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Structure investigations of layered soil – varved clay

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Abstract: *Structure investigations of layered soil – varved clay.* In the paper the results of laboratory investigations of structure of layered soil are presented. They focus on varved clay that is a soil composed of two alternately arranged varves with different texture and mechanical properties. An effect of such structure is an anisotropy of the material. Due to varying conditions during its formation process the soil exhibits some irregularities in composition and structure. Due to that modelling of mechanical behavior, like strength, may not provide satisfactory results. Main purpose of the examinations is an investigation of internal structure of layered soil – varved clay – in relation to its strength anisotropy and evaluation of the suitability of the use of two different techniques to assess the soil structure. Investigated material have been taken from area near city of Belchatów in central Poland. The examinations included investigation of particle size distribution of soil and its components, identification of lamination with use of scanning electron microscope (SEM) and computed microtomography technique (μ CT). First, the texture of each varve and varved clay as a composite have been estimated. Next, the investigation of surface perpendicular to the lamination have been carried out with SEM. Pictures of varves with different magnifications are presented. Also the varves arrangement and details of layers contact area are shown. Finally, investigation of internal structure of the soil have been performed by using microtomograph. The outcome is a series of radiographic images and reconstructed 3D model of tested soil. Presented results show complexity of the structure of varved clay that affect the mechanical behavior. Determination of the structure with use of presented techniques may be helpful in examination of strength properties and proper modeling of such soil.

Key words: varved clay, layered soil, structure, scanning electron microscopy, microtomography

INTRODUCTION

Varved clay is a clayey sedimentary soil, formed in glacier lakes, with visible layering. It is composed of two periodically repeated layers: dark (silty-clayey) and bright (silty-sandy) ones. During warm periods, when the glacier was melting, deposits were carried into the lake where coarser particles were deposited and composed light varves. In cold periods, when the lake was frozen, fine particles precipitate forming dark varves. The investigations of properties and structure of varved clays have been conducted by many authors. The characteristic and basic geotechnical parameters of Connecticut Valley varved clay have been described by De Groot and Lutenecker (2005). Similar scope of research have been presented by Lu et al. (2013) for deposits occurred along the Delaware River. In turn, Petterson et al. (1993) focus on variability of varve thickness of the varved clay in northern Sweden. Varved clay occurred in Poland have been investigated, i.e. by Myślińska (1965) and Kostrzewski and Florkiewicz (1995).

The consequence of layered structure is an anisotropy of mechanical behavior of the material. However, varying sedimentation conditions during its formation process cause irregularities in structure of the soil. Each varve can have different texture, thickness and mechanical properties. Due to this testing of mechanical properties, like strength, of such soil is troublesome. Moreover, it is difficult to generate directional failure characteristics, like for layered rocks (Ramamurthy 1993, Duveau et al. 1998), with adequate confidence. Due to this also modelling of mechanical behavior of the material is not a trivial issue. Main purpose of the examinations are an investigation of internal structure of layered soil – varved clay – in relation to its strength and evaluation of the suitability of the use of different techniques to assess the soil structure.

The article deals with varved clay occurred near city of Bełchatów, in central part of Poland. The laboratory examinations included investigation of particle size distribution of soil and its component varves, identification of lamination by using scanning electron microscope (SEM) and computed microtomography technique (μ CT). The following study focuses on macro scale, i.e. the layering and its possible impact on mechanical behavior of the material.

MATERIAL AND METHODS

The samples of varved clay were taken from an open-cast mine KWB Bełchatów, from the depth nearly 30 m below original ground level. Tested material, presented in Figure 1, is composed of dark layers with thickness up to about 5 mm and very thin bright varves. The results of investigations of strength ani-



FIGURE 1. Varved clay and its laminated structure

sotropy of the soil were presented earlier by Łydźba and Tankiewicz (2012) and Tankiewicz (2015a, b). Based on series of triaxial tests performed for different confinement and sample orientation author established directional failure characteristics for the material. The soil exhibits a high strength anisotropy that is associated mainly with occurring failure mode. Specimen may collapse by slipping across or along the varves, but in many cases the mechanism is more complex. It have been noticed that even for particular confinement and sample orientation the large scattering of estimated strength values is quite large. Utilization of normalization procedure improves the results, however, the scatter still can be observed, especially for lower confinement. Therefore, investigation of structure and composition of the material have been performed.

The particle size distributions of varved clay as a unity and bright and dark varves separately are presented in Table. The data have been obtained from three different representative samples taken for each varve and the varved clay. The analysis have been carried out with hydrometer method according to PKN-CEN ISO/

/TS 17892-4:2009. Classification of samples have been conducted in accordance with PN-EN ISO 14688:2006 and PN-EN ISO 14688-2:2006/Ap2:2012. The texture of dark varves is quite uniform. Dark layers consist mainly of clay fraction (diameter below 0.002 mm) and silt fraction (0.002–0.063mm) and they have been classified as a clay (Cl). The composition of bright layers is more variable, but the main fraction is silt. The percentage amount of sand (0.063–2 mm) is between 5.7 and 22.9%. The amount of silt is between 52.5 and 71.8%, for clay fraction it is around 20%. They have been defined as a silty clay (siCl) or sandy silty clay (sasiCl). For varved clay the amount of sand, silt and clay is 2.4–3.6, 53.2–67.7 and 28.7–44.4%, respectively. It can be named as a clay (Cl) or silty clay (siCl). The texture of varved clay isn't proportional to the texture of its constituents, which suggest that the percentage share of both varves is also various.

In order to determine the structure of the soil a series of laboratory tests have been conducted. First, the examinations with scanning electron microscopy (SEM) have been made. The instrument,

TABLE. The texture of tested material

Texture	Fraction content (%)				Type of soil
	sand 0.063–2 mm	silt 0.002–0.063 mm	clay <0.002 mm	silt + clay <0.063 mm	
Dark varves	0.2–0.4	36.5–51.2	48.6–63.1	99.6–99.8	Cl
Light varves	5.7–22.9	52.5–71.8	18.7–24.6	77.1–94.3	siCl/sasiCl
Varved clay	2.4–3.6	53.2–67.7	28.7–44.4	96.4–97.6	Cl/siCl

utilizing an electron beam, permits observation and characterization of a material and its surface. This technique is widely used in geosciences since the 1970s (Collins and McGown 1974, Al-Rawas and McGown 1999, Romero and Simms 2008). The images of varved clay from different parts of Poland have been presented by Grabowska-Olszewska et al. (1984). However, in the study authors focus on microstructure of soils. In this paper rather the macro scale, i.e. lamination thickness and its arrangement is considered. The investigations have been made with tabletop microscope TM3030 Hitachi on four representative samples with dimensions $20 \times 20 \times 20$ mm. Investigated surface has been perpendicular to the lamination.

Next, a non-destructive imaging method – computed microtomography (μ CT) – have been used. It is rapidly evolving technique that allows visualization of internal structure of materials. A series of radiographic images is used to reconstruct a three-dimensional model of scanned object. The images record differences in the degree of X-ray absorption, which depends on electron density, energy of the radiation, and bulk density of the material (Ketcham and Carlson 2001). The description of the technique and its applications were presented, i.a. by Taud et al. (2005), Lenoir et al. (2007), Pires et al. (2010). The examinations have been carried out with Sky-Scan1172 high-resolution X-ray microtomograph on representative specimen

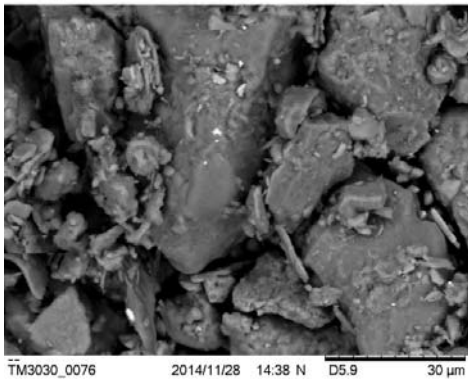
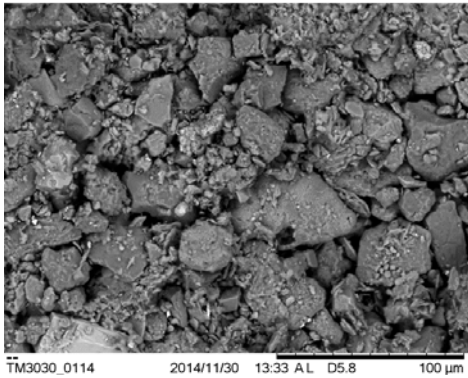
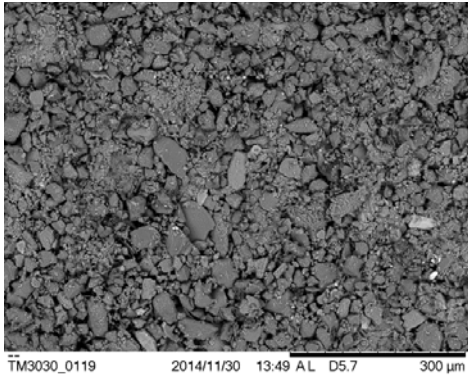
with diameter 38 mm and height around 30 mm. The lamination angle specified macroscopically was 15° . For attenuation evaluation purpose the sample with dimension $10 \times 10 \times 10$ mm was used.

RESULTS AND DISCUSSION

Microscopic observations using SEM allowed to identify the layering of tested soil. The material was observed at various magnifications and different settings in order to achieve the best images. The first observation was the differences in images of dark and light varves due to different texture of it. In Figure 2a the views of bright varves are presented at magnifications 250, 800, 2,000. Figure 2b shows the views of dark varves at the same values of magnifications. For silty-sandy light layers grains are clearly visible. During tests they have been measured and their diameter is between $30 \mu\text{m}$ (0.03 mm) and $200 \mu\text{m}$ (0.2 mm). That corresponds to the diameters of sand and silt fractions. Clayey-silty dark varves at this magnifications seems homogenous, what is associated with much smaller diameters of particles constituting them. The size of silt particles is from 2 to $63 \mu\text{m}$ and for clay particles it is below $2 \mu\text{m}$. At greater magnifications they were also observed.

During the investigations it was confirmed that a thickness of varves is variable. The thickest layers have up to 5 mm, but it was impossible to measure the thinnest ones without additional equipment. With the aid of microscope

a



b

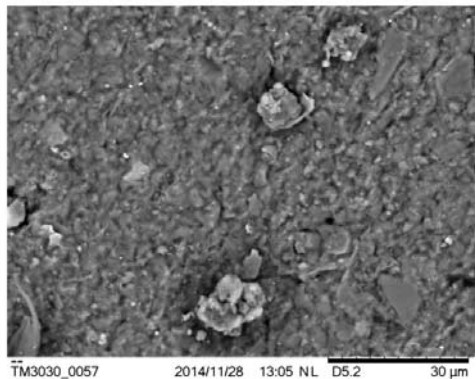
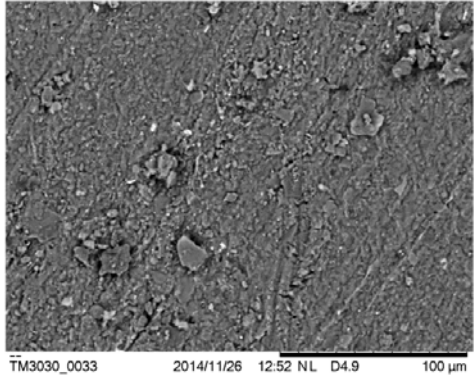
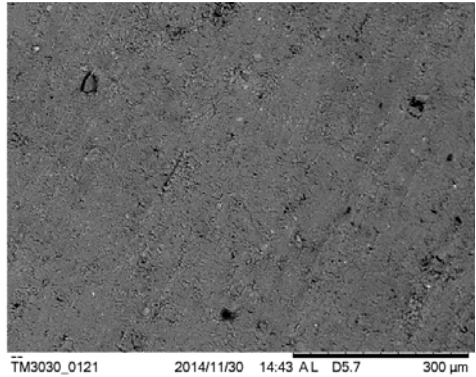


FIGURE 2. View of layers for magnifications 250, 800, 2,000: (a) bright silty-sandy, (b) dark clayey

they have been identified and measured. The images of stratification are provided in Figure 3. Thickness of thinnest varves

is about 150–200 μm. The precise measurement of the thickest layers was not possible due to size of observation field

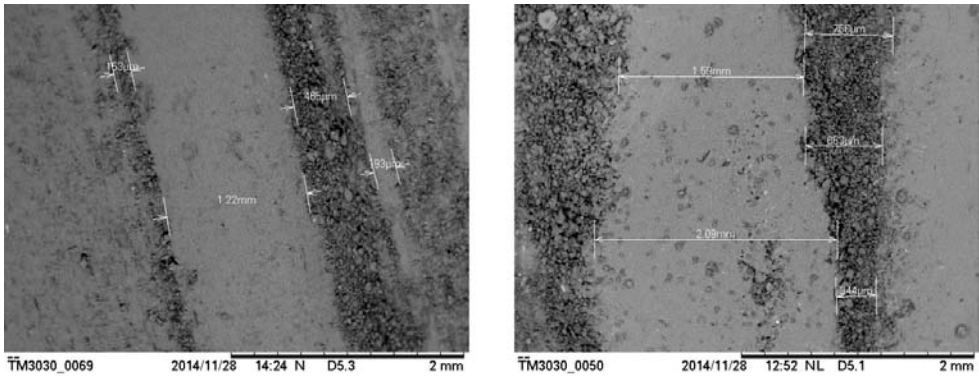


FIGURE 3. View of stratification of the varved clay

at minimum magnification ($50\times$). Subsequent layers have different thickness, which is effect of variable amount of deposit supplied in a given period. However, even for a specific varve, the thickness is not constants and can vary. Moreover, in some cases there is no possibility to distinguish the varves. Another issue is a layers contact area. Details of it are presented in Figure 4. Big difference in texture in dark and bright varves causes that the connection of layers is non-linear. Rather smooth transition one varve to another or corrugated contact line is observed. It is difficult to recognize the exact contact line, which can have great importance in case of material behavior during failure, especially in case of slipping along the lamination.

Scanning with μ CT permitted to reconstruct a spatial structure of tested soil. The specimen of varved clay was tested several times with different settings and resolutions to obtain the most pronounced image. The best quality images have been achieved by scanning

with voltage 89 kV, exposure time 960 ms, rotation step 0.15° and applying an aluminum and copper filter. The outcomes of μ CT scanning are presented in Figure 5. In the cross-sections (Fig. 5a) darker fields correspond to dark clayey varves and lighter ones – to sandy bright layers. In 3D reconstructed model (Fig. 5b) – colors are inversed. At both illustrations the layering is well visible. It is hard to distinguish specific varves, however, the general trend of lamination can be observed. Furthermore, it can be noticed that the stratification surfaces are not linear, but curved. Therefore, determining the precise orientation without such test is difficult, which may affect the evaluation of sample orientation and, in consequence, directional failure characteristics. Performing the internal structure examinations is necessary for the proper identification of the lamination trend. Nevertheless, taking account a non-linearity of lamination in modeling is problematic.

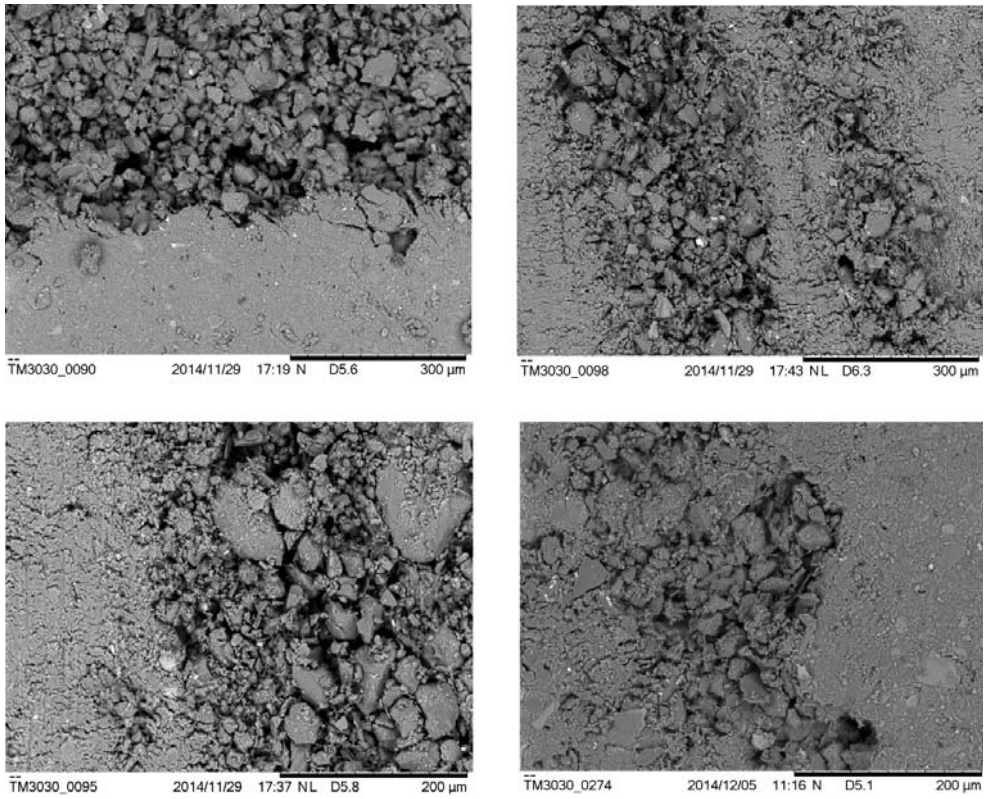
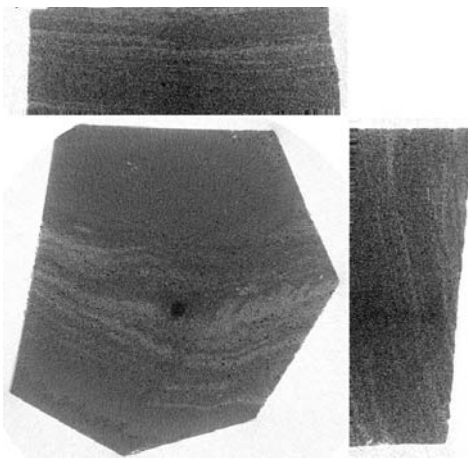


FIGURE 4. View of layers contact area

a



b

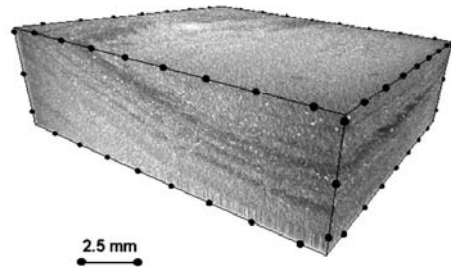


FIGURE 5. Results of μ CT scanning: (a) cross-sections of the sample, (b) model 3D

Next step was the separation of both types of varves by analysis of attenuation. The intensity of color in a greyscale in images created by μ CT is associated with X-ray absorption rate. Based on the analysis of image and color distribution components of the object with different absorption coefficient can be distinguished. In Figure 6 the view of the sample and graph of brightness of pixels in a section through the height of specimen are provided. The value 0 in grayscale corresponds to black, i.e. material with the lowest radiation absorption – air. The higher values matches to higher absorbed radiation. In a single cross-section of dark clayey varve the values of color vary from 130 to 220. For bright varve it is a little less, i.e. between 100 and 210. Analysis of full sample volume

allows separation of layers in a cross-section through the lamination. At the height of the sample color value of each section have been averaged. In Figure 6a some cracks can be seen. They were formed due to long time of scanning procedure and, in consequences, drying of the sample. During analyses they were omitted. For dark layers the mean value of color is about 175 and for bright ones about 150. In Figure 6b change in values is visible and consistent with the sample view. For the varves the attenuation differs and the transition between the layers is noticeable. However, it is indistinct and the difference in absorption is not very high.

Performed examinations allow to formulate the proposals for the evaluation of structure of layered soil in respect to

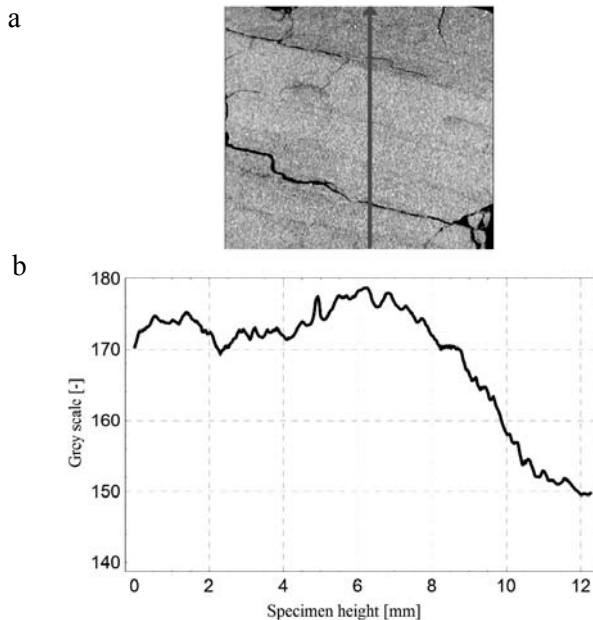


FIGURE 6. Attenuation for 3D sample: (a) view of specimen, (b) attenuation profile

strength properties and modeling of the material. Estimation of varves arrangement with use of SEM might be helpful. In cases of two-component mathematical models for which is essential to determine the share of each component such test will be adequate. However, due to variable thickness of layers it would be necessary to conduct a number of tests. On the other hand, the microtomography can be a useful tool for evaluating the results of strength examinations. Before the test, it permits to visualize the internal structure and layering of the sample. In case on anisotropic material adequate identification of orientation of the specimen is very important and difficult during sample cutting. The advantage of this test is its nondestructive character so the specimen can be subjected to further tests. After the test, next scan may allow for determining the exact trajectory of the failure surface and its position with respect to the layering. Utilization of μ CT for interpretation of shear strength test results for clayey soil have been presented earlier by Stefaniuk et al. (2014). Such approach would allow for better analysis of obtained strength results and taking into account structural effects on the modeling stage.

CONCLUSIONS

In the paper the results of laboratory examinations of structure of varved clay are presented. The study included tests with scanning electron microscope and microtomograph. Both techniques allowed

for investigation of layered structure of the soil. Scanning electron microscopy is a tool permitting the evaluation of thickness of varves and its arrangement. In structure of investigated material a lot of irregularities have been observed. The layers in the soil have different and variable thickness and the contact between the layers is quite complex. Computed microtomography allowed for three-dimensional evaluation of stratification of the material, which turned out not to be planar. Such features of the material affect its strength and failure modes and impede proper modelling and predicting its mechanical behavior. Varved clay, on account of its formation process, have a complex structure that cannot be described by simple bi-component material with periodically repeated same layers. However, determination of the structure with use of presented techniques may be helpful in examination of strength properties and mathematical modeling of such layered material.

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Streszczenie: Ocena struktury gruntu warstwowego – iłu warwowego. W artykule przedstawiono wyniki badań laboratoryjnych struktury gruntu warstwowego. Analizowanym materiałem był ił warwowy – grunt zbudowany z dwóch naprzemiennie ułożonych warstw o różnych składzie granulometrycznym i parametrach mechanicznych. Efektem takiej budowy jest silna anizotropia ośrodka. Ponadto ze względu na zmienne warunki w trakcie procesu formowania, ił warwowy wykazuje pewne nieregularności w składzie i budowie warw. Wobec tego określenie wytrzymałości i identyfikacja modelu matematycznego dla takiego ośrodka są problematyczne.

Celem badań był opis budowy iłu warwowego w odniesieniu do anizotropii wytrzymałości materiału oraz ocena przydatności dwóch różnych metod do określenia struktury gruntu warstwowego. Analizowany ił warwowy pochodził z terenów w okolicy Bełchatowa. Badania laboratoryjne obejmowały analizę granulometryczną gruntu oraz identyfikację struktury: powierzchniową, z wykorzystaniem elektronowego mikroskopu skaningowego (SEM), oraz przestrzenną, z wykorzystaniem nowoczesnej techniki obrazowania, tj. mikrotomografii komputerowej (μ CT). W pierwszej kolejności wykonano badanie składu granulometrycznego dla iłu warwowego, jako całości, oraz dla obu warw osobno. Następnie przeprowadzono wzrokową ocenę struktury z wykorzystaniem mikroskopu SEM. W efekcie otrzymano zdjęcia warstw ciemnej i jasnej przy różnych powiększeniach, obrazy przedstawiające układ warstwowania oraz szczegóły kontaktu warstw. Ostatnim krokiem było badanie w mi-

krotomografie. Wynikiem takiego testu jest seria obrazów radiograficznych oraz zrekonstruowany model 3D skanowanego obiektu, co pozwoliło na przestrzenną identyfikację warstwowania. Uzyskane wyniki badań wskazują na dużą złożoność budowy iłu warwowego, co wpływa na jego mechaniczne właściwości. Wykorzystanie prezentowanych technik do oceny budowy gruntu może być pomocne w badaniach wytrzymałości oraz właściwym modelowaniu takiego gruntu.

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