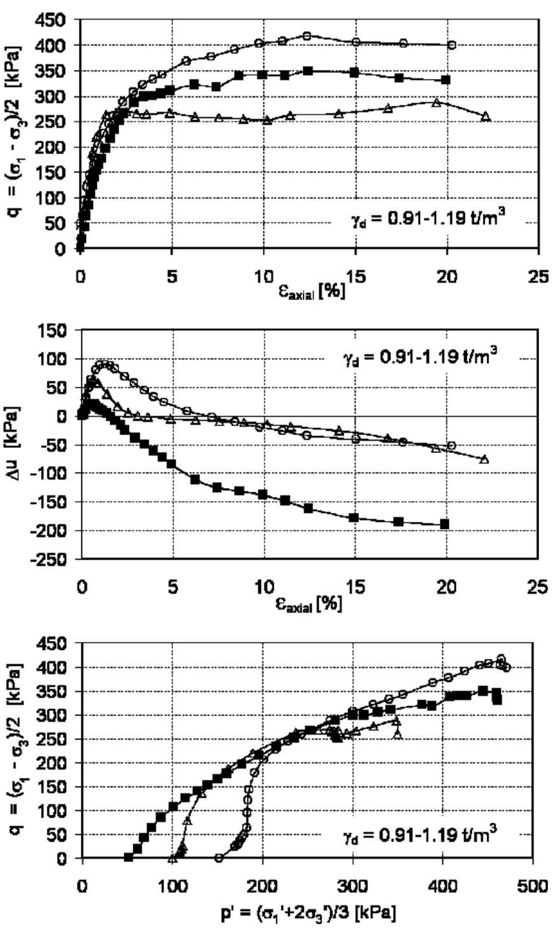

Fig. 13. Stress-strain curves, pore pressure, and effective stress paths obtained on CIU triaxial tests on undisturbed specimens of diatomite ($1\ t/m^3 = 9.8\ kN/m^3$)

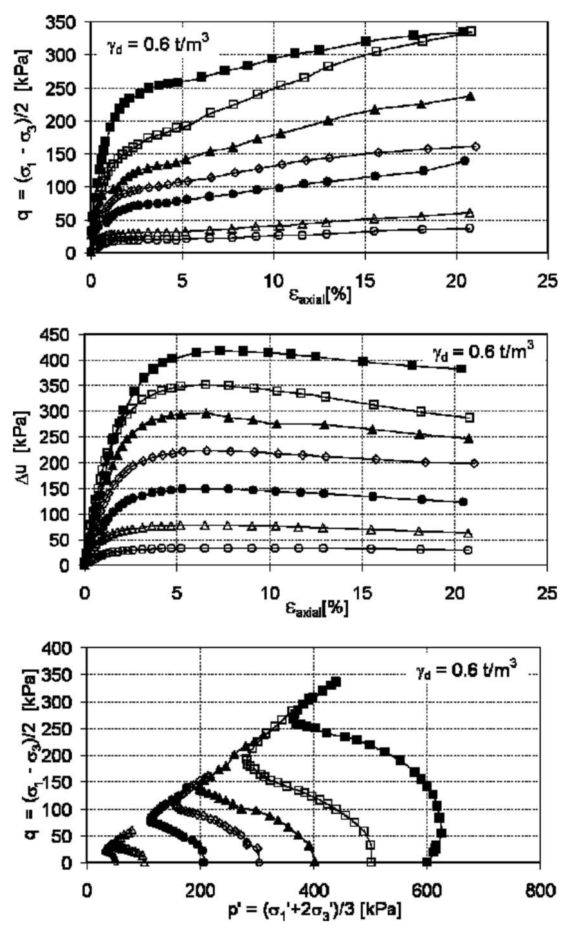

Fig. 14. Stress-strain curves, pore pressure, and effective stress paths obtained in CIU triaxial test on reconstituted specimens of diatomaceous soil ($1\ t/m^3 = 9.8\ kN/m^3$)

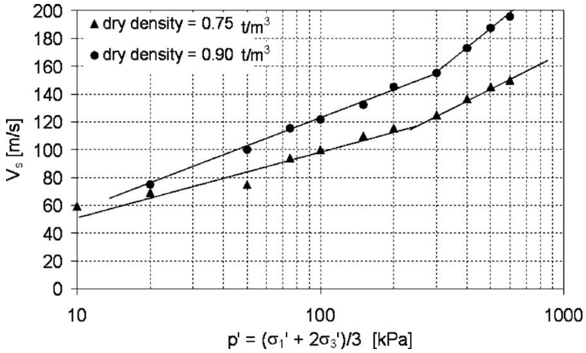

Fig. 15. Effect of density on shear wave velocity on reconstituted specimens of diatomaceous soil (1 t/m^3=9.8 kN/m^3)

the index properties as well as in the compressibility. In addition, considering the high volcanic activity that occurs throughout Japan, and the evidence of ash content in shallow waters in the central coastal region (Nagao et al. 2001), it is reasonable to expect the presence of volcanic ash in this soil deposit too. This soil deposit has been formed by sediment carried by rivers, and although the geological conditions are associated with a normally consolidated clay, all the experimental data indicate that this soil exhibits slight overconsolidation, typically characterized by an overconsolidation ratio of around 1.5 (Watabe et al. 2002). The results of consolidation tests consistently show a yield pressure in the case of shallow samples in the order of 200 kPa, values that are in the same range as allophane soils.

Another soil deposit known to contain diatoms is the San Francisco Bay mud. This is not surprising considering that for nearly 800 km along the California coast ranges, the Monterey formation, a marine diatomaceous unit, is extensively exposed. This unit is up to 2,000 m thick and consists mainly of biogenic silica (diatom), carbonate, detrital sediment, and volcanic ash (Barron 1987). The largest commercial diatomite deposits in the world are near Lompoc, California (Moyle and Dolley 2003). In addition to this, if the existence of the Sonoma volcanic complex is taken into account, then the presence of volcanic ashes in San Francisco Bay mud is to be expected. The upper 6 to 12 m of this clay, the so-called Young Bay mud, is described as marine sediments that consist of very soft clays and silts, normally consolidated, highly plastic, with a high compressibility, and dry densities ranging from 13.14 to 16 kN/m^3 (1.34 to 1.63 t/m^3). For this material, a sensitivity of eight has been reported by Duncan and Seed (1966). Undrained triaxial tests carried out on "undisturbed" samples of this material have been reported by Kirkgard and Lade (1991). The tested soil consisted of 55% silt and 45% clay, with a LL of 85 and a PI of 37. The triaxial tests indicate frictional angles at failure greater than 40 deg for consolidation pressures below 100 kPa, values that are substantially higher than the prediction given by Bjerrum and Simons (1960). Additionally, for the Young Bay mud, Stokoe and Lodde (1978) reported degradation curves of shear modulus as a function of shear strain that are well above the curves reported for sand and clay of similar PI.

Conclusions

The main distinctive geotechnical characteristics of soils containing diatom and allophane imogolite have been presented and discussed. Although these two soils appear to be quite distinct, they in fact have two important characteristics in common, namely, their environmental genesis and the porous nature of their particles. Allophane-imogolite soils have remarkably high void ratios, typically in the range of 2 to 6, and develop a soil structure characterized by a yield pressure resulting from the chemical weathering of the parent volcanic soil. The volcanic ash tested showed a yield pressure around 150 kPa. Below this pressure, the behavior is generally moderately contractive with some dilation, while above the yield pressure, the soil becomes totally contractive. The Atterberg limits, Proctor density, and grain size curves are strongly affected by drying, so all properties must be evaluated without any unnatural drying. Over a wide pressure range, the ϕ' value of the soils tested ranged from 39 to 43 deg, which is unexpectedly high when compared with sedimentary soils of similar density and PI. The "undisturbed" samples of diatom soil showed a clear preconsolidation pressure of about 800 kPa, and remolded samples tested at stresses up to 3.2 MPa did not present any particular stress point that could be associated with significant particle crushing. This result suggests that diatom particles are of high strength, at least up to the stress level used in the tests. Triaxial tests on "undisturbed" diatom samples with dry densities as low as 8.83 kN/m^3 (0.9 t/m^3) show an essentially dilative response. The resulting shear strength parameters were $c'=40$ kPa and $\phi'=45$ deg for the preconsolidated stage. In addition, over the rather wide range of confining pressure used in these tests, curvature in the failure envelope was definitely not observed, indicating high mechanical strength of the diatom particles. This means that when saturated, the water inside the particles is mechanically inert, and does not affect the pore water pressure generated in the interstices between particles and interaggregate. In contrast to the shear strength, shear wave velocities were low, and in the range of normally consolidated clays.

While diatoms and allophone-imogolite soils normally exist as separate entities, their common volcanic origin means they may also coexist in certain geological conditions. Such soils are likely to have very unusual properties, and be associated with areas of high seismic activity. The most outstanding example of such a soil is Mexico City clay.

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References

Antonides, L. E. (1997). "Diatomite." *United States geological survey, mineral year book 1997*, 24.1–24.6.

Barron, J. A. (1987). "Diatomite-environmental and geologic factors affecting its distribution." *Siliceous sedimentary rock-hosted ores and petroleum*, J. R. Hein, ed., Van Nostrand Reinhold, New York, 164–178.

Bertrand, S., et al. (2003). "Holocene sedimentation in Icalma and Puyehue lakes (Southern Chile): Instantaneous vs continuous records." *X Chilean Geological Congress*, Concepción.

Besoain, E. (1985). *Volcanic soils of Chile*, J. Tosso, ed., Instituto de Investigaciones Agropecuarias, Chile (in Spanish).

Bjerrum, L., and Simons, N. E. (1960). "Comparison of shear strength characteristics of normally consolidated clays." *No. 35*, Norwegian Geotechnical Institute Publication, 13–22.
Brownlee, C., and Taylor, A. R. (2002). "Algal calcification and silification." *Encyclopedia of life science*, MacMillan Publishing Group, ⟨www.els.net⟩.
Collins, K., and McGown, A. (1974). "The form and function of microfabric features in a variety of natural soils." *Geotechnique*, 24(2), 223–254.
Cradwick, P. D. G., Farmer, V. C., Russel, J. D., Masson, C. R., Wada, K., and Yoshinaga, N. (1972). "Imogolite, a hydrated aluminium silicate of tubular structure." *Nature (London), Phys. Sci.*, 240, 187–189.
Delage, P., and Lefebvre, G. (1984). "Study of the structure of a sensitive Champlain clay and of its evolution during consolidation." *Can. Geotech. J.*, 21(1), 21–35.
Diaz-Rodriguez, J. A., Lozano-Santa Cruz, R., Davila-Alcocer, V. M., Vallejo, E., and Giron, P. (1998). "Physical, chemical and mineralogical properties of Mexico City sediments: A geotechnical perspective." *Can. Geotech. J.*, 35, 600–610.
Duncan, J. M., and Seed, H. B. (1966). "Anisotropy and stress reorientation in clay." *J. Soil Mech. and Found. Div.*, 92(5), 21–50.
Dyvik, R., and Madshus, C. (1985). "Lab measurements of $G_{\max}$ using bender elements." *Proc., ASCE Annual Conv. on Advances in the Art of Testing Soils under Cyclic Conditions*, 186–196.
Kenney, T. C. (1959). "Discussion of 'Geotechnical properties of glacial lake clays,' by T. H. Wu." *J. Soil Mech. and Found. Div.*, 85(3), 67–79.
Khilnani, K., and Capik, M. L. (1989). "Diatomaceous soils: A new approach." *Civ. Eng. (N.Y.)*, 59(2), 68–70.
Kirkgard, M. M., and Lade, P. V. (1991). "Anisotropy of normally consolidated San Francisco Bay Mud." *Geotech. Test. J.*, 14(3), 231–246.
Locat, J., and Tanaka, H. (2001). "A new class of soils: Fossiliferous soils?" *Proc., Fifteenth Int. Conf. on Soil Mechanics and Geotechnical Engineering*, Vol. 3, 2295–2300.
MacKenzie, K. J. D., Bowden, M. E., Brown, I. W. M., and Meinhold, R. H. (1989). "Structure and thermal transformations of imogolite studies by ^{29}Si and ^{27}Al high-resolution solid-state nuclear magnetic resonance." *Clays Clay Miner.*, 37(4), 317–324.
Mesri, G., Rokshar, A., and Bohar, B. F. (1975). "Composition and compressibility of typical samples of Mexico City clay." *Geotechnique*, 25, 527–574.
Mitchell, J. K., and Soga, K. (2005). *Fundamentals of soil behavior*, 3rd Ed., Wiley, New York.
Moyle, P. R., and Dolley, T. P. (2003). "With or without salt—A comparison of marine and continental-lacustrine diatomite deposits." *Bulletin No. 2209-D*, Contributions to Industrial-Minerals Research, U.S. Geological Survey, available online at ⟨http://pubs.usgs.gov/bul/b2209-d/⟩.
Nagao, N., Toda, T., Takahashi, K., Hamasaki, K., Kikuchi, T., and Taguchi, S. (2001). "High ash content in net-plankton samples from shallow coastal water: Possible source of error in dry weight measurement of zooplankton biomass." *J. Oceanogr.*, 57, 105–107.
Paredes, M. (2005). "Geotechnical behavior of volcanic ash soils." MS thesis, Dept. of Civil Engineering, Univ. of Chile (in Spanish).
Seed, H. B. (1983). "Earthquake-resistance design of earth dams." *Proc., Seismic Design of Embankments and Caverns*, ASCE, New York, 41–64.
Seed, R. B., and Harder, L. F. (1990). "SPT-based analysis of cyclic pore water pressure generation and undrained residual strength." *Proc., H. Bolton Seed Memorial Symp.*, BiTech Publishers, Ltd., Vancouver, Canada, 351–376.
Shiwakoti, D., Tanaka, H., Tanaka, M., and Locat, J. (2002). "Influence of diatom microfossils on engineering properties of soils." *Soils Found.*, 42(3), 1—17.
Stokoe, K. H., and Lodde, P. F. (1978). "Dynamic response of San Francisco Bay mud." *Proc., Earthquake Engineering and Soil Dynamics*, Vol. 2, ASCE, New York, 940–959.
Tanaka, H., and Locat, J. (1999). "A microstructural investigation of Osaka Bay clay: The impact of microfossils on its mechanical behavior." *Can. Geotech. J.*, 36, 493–508.
Verdugo, R. (1992). "Discussion of 'The critical state of sands.'" *Geotechnique*, 42(4), 655–658.
Volpi, V., Camerlenghi, A., Hillenbrand, C., Rebesco, M., and Ivaldi, R. (2003). "Effect of biogenic silica on sediment compaction and slope stability on the Pacific margin of the Antarctic Peninsula." *Basin Res.*, 15, 339–363.
Wada, K. (1989). "Chapter 21: Allophane and imogolite." *Minerals in soil environments*, SSSA Book Series No. 1, G. B. Dixon, S. B. Weed, eds., Madison, Wis., 1051–1087.
Wada, S., and Wada, K. (1977). "Density and structure of allophane." *Clay Miner.*, 12, 289–297.
Wallace, K. B. (1973). "Structural behaviour of residual soils of the continually wet highlands of Papua, New Guinea." *Geotechnique*, 23(2), 204–218.
Watabe, Y., Tsuchida, T., and Adachi, K. (2002). "Undrained shear strength of pleistocene clay in Osaka Bay." *J. Geotech. Geoenviron. Eng.*, 128(3), 216–226.
Wesley, L. D. (1973). "Some basic engineering properties of halloysite and allophane clays in Java, Indonesia." *Geotechnique*, 23(4), 471–494.
Wesley, L. D. (1990). "Influence of structure and composition on residual soils." *J. Geotech. Engrg.*, 116(4), 589–603.
Wesley, L. D. (1994). "The use of consolidometer tests to estimate settlement in residual soils." *Proc., XIII ICSMFE*, Vol. 2, 929–934.
Wesley, L. D. (2002). "Geotechnical characterization and behaviour of allophane clays." *Proc., Int. Workshop on Characterisation and Engineering Properties of Natural Soils*, Vol. 2, 1379–1399.
Zeevaert, L. (1991). "Seismosoil dynamic of foundations in Mexico City earthquake, September 19, 1985 the twenty-third Karl Terzaghi lecture." *J. Geotech. Engrg.*, 117(3), 376–428.
Zhang, G., Germaine, J. T., Whittle, A. J., and Ladd, C. C. (2004). "Soil structure of a highly weathered old alluvium." *Geotechnique*, 54(7), 453–466.