Cemented soils: small strain stiffness

Rinaldi, V.A.
Universidad Nacional de Córdoba, 5000, Argentina

Santamarina, J.C.
School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA, U.S.A

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ABSTRACT: Most undisturbed natural soils have experienced some degree of post-depositional digenesis often leading to a cemented structure. Cemented soils display distinctly different characteristics from freshly remolded soils, including high small-strain stiffness, weakened stiffness-stress dependency, higher dilative tendency, stiffness loss after cementation breakage, proneness to strain localization, decreased liquefaction potential, and pronounced sampling effects particularly on small strain stiffness. Unsaturation often coexists with cemented soils, and in some cases the development of cementation is linked to diminishing saturation. At the microscale, the behavior exhibited by cemented soils can be analyzed in terms of simple yet robust micromechanical concepts to create a coherent physical-mechanical framework that explains deviations from the conventional understanding of soil behavior which centers on effective stress dependent stiffness. In view of cemented soils, proper site characterization must consider in situ measurements of shear wave velocity, and careful sampling techniques.

1. INTRODUCTION

The conventional understanding of soil behavior is founded on the principle of effective stress, and on the effective stress dependent frictional strength, stiffness, and volume change. Such understanding of soil behavior implicitly assumes a "freshly remolded soil". However, soils are not inert and digenesis can render different degrees of cementation, ranging from lightly cemented soils to rocks such as shales and sandstones. In addition, several soil improvement techniques involve the addition of cementing agents, like lime and Portland cement.

Cemented soils can exhibit properties that are very distinct from those of the original uncemented soil or the freshly remolded one. There is an increasing body of evidence that shows that cementation can have an important effect on small strain stiffness, threshold strain, volume change behavior, drained and undrained strength, deformation field, and dynamic phenomena such as liquefaction. Those results highlight the critical role that even light cementation can play on the static and dynamic performance of geosystems, and underscore the need to recognize cementation in design.

The small strain behavior of cemented soils is reviewed herein, starting with cementation agents and processes. Then, the observed small-strain response of cemented soils is surveyed to identify salient trends which are analyzed in terms of simple yet robust micromechanical concepts to create a coherent physical-mechanical framework.

2. CEMENTATION AND DEBONDING

Various digenetic mechanisms are involved in the post-depositional modification of soils (Bennet et al. 1991; Mitchell 1993). These include thermal processes (thermo-osmosis and thermal cyclic loading), mechanical processes (e.g., preloading, vibration, moisture fluctuations, clay migration and flocculation at contacts between coarse grains, yielding and creep at interparticle contacts), and chemical processes (e.g., dissolution and re-precipitation, mineral transformation, carbonation, oxidation, weathering, thixotropic hardening, salt leaching as in quick clays, ion exchange, and formation or addition of a dispersing agent).

Geo-chemical reactions such as dissolution, oxidation-reduction, and mineral precipitation are often facilitated or mediated by biological activity, allowing for much higher reaction rates (Ehrlich 1998; Chapelle 2001; Mitchel and Santamarina 2005; limitations in Rebata-Landa and Santamarina 2006). Bacteria are the dominant microorganisms in soils. Clear evidence of microbiological activity during soil formation is found in the fossil record (e.g., diatoms in Mexico city soils and Arike clay).

Soil particles may become bonded or cemented as the result of diagenetic process (process sometimes referred to as "structuration" – Leroueil and Vaughan 1990). The cementing agent may be present around particles, at particle contacts and precipitated in the pore space forming nodules. The type and amount of cementation, and its often uneven spatial distribution at small and large scales play an important role in the mechanical behavior of the cemented soil. The most abundant cementing agent in semi-arid regions is calcium carbonate, followed by oxides (Reeves 1976). The solubility of well-crystallized Si-minerals in water or acids is very low (e.g., quartz); however, even well crystallized quartz can develop cementing reactions if ground into a fine powder (specific surface 1 m^2/gr - Benezet and Benhassaine 1999). On the other hand, amorphous Si-minerals (e.g., volcanic glass in loess) or slightly crystallized Si-minerals (e.g., weathering products from feldespars, colloidal gels and zeolites) react with alkaline water to form strong cements that consist of aluminates and hydrated calcium silicates (Quintana et al. 2000); the resulting contact can be very strong (Feda 1982). The pH in these soils ranges from 8 to 10 (e.g., Argentinean loess and Mexico City soils).

While long periods are often associated with digenetic effects, important changes often take place in soils even within few hours. This is the case of thixotropic effects in clayey media as well as sandy soils after high-energy ground modification (Mitchell 1960 and 2008, Mewis 1979; Díaz-Rodríguez and Santamarina 1999). These mechanisms are not readily reproducible in the laboratory (Mitchell 1986).

Two cementation-loading formation histories can be distinguished (Figure 1): cementation-before-loading and loading-before-cementation. The effect of the cementation-loading history is relatively small on the attained stiffness (slightly higher for the case of loading-before-cementation). However its impact on the ability of the cementation to survive load removal and sampling is very different. Consider the case of cementation-before-loading (Figure 1-a): both the cement and the particle develop compressive stresses in response to the applied load; when the load is removed, the stresses vanish. In the case of loading-before-cementation (Figure 1-b; typical formation history in fast depositional environments), the grain contact is compressed but the cement is not; when the load is removed, the contact stretches and tensions the cement, which may break. Therefore, the case of loading-before-cementation is most sensitive to sampling. (Note: the stress induced in the cement layer depends on the relative stiffness between the mineral contact and the cementing agent).

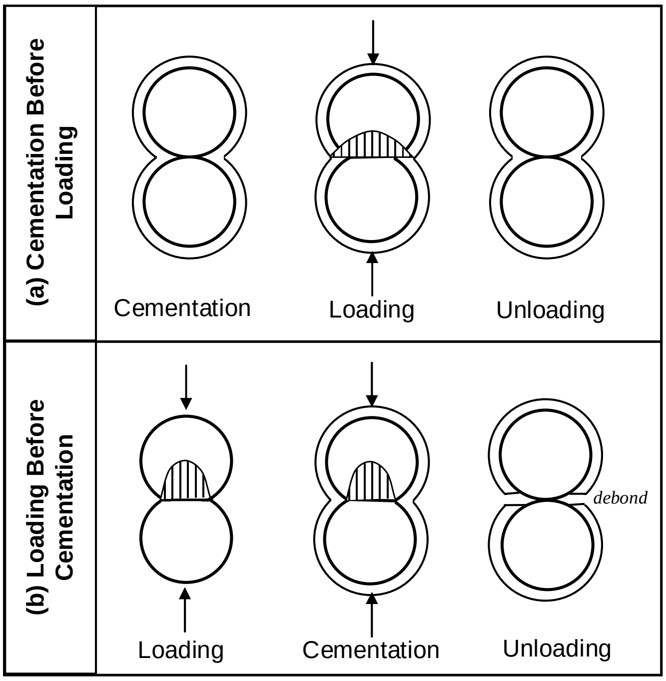

Fig. 1 Two different cementation-loading histories. Shaded parabolas denote stressed region at contact (see Fernandez and Santamarina 2001)

Laboratory studies of cemented soils have often involved artificially cemented soils prepared with cementing agents such as lime, gypsum, and Portland cement. The soil and the cement are mixed at a predetermined moisture content and compacted to the target density within molds. In most cases hardening takes place within the mold, then, cemented specimens are placed in the testing device (cementation-before-loading). Sometimes, the specimen is prepared by placing the fresh soil-cement mixture in the final device, e.g., triaxial cell, confined, and left to cure under constant effective confinement before testing (loading-before-cementation).

Debonding or dececementation results when the granular skeleton is strained or when the cementing substance is dissolved. Strains may be caused by changes in interparticle forces of any kind: capillary forces (expansion, saturation collapse, desiccation shrinkage), electrical forces in relation to pore fluid chemistry (both shrinkage and swelling), and interparticle skeletal forces (isotropic loading or unloading including the effects of heating or freezing, deviatoric loading, cyclic loading and fatigue). The dissolution of cementation is primarily associated to changes in moisture content (e.g., dissolution of precipitated salts and dispersion of flocculated clay bridges), changes in pH (e.g., dissolution of carbonates when reservoir water acidifies), and low salt concentration fluid flow. Experimental evidence for some of these "destructuration" mechanisms is presented in Leroueil and Hight (2003).

Debonding and particle crushing may take place within the same stress range, for example, when particles are made of the same mineral as the cement; this is the case of carbonate sands. Laboratory tests such as the slaking test, pinhole test, electron microscopy, X-ray diffraction and chemical tests can provide valuable insight related to the type of cementing agents, strength of bonding, solubility and their distribution in the soil mass. Sometimes, the effect of soil structuration and the presence of cemented nodules can be identified by sieve analysis. One test is run on a fully destructured specimen; the other test is run by placing a structured specimen on top of the coarsest sieve of the series and gently washing it until the water leaving the bottom sieve #200 has not fines in suspension (the test must be run with properly buffered and salt saturated water to prevent dissolution). Figure 2 shows sieve data for a lightly cemented loess: the difference between the grain size distribution curves highlights the presence of stable cemented nodules that remain after saturation.

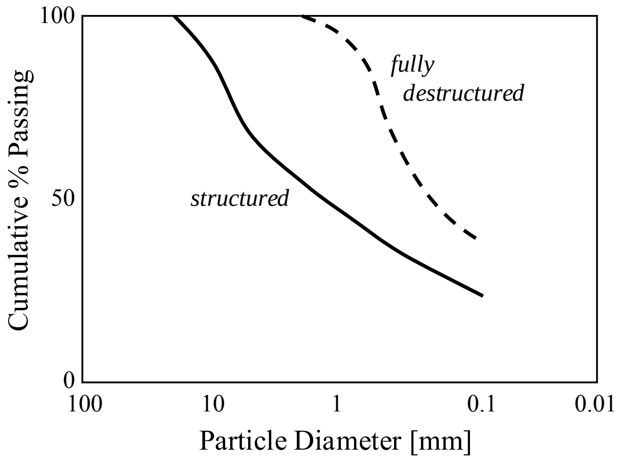

Fig. 2: Grain size distribution of a structured specimen (by washing) and the same soil but fully destructured (Rinaldi and Capdevila 2006).

3. UNSATURATION AND CEMENTATION

Many cemented soils develop in arid to sub-humid climates. High suction and cementation coexist in such formations, and together control the stress-strain behavior of the soil. Capillarity and cementation have a similar impact on the observed macroscale response: increased small-strain stiffness, yield stress and strength, decreased volume contraction during isotropic loading, higher dilative tendency under deviatoric loading, and a higher propensity to localization (Rinaldi and Capdevila, 2006; Cho and Santamarina 2001). A notable distinction is the higher deformation threshold required to break menisci than cementing bonds.

The impact of unsaturation may be removed by testing saturated specimens (Terzaghi and Peck 1948; Walsh 1997). However, this alternative may not be applicable when moisture determines cementation, for example, when excess soluble salts precipitate at interparticle contacts during desiccation, or when moisture reduction causes the migration of fine particles towards contacts followed by their flocculation and the formation of clay bridges (see also Alonso and Gens, 1994).

The combined effects of suction and cementation during soil formation may stabilize the fabric of the soil at a very high void ratio. This is the case of wind-blown sands and loess that form in semi-arid regions (Aitchinson 1973), as well as volcanic ash soils that evolve in situ by the water-mediated digenesis of volcanic ash (Lizcano et al 2006). These soils have very open fabric and are prone to instability and collapse during wetting and/or shear.

4. SMALL-STRAIN BEHAVIOR

The study of the small strain behavior of cemented soils was initially hampered by difficulties in field measurements (now routinely performed with down-hole, cross-hole, and SASW tests), sampling effects (partially overcome by complementary studies with artificially cemented specimens), experimental challenges in performing accurate measurements of stiffness and damping at very small strains (overcome by wave propagation methods using bender elements and resonant column tests), coupling effects between caps and cemented soils in resonant column tests (usually corrected by using epoxy resins), and local deformation near end-caps in triaxial-type devices (corrected with the use of local deformation measurements).

Improved field and laboratory testing methods have led to numerous publications that document small strain measurements, and show the relevance of small-strain stiffness in design.

4.1 Micromechanical Considerations

The small strain stiffness E_{tan} of a granular material depends on the flatness of contacts, as captured in Hertz theory for a system of two spheres (Figure 3-a – see Santamarina et al. 2001 for a detailed discussion of concepts presented in this section)

$$\frac{E_{tan}}{E_g} = \frac{1}{2\left(1-\nu_g^2\right)} \frac{r_c}{R} \tag{1}$$

where E_g and ν_g are Young modulus and Poisson ratio for the mineral that makes the grain, and R and r_c are the particle radius and the radius of the contact area. The contact radius r_c increases proportional to the applied normal stress σ (assuming a simple cubic packing array),

$$r_c = \sqrt[3]{3(1-\nu_g^{\ 2})\frac{\sigma}{E_g}R} \tag{2}$$

A "flatter" contact (i.e., larger r_c) is also attained during diagenesis and cementation. Consider the precipitation of a cementing layer of thickness 't' around contacting particles with a virtually null applied load $\sigma \sim 0$. From trigonometry, the resulting contact radius becomes (Figure 3-b).

$$r_c = \sqrt{(R+t)^2 - R^2} \approx \sqrt{2tR} \tag{3}$$

where the approximation applies for $t \ll R$. A cursory comparison of Equations 2 and 3 reveals that cementation can effectively increase the contact radius and the stiffness of the soil in comparison to mechanical loading (Equation 1).

Semi-empirical velocity-stress power equations capture the stress-dependent nature of shear wave velocity V_S in *uncemented soils*

$$V_S = \sqrt{\frac{G_{max}}{\rho}} = \alpha\left(\frac{\sigma'_{mean}}{1kPa}\right)^{\beta} \tag{4}$$

where α [m/s] is the velocity at 1 kPa confinement, σ'_{mean} is the mean effective stress in the polarization plane and β is the exponent. Typically, α and β parameters are inversely related as $\beta \sim 0.36 - \alpha/700$. Higher β and lower α values apply to soft clays, while dense round sands exhibit the lowest β and highest α values among uncemented soils.

4.2 Small Strain Stiffness During Loading

In the case of *cemented soils*, the previous equations permit predicting the variation of stiffness with the amount of cementation and applied confinement (Figure 3c). Two regions are identified:

- The cementation-controlled region at low stress. In this region, the stiffness is determined by the degree of cementation, and the state of stress has almost no effect on stiffness. Thus, if Equation 4 is fitted to cemented soil data, the α-factor increases with cementation and the β-exponent decreases towards $\beta \to 0$, i.e., stress independent stiffness.
- The stress-controlled region at high stresses, where stiffness increases with confinement as in an uncemented soils.

The cementation-controlled region extends to the yield stress σ_y (discussed later in the text).

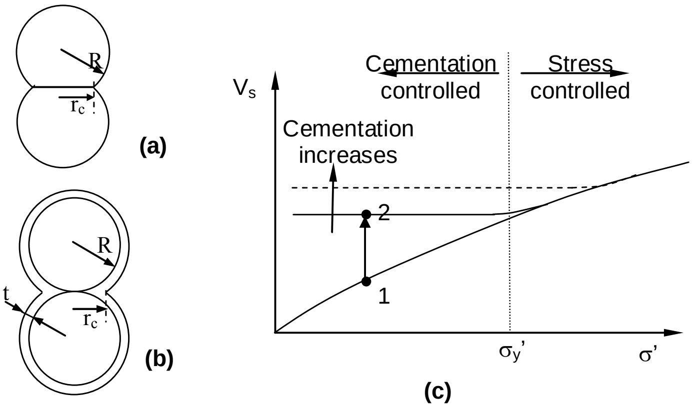

Fig 3: Effect of cementation on the shear wave velocity of soils.

Figure 4 shows the correlation between stiffness and $CaCO_3$ in natural soils. Examples of artificially cemented soils with different amounts of cementation and stress levels can be found in Tan et al. (2003).

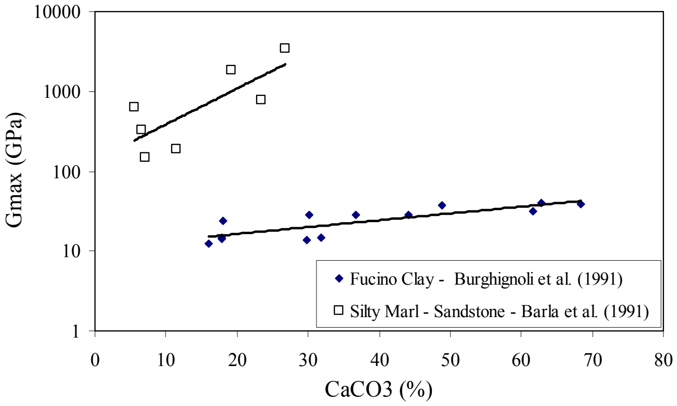

Fig 4: Variation of the maximum shear modulus G_{max} with carbonate content for two natural clays.

Trends measured on sampled natural soils may not necessarily match those sketched in Fig. 3. The case of a naturally cemented, collapsible soil specimen is presented in Figure 5 (Rinaldi and Claria, 1999). The specimen was extracted by block sampling, hand trimmed and loaded in an oedometer cell. The soil is unsaturated, therefore, both P- and S-wave velocities assess the stiffness of the skeleton. Both V_S and V_P increase steeply during recompression as hairline cracks close. Then, the soil collapses under pressure, the soil structure fails and stiffness decreases towards the stress-dependent remolded soil trend (see Yun and Santamarina 2005).

The evolution of the small strain Poisson's ratio ν computed with V_P and V_S is shown on Figure 5 as well; the value remains in the range of ν≈0.15-0.20; this is a typical range for small-strain Poisson's ratio in unsaturated soils.

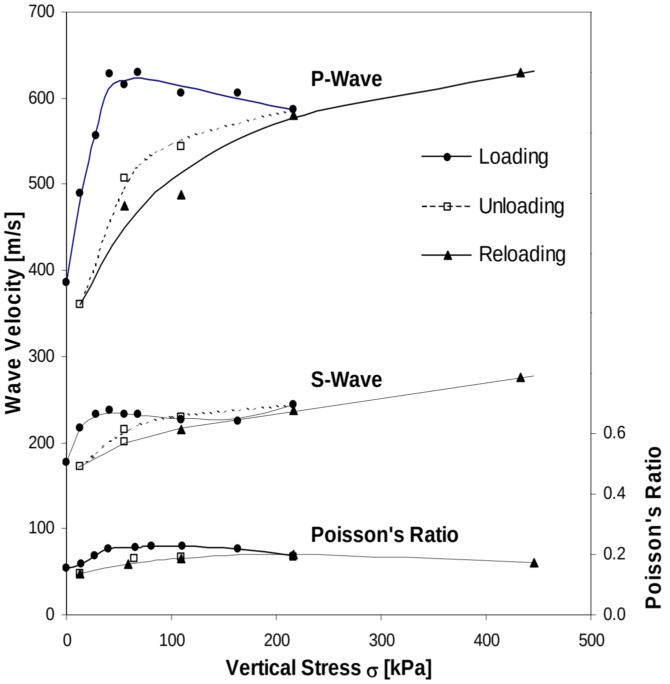

Fig 5: Evolution of compression and shear wave velocities, and Poisson's ratio of lightly cemented Argentinean loess in zero-lateral strain during loading, unloading and reloading (w% = 28 % and e_o ≈ 1 - data from Claria and Rinaldi 2002).

4.3 Stiffness and Strength

Terzaghi and Peck (1948) recognized that the sensitivity of the soil stiffness G to the state of stress increases with the strain level (experimental evidence is shown in Jardin 1994; an analytical expression that combines the hyperbolic formulation and the Coulomb criterion can be found in Santamarina et al. 2001). The variation of the small strain stiffness with stress is $G_{max}=\alpha^2\rho(\sigma_{mean}/kPa)^{2\beta}$ (follows from Equation 4). On the other hand, the large strain stiffness is a measure of the strength, and it is linearly dependent on the state of stress, as prescribed by the Coulomb failure condition $\tau_{ult}=c+\sigma\tan\phi$. Therefore, the stiffness-to-strength ratio becomes

$$\frac{G_{max}}{q_{max}} = \frac{\alpha^2\rho\left(\frac{\sigma}{kPa}\right)^{2\beta}}{c+\sigma\tan\phi} \xrightarrow{c=0} = \psi\left(\frac{\sigma}{kPa}\right)^{2\beta-1} \qquad (5)$$

where ψ combines α, ρ and tanϕ. The small-strain stiffness is plotted vs. strength for various naturally cemented clays in Figure 6 (an alternative compilation can be found in Tatsuoka and Shibuya 1991). For these data, the ratio G_{max}/q_{max} remains between 200 and 700. Yet, individual datasets are not necessarily aligned with the 1:1 bounding lines, as predicted by Equation 5. Inclined lines for various β-exponents are shown for reference in Figure 6.

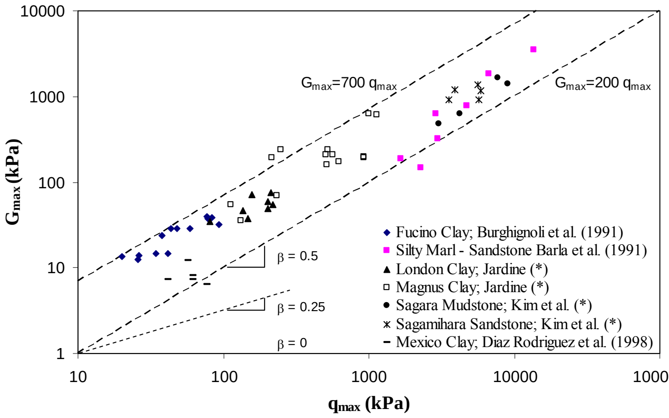

Fig 6: Variation of maximum shear modulus G_{max} with peak deviator stress q_{max} for clays with various degrees of cementation. References denoted with (*): from Tatsuoka and Shibuya (1991)

4.4 Sampling Effects

Differences between field and laboratory measured properties can be important in cemented soils due to stress relaxation and microcracks development during sampling, aging of the specimen after sampling, boundary conditions in the testing cell (i.e. cap effects), soil heterogeneities and scale effect (samples are not representative), frequency and wavelength effects (field tests are performed at much lower frequencies as compared to laboratory test), and soil anisotropy (see: Ladd et al. 1977; Jamiolkowski et al. 1985, Tatsuoka and Shibuya 1991, Hight and Leroueil 2003).

Several parameters have been used to assess the extent of sample disturbance in soils, including: volumetric change during recompression to the in situ state of stress (Andresen and Kolstad 1979; Lo Presti, et al. 1999; "specimen quality designation" in Terzaghi et al. 1996), vertical strain $\Delta e/e_o$ at the in situ state of stress as a function of overconsolidation ratio (Lunne et al. 1997), residual pore pressure or sampling effective stress (Ladd and Lambe 1963), change in stiffness at moderate strains (Jardine 1994), change in small strain stiffness G_{max} (Landon et al. 2007), and imaging techniques such as X-rays.

Three wave velocities characterize the degree of cementation and sampling effects: the velocity in the field V_F, the velocity in an "undisturbed specimen" in the laboratory V_{lab} (confined to the in situ state of stress), and the velocity of a freshly remolded specimen V_R (confined to the in situ state of stress, at the same void ratio). The ratio V_F/V_R captures the extent of cementation and the ratio V_{lab}/V_F indicates the stiffness loss upon sampling. As discussed above, these velocity measurements should be conducted at the same saturation conditions.

Data for freshly remolded soils are seldom reported together with field and undisturbed sample velocities (in some cases, specimen conditions required to determine V_R are not attainable, for example in metastable soils or in carbonate sands which experience particle breakage). Therefore, sampling effects are herein analyzed in terms of the velocity ratio V_{lab}/V_F vs. the shear wave velocity measured in the field V_F. Data compiled from the literature are plotted in Figure 7, where sandy and clayey soils are discriminated to highlight the effect of threshold strain on sampling effects (reported G_{max} values were converted to V_S - A complementary compilation is presented in Toki et al. 1995). The following observations can be made:

- The change in velocity may exceed ±50%.
- Soft clayey specimens can either loose stiffness or gain stiffness upon sampling. Stiffness gain appears to be associated to volume reduction upon re-consolidation.
- In general, cemented sands loose stiffness (loose weakly cemented sands that may experience a high increase in coordination number can render $V_L>V_F$)
- Data for stiff clays, mudstones and strongly cemented sands approach the range of measurement error, estimated as ±5%.

While different sampling methods were used to extract the specimens, including Shelby tubes, block samples and rotary drilling, the scatter in the data does not support conclusive observations related to sampling method

The re-scaling of laboratory modulus degradation curves as a function of $G_{max\text{-}field}/G_{max\text{-}lab}$ must be cautiously considered. Specimen-size dependent experimental features will not scale appropriately.

A limited study was conducted in a cemented residual soil formation to separate the effects of sampler insertion into the formation and specimen removal from the sampler. The shear wave velocity was measured: (1) in the field, (2) inside the Shelby tube by carefully cutting the tube and k_o-reloading the specimen inside the tube with simultaneous velocity measurements, and (3) in resonant column, after extracting the specimen and subjecting it to isotropic recompression. Results show that sample removal from the sampler was the more detrimental step.

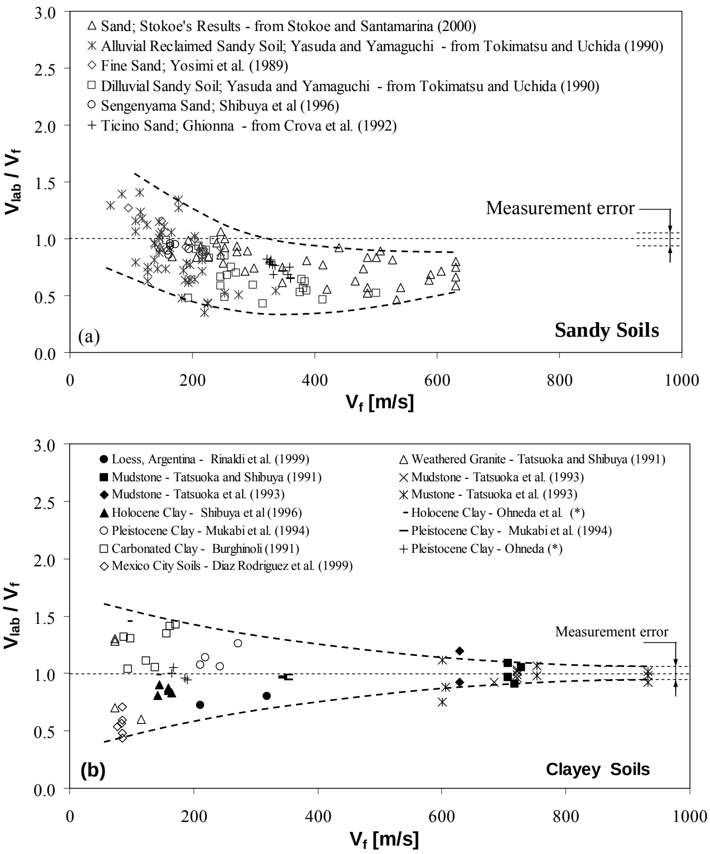

Fig 7: Sampling effects. Comparison of shear wave velocity measured in the laboratory V_{lab} and in the field V_f. (a) Sands. (b) Clayey soils. References denoted with (*): from Tatsuoka and Shibuya (1991)

CLOSING COMMENTS

Diagenetic cementation should be expected in all undisturbed natural soils. Cemented soils have distinctly different characteristics from freshly remolded soils. In particular, they deviate from the conventional understanding of soil behavior in terms of effective stress dependent stiffness, strength and volume change. Salient characteristics of cemented soils include

- High small strain-stiffness, which is often independent of the effective confinement.
- Cementation-dependent behavior at low confinement, with a transition towards stress-dependent soil-like behavior at high confinement or at high strains.
- Stiffness loss after decementation (in most cases irrecoverable in the short term).
- Pronounced sampling effects, particularly on small strain stiffness.
- Cementation may be linked to low water content in uncemented soils. The main difference between unsaturation and cementation effects is the associated threshold strain.

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