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Characterization of fine-grained soils by means of insitu and laboratory tests

Caractérisation des sols à grains fins au moyen d'essais insitu et en laboratoire

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ABSTRACT: Postglacial sediments, characterized by a silt-dominated grain size distribution, define the soil layering of basins in various Alpine regions. Due to the difficult recovery of undisturbed soil samples, insitu investigations, such as seismic piezocone penetration (SCPTu) are becoming increasingly popular for the characterization of fine-grained soils. This paper presents an improved characterization of the stress-strain behaviour of fine-grained sediments by means of insitu & laboratory tests, covering also the effect of sedimentation and age on the soil stiffness. Soils of comparable grain size distribution but different age were investigated at three test sites: two postglacial sediments at the test sites *Extension Lokalbahn Salzburg* and *Rhesi* as well as less than 100 years old sediments at *Water storage Raggal*. Besides cone penetration and seismic flat dilatometer tests, soil samples were recovered at all test sites for additional laboratory testing. The findings show that both, sedimentation processes and age of sediments influence the insitu measurements and physical soil parameters (e.g. density, stiffness). SCPTu and oedometer tests further help to understand that increasing age and advanced sedimentation lead to an increase of stiffness.

RÉSUMÉ: Les sédiments postglaciaires, caractérisés par une distribution granulométrique dominée par les limons, définissent la stratification des sols des bassins de diverses régions alpines. En raison de la difficulté de récupérer des échantillons de sol non perturbés, les études in situ, telles que la pénétration sismique du piézocône (SCPTu), deviennent de plus en plus populaires pour la caractérisation des sols à grains fins. Cet article présente une caractérisation améliorée du comportement contrainte-déformation des sédiments à grains fins au moyen d'essais in situ et en laboratoire, portant également sur l'effet de la sédimentation et de l'âge sur la rigidité du sol. Des sols de distributions granulométriques comparables mais d'âges différents ont été étudiés sur trois sites de test : deux sédiments postglaciaires aux sites tests *Extension Lokalbahn Salzburg* et *Rhesi* ainsi que des sédiments de moins de 100 ans au *stockage d'eau Raggal*. Outre les tests de pénétration au cône et les tests sismiques au dilatomètre plat, des échantillons de sol ont été prélevés sur tous les sites de test pour des analyses supplémentaires en laboratoire. Les résultats montrent que la procédure de sédimentation et l'âge des sédiments influencent les mesures in situ et les paramètres physiques du sol (par exemple, la densité, la rigidité). Les tests SCPTu et oedomètre aident à comprendre que le vieillissement ainsi que la procédure de sédimentation avancée mènent à une augmentation de la rigidité.

KEYWORDS: insitu testing, seismic cone penetration test, fine-grained soils, stiffness, structure.

1 INTRODUCTION

The Alpine region (e.g. Austria, Italy, Germany, Switzerland) is characterized by various basins - formed during the last glacial period - which remained as lakes after the melting period. These basins were filled over thousands of years mainly by fine-grained sediments and form the underground of economically important regions and cities (e.g. Salzburg, Bregenz or Rosenheim) today.

Over the last centuries, a lot of experience has been collected on constructional possibilities and geotechnical limits in such soils. It was observed that the amount of settlements differs strongly between basins even if the grain size distribution is similar. Multi-storey buildings in Salzburg city, situated on shallow foundations, often show relatively small settlements under static loading. On the other hand, it was observed that dynamic loads introduced by heavy construction measures (e.g. soil improvement measures, jet grouting) can lead to significant settlements. Therefore, it is assumed that these fine-grained sediments can have microstructural bonds within the grain-to-grain matrix which lead to an increase in strength and stiffness. At the same time, these bonds are weak and can be partially or fully destroyed due to heavy construction measures or non-adequate soil sampling techniques, leading to unrealistic low constrained moduli from oedometer tests. On the other hand, insitu tests are becoming increasingly popular in geotechnical engineering. Especially the seismic piezocone penetration test (SCPTu) is widely used for soil classification and parameter identification. Thereby, a cone with a cross-section area equal to 10 or 15cm² is pushed under constant penetration rate of 2cm/s into the soil using a pushing device (e.g. truck or rig). Simultaneously, the tip resistance q_c, sleeve friction f_s and dynamic porewater pressure u_2 are measured continuously over depth. The measurement of the porewater pressure is usually performed above the cone at position u_2. Intervals of usually 50cm are chosen to determine the shear wave velocity V_S. Thereby, the penetration procedure is interrupted, and a hammer blow is used to generate a shear wave at the top surface. The signal propagates through the soil and gets detected above the cone by two geophones with a defined distance to each other. Consequently, it becomes possible to determine the shear wave velocity in the depth of the probe by measuring the time delay between the arrival signals at the upper and lower geophones (Marchetti 2018).

In the past, numerous correlations have been developed for sands and clays to determine soil parameters based on q_c, f_s, u_2 and V_S. At the same time, it should be noted that existing correlations often include empirical factors, which have been defined for specific locations based on laboratory tests (Schnaid 2009). Consequently, their application is limited to other locations (e.g. fine-grained sediments in Austria). For this reason, Graz University of Technology in cooperation with the Federal Chamber of Architects and Chartered Engineering Consultants started the research project PITS (Parameter identification using insitu tests in silts) to enable an improved characterization of stiffness and structure in fine-grained sediments using SCPTu and SDMT (seismic flat dilatometer test). Fine-grained sediments of comparable grain size distribution but different age have been investigated at three test sites (TS1 – Extension Lokalbahn Salzburg, TS2 – Rhesi, TS3 – Water storage Raggal) using insitu and laboratory tests. In the present article SCPTu and (incremental load) oedometer tests are compared to discuss new and existing methods of stiffness determination based on SCPTu. Furthermore, the influence of sedimentation history / age on soil properties and structure is addressed.

2 TEST SITES

In the course of the research project PITS, insitu tests were carried out within Austria (Europe) to enable an improved characterization of postglacial sediments. Besides piezocone penetration tests (CPTu) and seismic flat dilatometer tests (SDMT), soil sampling for additional laboratory investigations was executed. In the following, the shear wave velocity determined by SDMT and CPTu measurements are summarized and named as SCPTu. In the present article, results from three test sites, namely TS1 – Extension Lokalbahn Salzburg, TS2 – Rhesi and TS3 – Water storage Raggal, are discussed. The test execution has been performed by Premstaller Geotechnik ZT GmbH and Studio Marchetti Srl. It should be noted that test sites TS1 and TS2 are situated within basins which were formed by glaciers (postglacial sediments). The fine-grained sediments at test site 1 were deposed between 15 and 25 ka years ago (Starnberger et al. 2014) and are older compared to those investigated at test site 2 (which were sedimented probably within the last 2 to 5 ka years). The sediments investigated at TS3 – Water storage Raggal have been deposited after the construction of the dam over the last 50 years.

2.1 *Test site 1 – Extension Lokalbahn Salzburg*

Test site 1 (TS1) was executed in Salzburg city close to the main train station (see Figure 1a). Within a rectangular area of approximately 12x8m, numerous CPTu were performed on variable penetration rate using u_1 and u_2 probes. Furthermore, standard and MEDUSA SDMT (Marchetti 2018) with a total length of approximately 25m were carried out using the CPT-Truck shown in Figure 1b. The individual tests have a minimum distance of 1.5m to each other and a mutual influence is excluded. It should be noted that only CPTu executed on a standard rate of 2cm/s in combination with porewater pressure measurements at position u_2 are further discussed in this article. In a second step, a percussion core drilling was executed for soil sampling. In defined depth levels, PVC tubes (length = 600mm, diameter = 100 or 125mm) were pushed into the soil and sealed at the top and bottom using paraffin. Further (disturbed) soil samples were recovered for determinations of grain size & Atterberg limits. As shown in Figure 2a, the soil can mainly be subdivided in three layers: L1 – sandy gravel, L2 – sand-silt alterations and L3 – clayey silt. It becomes evident that fine-grained sediments are characterized by smaller q_c, f_s and V_S values. On the other hand, large excess porewater pressures are generated. Under drained conditions the relationship is vice versa. During test execution and sampling the groundwater table was situated about 1.5m below ground surface.

2.2 *Test site 2 - Rhesi*

Test site Rhesi is situated in the western part of Austria about 2 km south of lake Constance (see Figure 1a) in the forelands of the river Rhine. As for test site 1, CPTu were performed on variable penetration rate using u_1 and u_2 probes. In addition to standard and MEDUSA SDMT, heavy dynamic probings DPH were executed within the 75x25m large test site. All tests were carried out to a depth of -25m. Two rotary core drillings were executed for undisturbed soil sampling. Starting from the bottom of the borehole a PVC tube (length = 400mm, diameter = 125mm) was pushed into the soil and subsequently sealed at the top and bottom with paraffin. Based on the SCPTu measurements shown in Figure 2b the subsurface can be again subdivided in 3 main layers: L1 – silty sand, L2 – sand-silt alterations and L3 – clayey silt. From the insitu measurements it becomes clear that with increasing depth the fines content rises, which agrees with test site TS1. The ground water table was situated about 1m below ground surface during test execution.

2.3 *Test site 3 – Water storage Raggal*

In order to investigate the influence of aging on the stress-strain behaviour (of fine-grained sediments), significantly younger sediments were investigated within the reservoir of water storage Raggal. Since the reservoir was filled with water during test execution, a floating pontoon in combination with CPT-Fox series - Stand Alone CPT system (Geomil equipment - Fox 2021) were used as pushing device (see Figure 1c). The pontoon was braced at the four corners using steel cables to minimize horizontal displacements during test execution. Furthermore, it was required to use additional casing tubes to avoid buckling of penetration rods between pontoon and sediment surface (water depth equal to 7m). CPTu in combination with u_1 and u_2 probes as well as Medusa SDMT were executed on standard rate. A custom-made shear wave hammer was lowered to the reservoir bottom to enable a determination of the shear wave velocity. The hammer blow was achieved via a drop weight, which was released by a rope. To enable a direct comparison of the test results, all insitu tests were executed within an area of approximately 10 x 5m. Furthermore, soil samples were recovered in defined depths using the CPT ranger system (Geomil equipment - Ranger 2021). Due to the buckling problem and the limited weight of the pontoon, the sediments were investigated down to a depth of approximately 15m. As shown in Figure 2c, the young sediments consist of sand-silt alterations (L1). The water section (ground surface to top of reservoir) is indicated by W in Figure 2.

The range of soil classifications are summarized for all test sites and lithologies in Table 1 according to ASTM D2487-11 (Unified Soil Classification System) & EN ISO 14688-1.

Table 1. Soil classifications according to ASTM D2487-11 (USCS) and EN ISO 14688-1 for TS1, TS2 and TS3.

Lithology	**ASTM D2487-11 (USCS)**	**EN ISO 14688-1**
TS1 – L1	GM	si' sa Gr
TS1 – L2	CL → SC	sa" cl Si → si Sa
TS1 – L3	CL	$\overline{cl}$ Si → sa" cl Si
TS2 – L1	CH → SC	sa' Cl/Si → cl" gr' si Sa
TS2 – L2	CL → SC-SM	sa' cl Si → cl' si Sa
TS2 – L3	CL → CH	sa" cl Si → sa" Cl/Si
TS3 – L1	OL → SP-SM	cl' sa' Si → si' Sa

3 INSITU & LABORATORY DATA

It is shown in Figure 2, that all three test sites are characterized by a changing grain size distribution over depth. Thereby, q_c, f_s and V_S increase with increasing coarse fraction, while u_2 is decreasing to the hydrostatic level (for drained conditions). On the other hand, the described trend is the opposite in fine-grained sediments. To enable a direct comparison of insitu and laboratory data of all three test sites, fine-grained sections are filtered based on grain size distribution and Atterberg limits and marked by the black solid line in Figure 2. The empty symbols (without filling) represent the corresponding laboratory results (see Figure 3). For the sake of completeness, results of coarser sections (Figure 2: dashed line; Figure 3: symbols with gray fillings) are also presented. In the following, reference is only made to the fine-grained sections. As shown in Table 2, the fines content (% < 75μm) at all three test sites is above 90%.

Figure 1. (a) Location of test sites TS1 - Extension Lokalbahn Salzburg, TS2 – Rhesi & TS3 – Water storage Raggal, (b) CPT-track used as penetration device at TS1 & TS2, (c) floating pontoon & CPT-fox system (Geomil equipment - Fox 2021) used as penetration device at TS3.

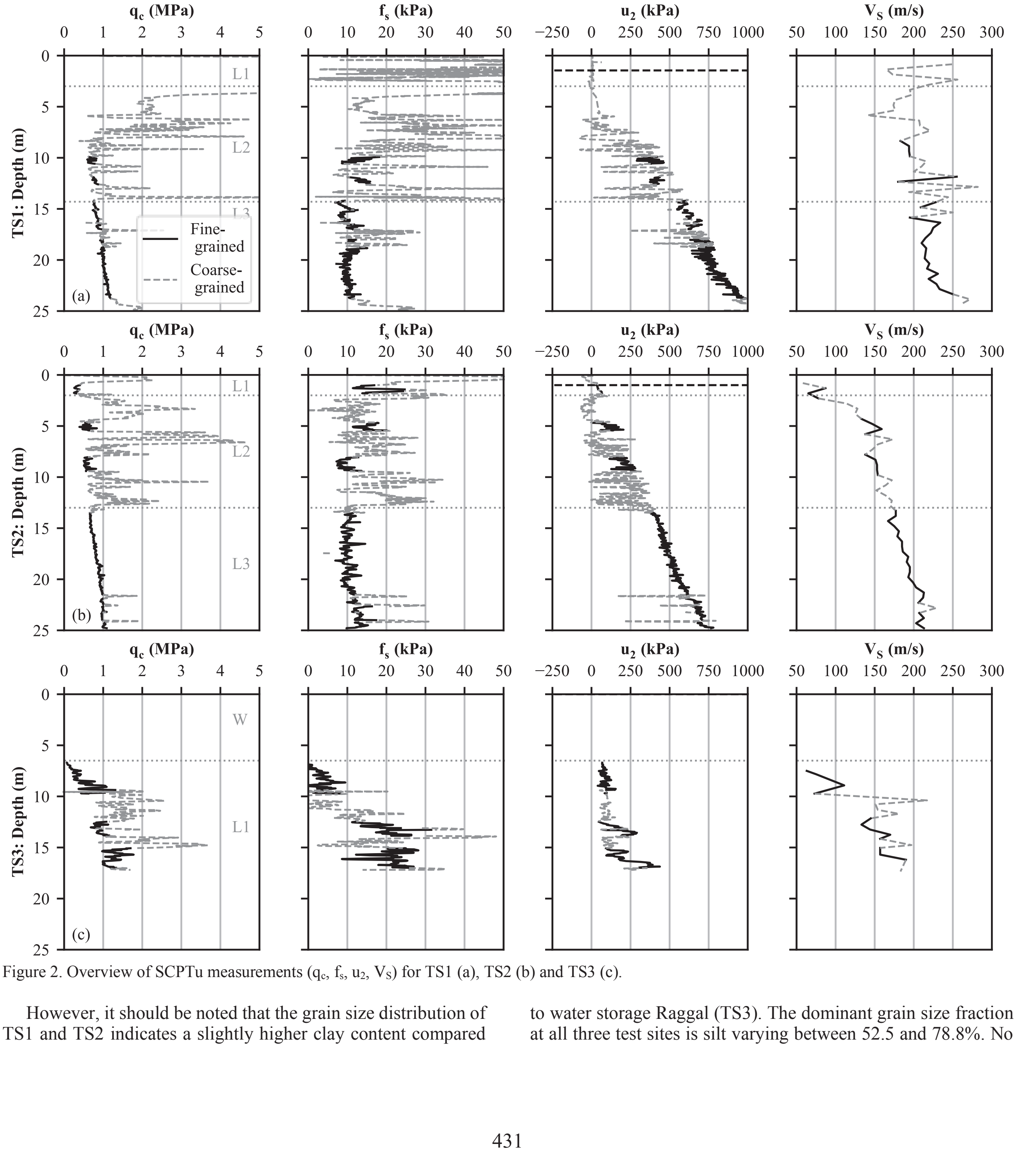

Figure 2. Overview of SCPTu measurements (q_c, f_s, u_2, V_S) for TS1 (a), TS2 (b) and TS3 (c).

However, it should be noted that the grain size distribution of TS1 and TS2 indicates a slightly higher clay content compared to water storage Raggal (TS3). The dominant grain size fraction at all three test sites is silt varying between 52.5 and 78.8%. No gravel content was detected in soil samples of this fine-grained sections.

Table 2. Grain size distribution of fine-grained sections: at TS1, TS2 and TS3.

Test sites	Fines % <75μm	Clay % <2μm	Silt % 2-63μm	Sand % 63-2000μm
TS1	97.4-100	23.2-30.4	69.7-75.2	0.9-3.3
TS2	91.3-97.2	18.1-43.5	52.5-78.3	3.6-6.9
TS3	90.2-93.7	11.1-14.1	73.7-78.8	8.5-12.5

Most fine-grained sections at TS1 & TS2 are classified as medium plasticity clays according to USCS. As shown in Figure 3c all circle and diamond symbols (white marker) are situated on or above the A-Line in the Casagrande chart. The liquid limit LL and plasticity index PI increase below 22m at TS2. Based on USCS, the latter are classified as high plasticity clays. At water storage Raggal (TS3 – see Figure 3c: triangular symbols), Casagrande results are situated slightly below the A-Line. This reduction in the plasticity index (PI) can be related to a high organic content varying between 4 and 7 %. In Figure 3a and Figure 3b the natural water contents w_{nat} and dry densities ρ_d of all three test sites are shown over depth, where w_{nat} varies between 32.7-37.7 % (TS1), 34.9-38.5 % (TS2) and 40.5-44.1 % (TS3). It can be seen that the highest and lowest water contents were measured at TS1 and TS3, respectively. The trend is exactly the opposite for ρ_d: 1.41-1.48 g/cm³ (TS1), 1.28-1.33 g/cm³ (TS2) and 1.21-1.23 g/cm³ (TS3). Based on this data it is evident that both parameters are strongly influenced by the sedimentation history. An increase in sedimentation age and consolidation time leads to a decrease in water content w_{nat} and an increase in dry density ρ_d.

4 STIFFNESS & STRUCTURE

In order to enable a direct comparison of SCPTu executed at TS1, TS2 and TS3, the insitu measurements are plotted against the effective vertical stress σ'_v in Figure 4a. This step is necessary since the soil density varies between all three test sites. The fine-grained sections of TS1, TS2 and TS3 are presented by solid black, dashed grey and dotted light grey lines, respectively. Especially the insitu measurements of TS1 and TS2 are in good agreement. Results from TS3 are only available to an effective vertical stress equal to 75 kPa. The increase in tip resistance q_c and sleeve friction f_s can be related to the slightly smaller clay content and higher sand content (see Figure 4 - dotted light grey line). Near the surface both measurements are smaller, since a suspension-like mixture of soil and water is present. The measured porewater pressure u_2 and shear wave velocity V_S are in good agreement with TS1 and TS2. The increase of all insitu measurements over depth correlates with an increase in effective vertical and horizontal stress. For this reason, the insitu measurements were normalised according to Equation 1, 2 & 3 as follows:

$$Q_t = (q_t - \sigma_v)/\sigma'_v \quad (1)$$

$$F_R = [f_s/(q_t - \sigma_v)]100\% \quad (2)$$

$$B_q = (u_2 - u_0)/(q_t - \sigma_v) \quad (3)$$

where q_t is the cone resistance corrected for water effects, where $q_t = q_c + u_2(1 - a)$; a is the cone area ratio, typically between 0.8 and 0.9; σ_v is the insitu total vertical stress and u_0 is the insitu porewater pressure. For the same subsoil conditions, normalised parameters should stay constant. This is the case for TS1 and TS2 within L3 (see Figure 2). In upper sections, Q_t increases while F_r and B_q decrease. This can be related to a higher heterogeneity within lithologies L1 and L2. Again, TS1 and TS2 test sites are in good agreement, while TS3 shows a slightly higher Q_t and smaller F_r and B_q values.

Existing correlations for CPTu normally use q_c or q_t as input value to determine the constrained modulus in fine-grained soils. In order to evaluate existing approaches based on SCPTu, additional incremental load (IL) oedometer tests were carried out on "good quality" soil samples recovered within fine-grained sections at each test site. Nevertheless, sample disturbance could not be fully avoided during the sampling. Figure 5 shows the evolution of void ratio e during primary loading as well as un- and reloading for several oedometer tests. The sampling depth for each test is presented on the top right of the diagrams. It can be seen that the individual curves are in good agreement within a test site. At the same time, it becomes obvious that curve inclinations differ strongly between all three test sites. In addition, the compression index C_C and swelling index C_S were determined for all tests using Equation 4. Additionally, Cam Clay parameters λ and κ (Muir Wood 1990) were obtained as summarized in Table 3.

$$C_C = (e_0 - e_1)/\log(\sigma'_1/\sigma'_0) \quad (4)$$

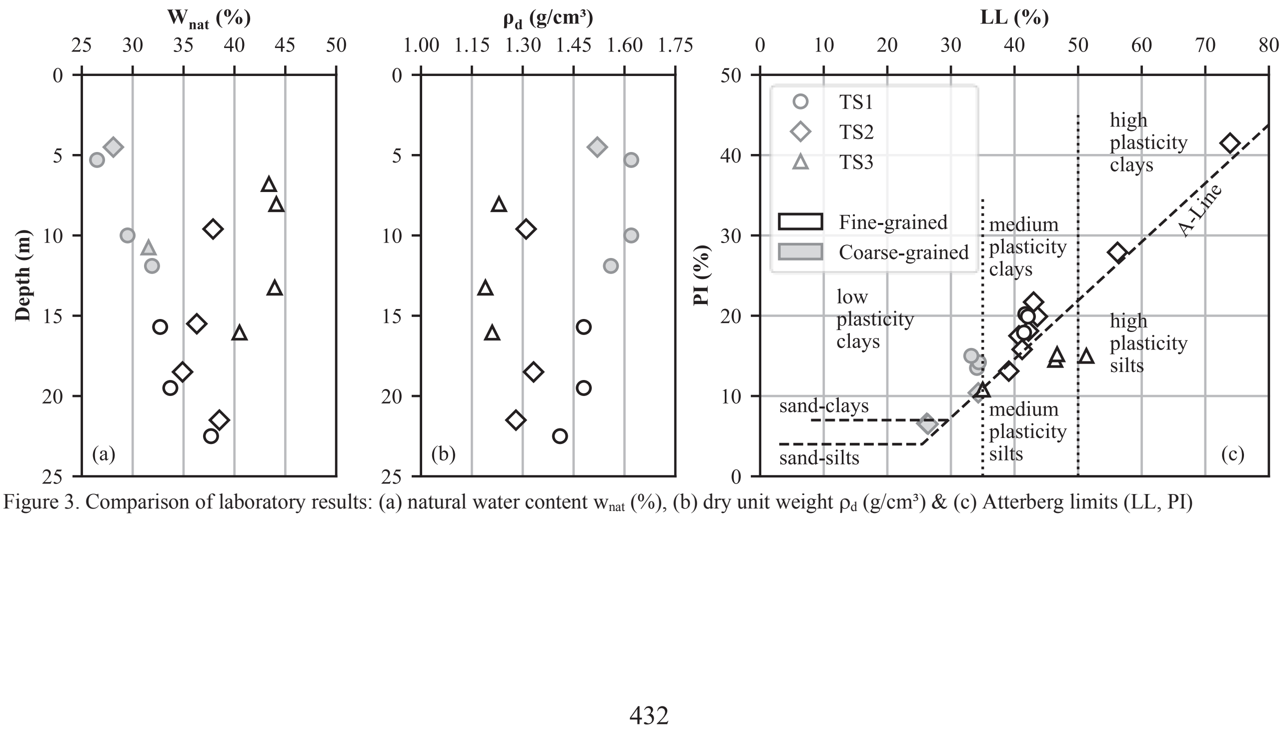

Figure 3. Comparison of laboratory results: (a) natural water content w_{nat} (%), (b) dry unit weight ρ_d (g/cm³) & (c) Atterberg limits (LL, PI)

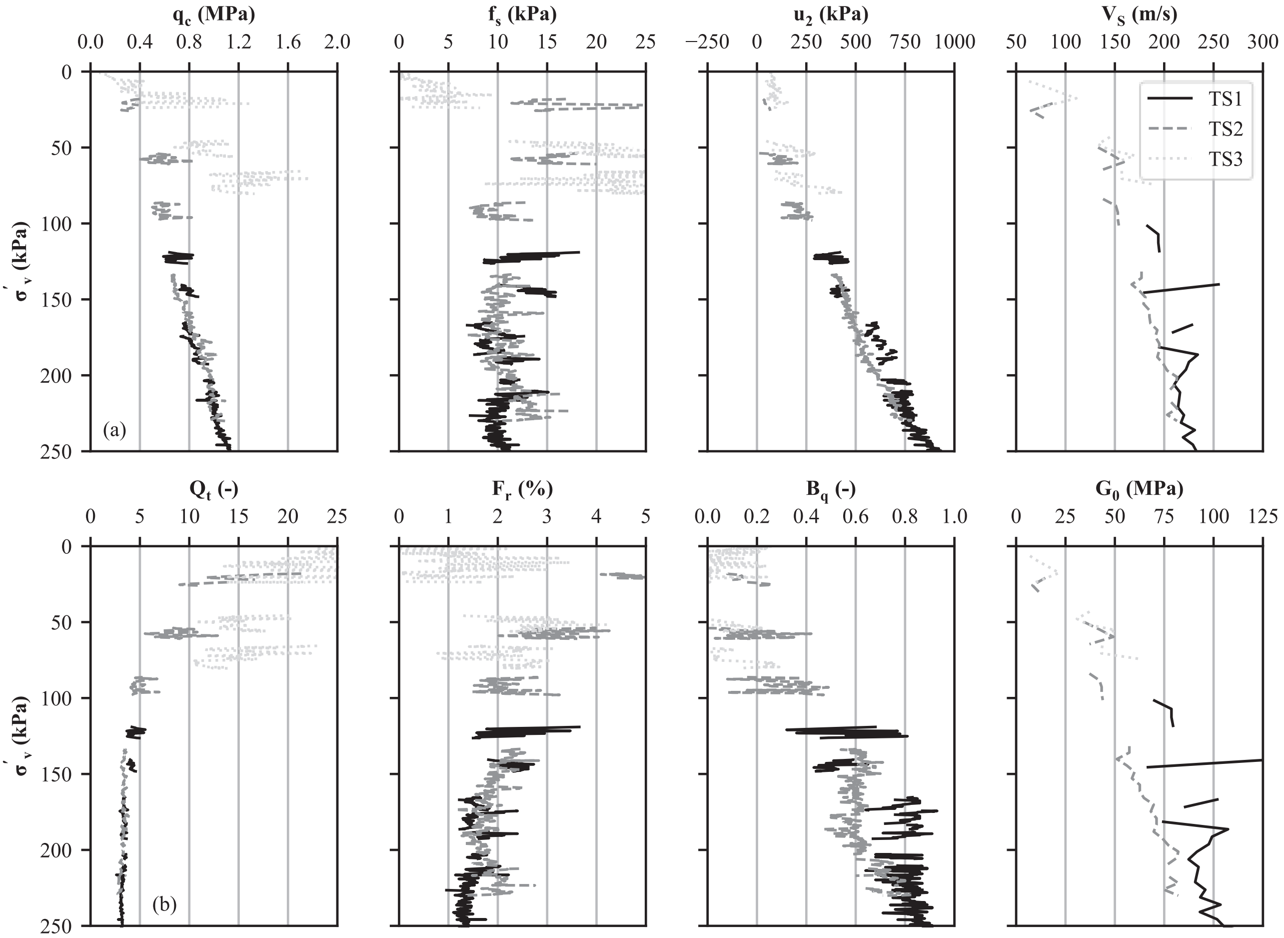

Figure 4. Comparison of SCPTu measurements (q_c, f_s, u_2, V_S) and normalized parameters (Q_t, F_r, B_q, G_0) for TS1, TS2 and TS3.

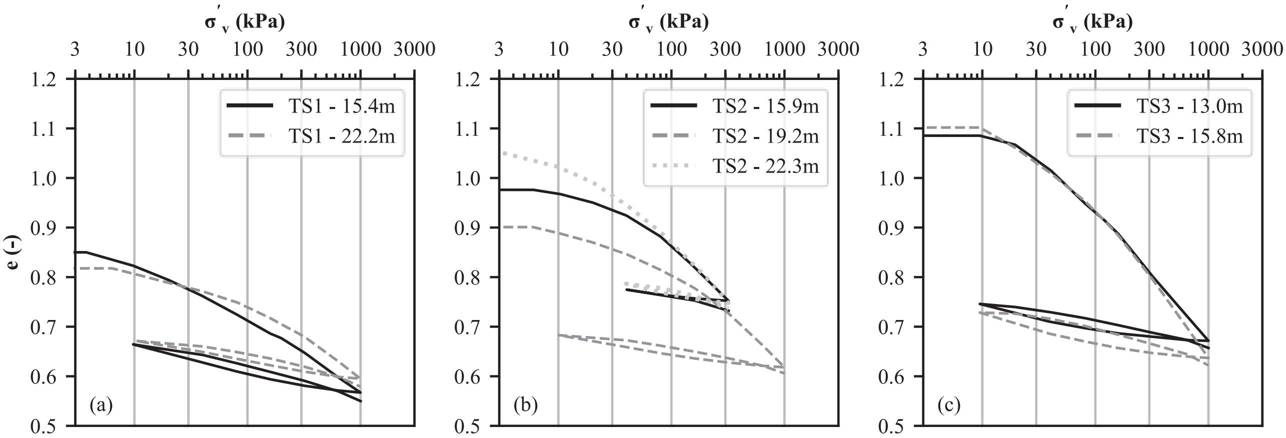

Figure 5. Oedometer curves obtained from incremental load (IL) tests for all three test sites: (a) TS1, (b) TS2, (c) TS3

The compression indices C_C vary between 0.162-0.171 at TS1, 0.219-0.253 at TS2 and 0.271-0.310 at TS3. The stiffness moduli strongly correlate with the sedimentation history (age) and density. The older the sediment (and the higher the density), the higher the stiffness for primary loading (smaller C_C & λ). This trend is less evident in the unloading-reloading stiffness (C_S, κ). Nevertheless, it is noted that the ratio of C_C/C_S tends to decrease with age and density. Based on oedometer tests, different stiffness values for primary loading have been determined at all test sites. At the same time, it is shown that this difference is not reflected by q_c and Q_t.

On the other hand, the shear wave velocity V_S can be used to determine the small strain shear modulus G_0 based on Equation 5:

$$G_0 = \rho \cdot {V_S}^2 \tag{5}$$

where ρ is the bulk density of the soil. In Figure 4b the distribution of G_0 over σ'_v is shown for all three test sites. In contrast to q_c and Q_t, the curves differ clearly for similar effective stress levels. Furthermore, it can be seen that SCPTu results of TS1 are higher compared to TS2, which agrees with oedometer results. The measurements of TS3 can (unfortunately) only be compared for a low stress level. However, for this section they are in a good agreement with TS2.

Table 3. Summary of oedometer results for all three test sites: Compression index C_C, Swelling index C_S, Cam clay parameters λ & κ.

Oedometer test	C_C (-)	C_S (-)	λ (-)	κ (-)
TS1 – 15.4m	0.162	0.048	0.070	0.021
TS1 – 22.2m	0.171	0.038	0.074	0.017
TS2 – 15.9m	0.224	0.025	0.097	0.011
TS2 – 19.2m	0.219	0.032	0.095	0.014
TS2 – 22.3m	0.253	0.043	0.110	0.019
TS3 – 13.0m	0.271	0.037	0.117	0.016
TS3 – 15.8m	0.310	0.045	0.135	0.020

In a final step, it is investigated whether and how strong the investigated sediments are structured. This is done by using the approach according to Robertson (2016). It is assumed that structure tends to increase G_0 more than the cone resistance corrected for water effects q_t. Robertson introduced the modified normalized small-strain rigidity index K^*_G to define the transition between structured and unstructured soils. The parameter is defined based on Equation 6, 7 & 8 as follows:

$$K_G^* = (G_0/q_n)(Q_{tn})^{0.75} \tag{6}$$

$$q_n = q_t - \sigma_v \tag{7}$$

$$Q_{tn} = [(q_t - \sigma_v)/p_a](p_a/\sigma'_v)^n \tag{8}$$

where p_a is the atmospheric reference pressure and n is a stress exponent that varies with soil behaviour type.

Soils with $100 < K^*_G < 330$ are classified as ideal soils with no to little microstructure. On the other hand, soils with $K^*_G > 330$ tend to have significant microstructure and CPT-based empirical correlations may have less reliability. For the present case, K^*_G was calculated for the fine-grained sections shown in Figure 2. The resulting values are visualized by means of a box plot in Figure 6. Median, mean as well as 25 and 75% quartile values are represented by triangles, circles and dotted lines. All K^*_G values are situated at or slightly below the transition between ideal and structured soils. However, it should be noted that with increasing age (sedimentation history) K^*_G increases. The highest and lowest K^*_G values were determined at TS1 and TS3, respectively. While the results from TS2 and TS3 are slightly below $K^*_G = 300$, the results from TS1 are on and above the transition value. As already addressed by Robertson (2016), G_0 is much more influenced by structure compared to q_t.

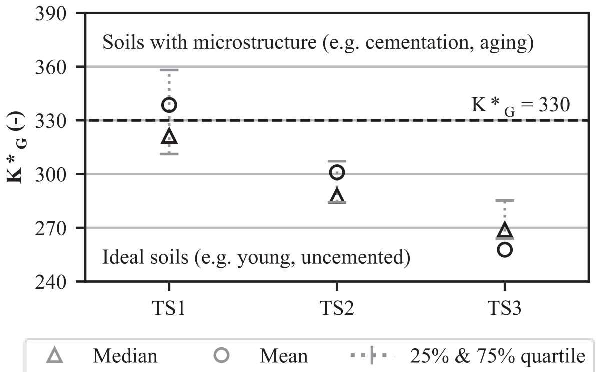

Figure 6. Detection of soil microstructure by means of normalized small-strain rigidity index K^*_G (Robertson 2016): Visualization using box plots.

5 CONCLUSIONS

Within the research project PITS (Parameter identification using insitu Tests in silts) insitu tests (SCPTu, SDMT, DPH, HPT) were carried out at numerous test sites in Austria. Furthermore, soil samples were recovered at each location to enable extensive laboratory testing. In the present contribution, fine-grained sediments of similar grain size distribution but different age are investigated at TS1 - Extension Lokalbahn Salzburg, TS2 - Rhesi and TS3 – Water storage Raggal using seismic piezocone penetration tests (SCPTu) and oedometer tests.

It is shown that aging strongly influences the natural water content w_{nat} and dry density ρ_d. While w_{nat} decreases with increasing age, the relationship is exactly the opposite for ρ_d. Oedometer results indicate that the compression index C_C and Cam clay parameter λ decrease with increasing age (increase in stiffness). This trend could not be confirmed for the unloading-reloading stiffness (C_S, κ).

On the other side, a difference in stiffness between the three test sites could not be derived based on the comparison of CPTu measurements (q_c, f_s, u_2) and normalised parameters (Q_t, F_r, B_q). In a further step, the small strain shear modulus G_0 is calculated based on the shear wave velocity V_S (determined insitu) and the bulk density (determined in the laboratory). Based on the latter approach, the expected differences in stiffness are observed. Therefore, it is recommended to determine the stiffness in fine-grained soils based on G_0 (using SCPTu, SDMT or cross hole tests), instead of using empirical factors in combination with q_t.

The modified normalised small-strain rigidity index K^*_G is used to characterize the sediments microstructure. According to Robertson (2016), the investigated sediments show some microstructural bonds which become stronger with increasing age. At the same time, it should be noted that only the fine-grained sediments of TS1 (oldest sediment) exceed the transition value between unstructured and structured soils. Further research is required to confirm the statements of the last paragraph.

6 ACKNOWLEDGEMENTS

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