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Characterization of young sediments using CPTu and Medusa SDMT

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ABSTRACT: Piezocone penetration tests (CPTu) and seismic flat dilatometer tests (SDMT) present costand time-efficient insitu investigation techniques for onshore as well as offshore projects. Since soil sampling is often related to a strong soil disturbance in fine-grained sediments, parameter identification is frequently based on insitu measurements in combination with correlations. As shown in previous studies, correlations are more difficult to develop in silt-dominated sediments. To overcome this problem, the research project PITS (parameter identification using insitu tests in silts), was launched by Graz University of Technology in cooperation with the Federal Chamber of Architects and Chartered Engineering Consultants. To investigate the influence of time effects (age) and microstructure on the load-settlement behaviour of normallyto slightly underconsolidated sediments, deposits younger than 50 years have been investigated at the water storage reservoir Raggal (Austria) using CPTu as well as Medusa SDMT. Both probes were pushed first through the water and subsequently into the sediments by means of a stand-alone pushing device, where the testing setup was installed on a floating pontoon. In order to prevent buckling of the penetration rods, additional casing tubes (along the water) were used. In a last step, soil sampling was executed using the CPT-Ranger system by Geomil. To characterize and quantify the sediments microstructure, shear wave velocities determined insitu by means of SDMT ($V_{S,SDMT}$) are compared with measurements on reconstituted soil samples using bender elements ($V_{S,BE}$). Ratios $V_{S,BE}/V_{S,SDMT} \approx 1$ indicate the presence of no or moderate soil microstructure. On the other hand, postglacial deposits of similar grain size distribution are characterized by smaller $V_{S,BE}/V_{S,SDMT}$ ratios, indicating a higher microstructure.

1 INTRODUCTION

1.1 *Motivation*

Fine-grained sediments define the soil layering of various basins and valleys within Alpine regions. Many of these basins and valleys were formed during several glacial periods and remained as lakes after the melting. Over thousands of years they have been filled by mainly fine-grained sediments. Therefore, such (geologically) young soils are often characterized by a high groundwater table and are generally in a normally consolidated or slightly under consolidated state. In the area of Salzburg or Bregenz it was observed that such sediments often present unexpected low settlements under static loading on shallow foundations. 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. One possible explanation for this observation might be related to microstructural bonds within the grain-to-grain matrix, which lead to an increase in strength and stiffness (Leroueil 1992). At the same time, they can easily be destroyed due to heavy construction measures or non-adequate soil sampling techniques. On the other hand, insitu tests and especially seismic measurements (e.g. seismic piezocone penetration test SCPTu or seismic flat dilatometer test SDMT) are becoming increasingly popular to quantify and characterize microstructure (Robertson 2016).

To gain an improved understanding of structure in postglacial deposits by means of insitu tests Graz University of Technology in cooperation with the Federal Chamber of Architects and Chartered Engineering Consultants initiated the research project PITS (parameter identification using insitu tests in silts).

1.2 *Aim*

The present paper tries to investigate how aging can influence the development of microstructure.

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Therefore, young sediments with an age of approximately 50 years deposited in the water storage reservoir Raggal (Austria) have been investigated using CPTu, SDMT and laboratory tests (e.g. oedometer, bender element).

Based on the comparison of shear wave velocities, determined insitu (Medusa SDMT) and in the laboratory on reconstituted samples (bender element), the degree of microstructure could be quantified and is further compared with measurements of post-glacial (older) sediments.

2 INSITU TESTS

2.1 *Piezocone penetration test - CPTu*

The piezocone penetration test (CPTu) is a widely used insitu test for soil classification and parameter identification. During test execution, a cone with a cross-section area equal to 10 or 15 cm^2 is pushed under constant penetration rate (2 cm/s) into the soil using a pushing device (e.g. truck, rig or demountable systems). Simultaneously, the tip resistance q_c, sleeve friction f_s and dynamic pore water pressure u_i are measured continuously over depth. The measurement of the pore water pressure is usually performed above the cone at position u_2. Alternatively, the pore water pressure can be measured directly at the cone (position u_1). Normalized parameters can be calculated based on insitu measurements and further used for soil classification (using soil behavior type chart) or in combination with correlations to identify soil parameters.

2.2 *Seismic Medusa flat dilatometer test - Medusa SDMT*

The flat dilatometer is an insitu soil testing equipment developed by Professor Silvano Marchetti in the late 1970s (Marchetti 1980). A steel blade – containing a thin, expandable, circular steel membrane mounted on one side – is pushed into the soil on a constant penetration rate equal to 2 cm/s. The blade is connected to a pneumatic electrical cable running through the penetration rods, up to a control unit at surface. In the standard testing procedure, the penetration is stopped every 20 cm. When performing a classic DMT, the membrane is inflated with gas to obtain two pressure readings at defined deformations of the membrane: the A-pressure (center of the membrane deforms 0.05 mm) and B-pressure (center of the membrane deforms 1.10 mm). A third pressure reading, the C-pressure (closing pressure), can optionally be taken by slowly deflating the membrane soon after B until it returns to position A.

The Medusa dilatometer (Medusa DMT) is a self-contained, fully automated version of the flat dilatometer, able to autonomously perform dilatometer tests without the pneumatic cable and gas tank. A motorized syringe, driven by an electronic board powered with rechargeable batteries, hydraulically expands the membrane to obtain the A, B and C pressure readings, which are acquired and stored automatically at each test depth (Marchetti 2014).

Since the test execution is performed automatically, the influence of operators can be reduced significantly, alternative timing of measurements become feasible and repeated A-pressure readings can be carried out accurately.

The seismic flat dilatometer is a combination of the flat dilatometer (or Medusa DMT) with the seismic module for measuring the shear wave velocity V_S behind the blade. The seismic module is a cylindrical element situated above the DMT blade and equipped with two receivers fixed at a vertical distance of 0.50 m. The measurements are commonly performed at depth intervals equal to 50 cm while stopping the penetration procedure. The shear wave source – located at the ground surface or in the present case at the lake floor bottom - generally consists of a S-hammer which strikes horizontally a rectangular steel plate pressed against the soil. The generated shear wave first reaches the upper receiver, then, after a delay, the lower receiver. The seismograms acquired by the two receivers, amplified and digitized at depth, are transmitted to a computer at the surface for real-time interpretation of V_S (Marchetti et al. 2008).

3 TEST SITE WATER STORAGE RAGGAL

3.1 *General information*

The water storage reservoir Raggal (see Figure 1), located in the western part of Austria, is operated by the energy operator *illwerke vkw* and is part of the hydropower plant *Oberstufe Lutz*. Due to natural sedimentation, about 50,000 m^3 of material are deposited within the storage every year. To prevent blockage of important water intake points and to pass the annual inflow of sediments through the dam, these sediments are regularly removed near the dam using a dredger (see Figure 1).

3.2 *Investigation*

In a first step, the thickness of the sediments was investigated by means of echo soundings. The excavation works on the one hand and the location of insitu tests on the other hand have been designed/defined based on the latter. With increasing distance from the dam, the flow velocity rises and the deposited sediments become coarser. This relationship could be confirmed based on aerometer and sieve analyses on soil samples, recovered from the reservoir. In the front third of the water reservoir - where the finest sediments are deposited - *illwerke vkw* carried out excavation works during our investigation campaign. In order not to hinder the excavation work and to ensure all safety regulations, the insitu tests were carried out approximately 300m behind the concrete-dam (see Figure 1). Based on echo soundings it could be ensured to investigate sediments of approximately 20 m thickness. All insitu tests were carried out starting from a floating pontoon within a rectangular area of approximately 10 x 5 m to ensure the comparability of test results (see Figure 1).

The insitu campaign consisted of piezocone penetration tests (CPTu) with pore water pressure measurements at position u_1 and u_2, seismic Medusa flat dilatometer tests (Medusa SDMT) and soil sampling by means of CPT-Ranger. All tests were executed in collaboration with the companies mjp ZT GmbH and Studio Prof. Marchetti.

Figure 1. Water reservoir Raggal: Overview and location test site.

4 TEST EXECUTION

4.1 *Floating pontoon and pushing device*

Since the reservoir was filled with water during test execution, all insitu tests were executed from the floating pontoon presented in Figure 2a (which is usually used for sediment transportation). The construction is composed of four air-filled steel boxes (two boxes each side), connected by three 2.8m long IPE300 profiles. The external dimensions and weight of the barge amount to 10 m x 8 m and 13 tons respectively. The mobile stand-alone system by Geomil (Fox-150) was used as pushing device for all insitu tests. Thereby, a separate power pack, driven by a petrol motor, powers the Fox-150 hydraulically. In order to avoid any tilting during test execution, it was tried to fix the penetration device on the floating-pontoon center. In a first step, HEA profiles were clamped onto the IPE300 profiles. Subsequently, the "stand-alone system" was attached to the (longitudinal assigned) HEA profiles using two GEWI bars (see Figures 2b and 2d). Free areas were covered by wooden constructions to ensure work safety during test execution (see Figures 2e and 2f). Finally, the floating pontoon was moved to the desired position using a motorboat and additionally fixed at the shore using four steel cables (see Figure 2g).

4.2 *Piezocone penetration test and seismic Medusa flat dilatometer test*

The water depth and the thickness of the sediment deposits were approximately 7 m and 20 m respectively during test execution. In order to prevent any buckling of penetration rods along the water section, additional casing tubes (with a slightly larger inner-diameter than the outer diameter of the pushing rods) were used to increase the cross-section and moment of resistance. In a first step, CPTu or SDMT probes were lowered to the lake floor bottom ensuring an embedment depth of approximately 2 m. Afterwards, casing tubes were lowered by using the stand-alone system. Once the casing tubes reached the lake bottom (sediment top surface) the penetration process was continued by means of pushing rods. Consequently, casing tubes were installed along the water section only. Due to the buckling problem and the limited weight of the pontoon, the sediments were investigated down to a depth of approximately 15 m. After reaching the final testing depth, first the casing tubes and subsequently the penetration rods were pulled back.

To determine the shear wave velocity, the S-hammer shown in Figure 3a was designed and built in cooperation with Studio Prof. Marchetti and Behensky. The shear wave is triggered using a 45kg drop-weight. Since water does not allow the transmission of shear waves, the S-hammer was lowered from the floating pontoon to the lake bottom using two winches (see Figures 3b and 3c). During the lowering procedure, additional casing tubes were continuously attached to the head of the structure to verify its position. A rope was used to lift and release the 45kg drop weight from the floating pontoon (see Figure 3c). The shear wave velocity was determined at 50 cm intervals.

4.3 *Soil sampling and laboratory testing*

In a final step, soil sampling for laboratory testing was executed in 5 depth levels using the CPT-Ranger system. All recovered samples (length = 50 cm, diameter = 7 cm) were carefully transported to Graz University of Technology and further investigated at the geotechnical laboratory. The sediments were characterized with respect to their particle size distribution, Atterberg limits, natural density, natural water content and oedometer stiffness. Furthermore, the shear wave velocity of reconstituted soil samples was determined at different insitu stress levels using bender element tests within a triaxial cell. All reconstituted soil samples were artificially mixed considering the insitu density and water content.

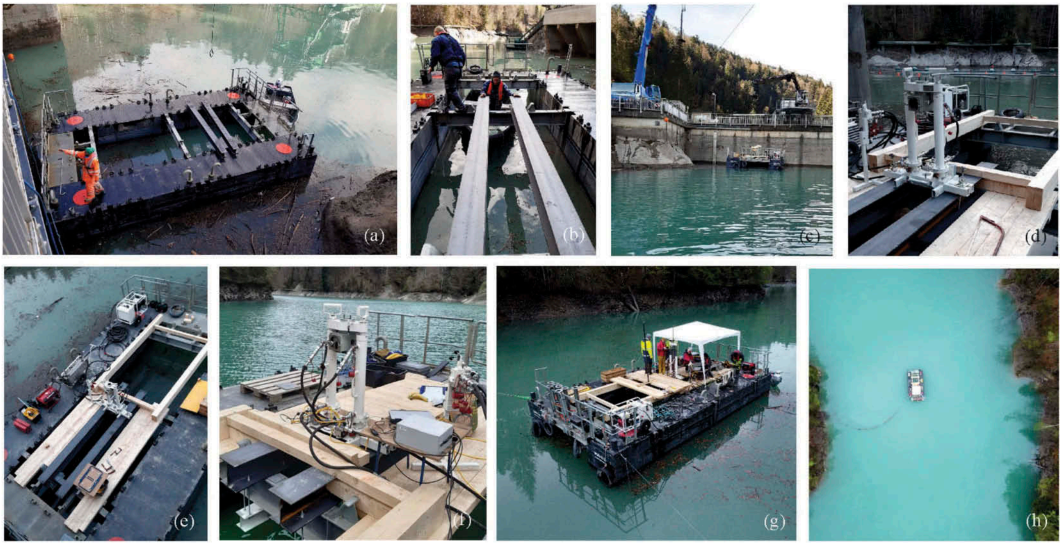

Figure 2. Test execution: Floating pontoon and pushing device.

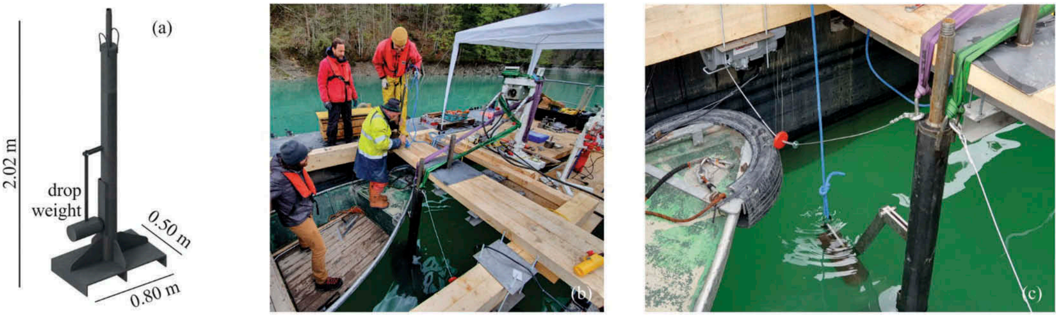

Figure 3. Test execution: Seismic measurements.

5 RESULTS

5.1 *Insitu and laboratory results*

The sedimentation history of the water reservoir Raggal is composed of a sequence of fineand coarse-grained layers. As shown in Figure 4, these sand-silt alterations are characterized by an erratic distribution of CPTu measurements over depth (lithology L1). The tip resistance q_c and sleeve friction f_s vary between 0.7 - 3.5 MPa and 5 - 50 kPa respectively. The measured pore water pressure u_2 corresponds to the hydrostatic (insitu) pore water pressure u_0 within sand-dominated layers and rises ($u_2 > u_0$) with higher fines content. This varying trend is also reflected by DMT intermediate parameters I_D (= 0.4 - 5), K_D (= 0.5 - 6) and E_D (= 0.5 – 12 MPa) in Figure 4.

The soil behaviour type index I_C – based on Robertson 1990 – classifies the sediments as “silty sand to sandy silt” and “clay to silty clay” (see Figure 4d). The DMT classification system according to Marchetti (1980) is based on the material behaviour index I_D and leads to a similar result (“silty sand to sand” and “clayey to sandy silts”).

In a second step, all recovered soil samples have been classified based on their particle size distribution and Atterberg limits according to EN ISO 14688-1 and ASTM 2487-11 (USCS). The particle size distribution of five depths is presented as a bar chart in Figure 5a (red = clay, green = silt, blue = sand). It is evident that sections with increased sand content are represented by higher I_D (DMT) and lower I_C (CPTu) values. On the other hand, four soil samples - classified as clayey, sandy silts (cl’ sa’ Si) according to EN ISO 14688-1 - have been recovered within fine-grained sections. These sediments present a fines content (<0,075mm) larger than 90 % and are classified as organic silts (OL, OH) based on USCS (see Figure 5c). Due to their high organic

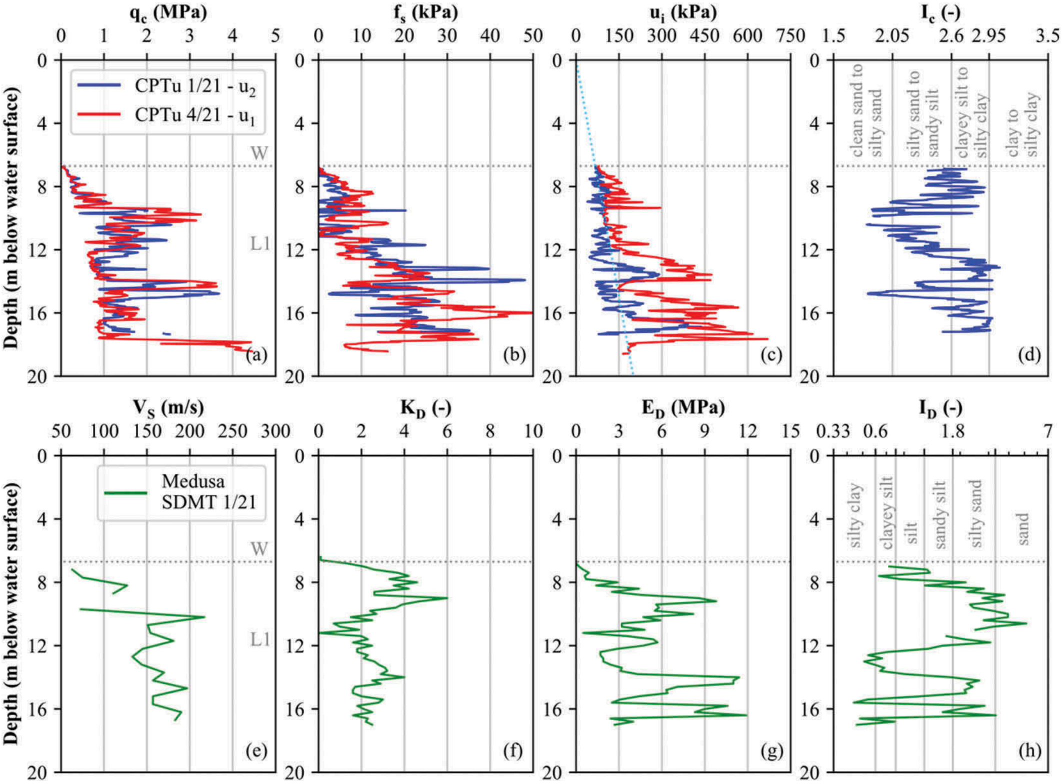

Figure 4. CPTu and SDMT results: (a) tip resistance q_c, (b) sleeve friction f_s, (c) dynamic pore water pressures u_1 and u_2, (d) soil behaviour type index I_C, (e) shear wave velocity V_S, (f) horizontal stress index K_D, (g) dilatometer modulus E_D and (h) material behaviour index I_D.

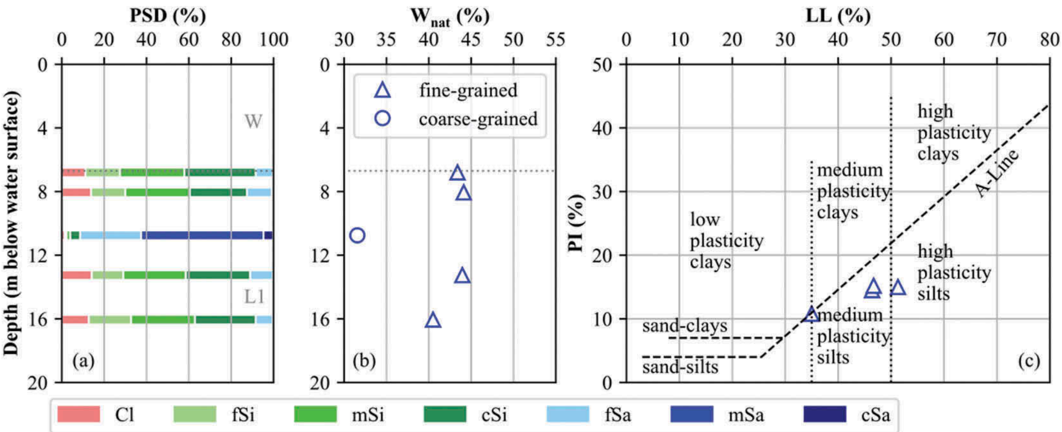

Figure 5. Laboratory results: (a) particle size distribution PSD, (b) natural water content w_{nat} and (c) Atterberg limits.

content (2-3 %), all points are situated below the A-line within the Casagrande diagram.

A small insitu density ($\rho_d \approx 1.2$ g/cm³, $\rho_{sat} \approx 1.75$ g/cm³) and a high natural water content $w_{nat} > 40$ % was expected and furthermore determined within fine-grained (under-consolidated) layers. Nevertheless, it should be noted that natural water contents decrease and insitu densities increase with increasing particle size distribution.

5.2 *Microstructure*

The insitu shear wave velocity $V_{S,SDMT}$ determined by means of Medusa SDMT is presented in Figure 4e. As described earlier in section 4.1 for CPTu and DMT measurements and intermediate parameters, also the shear wave velocity is strongly influenced by the particle size distribution. Thereby, layers of higher sand-content are characterized by higher V_S values.

In order to quantify the degree of microstructure, bender element tests were performed in a second step on reconstituted soil samples using a triaxial device. It is important to note that material of soil samples recovered at -6.8 m, -8.1 m, -13.3 m and -16.1 m (all characterized by a similar particle size distribution as shown in Figure 5a) was used for this experimental approach. After a K_0-consolidation, the shear wave velocity was determined for different insitu stress levels. The bender element results are shown in Figure 6a by blue triangles and are compared with SDMT results. Thereby, a regression (grey dotted) line - which goes through fine-grained sections where soil sampling was executed - is used for comparison. Based on the ratio $V_{S,BE}/V_{S,SDMT}$ it is evident that shear wave velocities determined in the laboratory by means of bender elements ($V_{S,BE}$) and in situ using Medusa SDMT ($V_{S,SDMT}$) are in good agreement. Since $V_{S,SDMT}$ and $V_{S,BE}$ differ only slightly, it can be assumed that the investigated sediments within the reservoir Raggal are characterized by no or moderate microstructure.

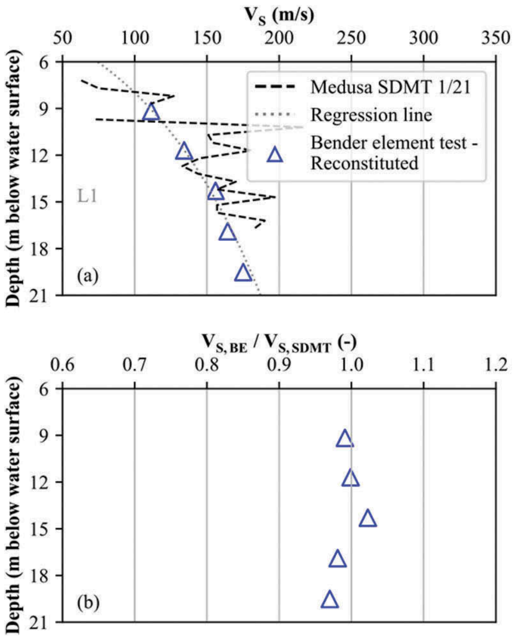

Figure 6. Shear wave velocity V_S: Comparison of SDMT and bender element tests.

6 CONCLUSION

Alpine regions are often characterized by basin landscapes, which were filled by fine-grained sediments after the last glacial period. These (normally to slightly under-consolidated) sediments often show small settlements under static loading, leading to the assumption that they might be characterized by a microstructure. Various authors (e.g. Robertson 2016) showed that structured soils present a higher shear wave velocity compared to unstructured (ideal) soils. The present paper investigated whether and to what extent young sediments, deposited in the water storage reservoir Raggal, are characterized by microstructure. In a first step CPTu, Medusa SDMT and soil sampling was performed from a floating pontoon using a mobile pushing device. The investigated sediments are composed of sand-silt alternations and are characterized by a small insitu density and a high water content $w_{nat} > 40$ %. In a second step bender element tests were performed on reconstituted soil samples and compared with the SDMT results. It was shown that shear wave velocities determined on reconstituted soil samples are in good agreement with SDMT results ($V_{S,BE}/V_{S,SDMT} \approx 1$), indicating no or little microstructure. Within the research project PITS, similar investigations have been performed in older sediments (e.g. rhine valley, basin of Salzburg) too. In these cases $V_{S,BE}/V_{S,SDMT}$ ratios were significantly smaller than 1, indicating a stronger microstructure in postglacial deposits. The present contribution showed that $V_{S,BE}/V_{S,SDMT}$ ratios are a potential indicator to quantify and characterize soil microstructure.

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