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Research paper

Characteristic of small-strain stiffness of fine-grained soils based on advanced laboratory tests

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Abstract: The non-linearity of the modulus in the zone of small deformations has become one of the three basic concepts of modern soil mechanics, together with “effective stresses” or “critical state”. It is therefore necessary to obtain suitable parameters to describe these phenomena through the development of modern measuring equipment and new research methods. Limitations in the availability of the research area or research equipment indicate the need to create a data set, in the formula of regional assessments. The article presents a compilation of data on the deformation characteristics of soils covering about 75% of the country’s area, which are the most common subsoils for building. Descriptions, images of microstructures, and a record of mechanical parameters are presented for various age-old glacial clays and marginal clays and loesses. Emphasis is placed on parameters obtained from triaxial tests, including the determination of the shear modulus at small deformations obtained from BET measurements. In combination with the patented solution of sample strain measurement, complete deformability curves of the tested samples were obtained, indicating model reference curves developed for the above soil types. The statistically significant amount of data collected allowed the creation of a specific portfolio for selected soils as a starting point for assessing deformability. This corresponds to the current expectations regarding the characteristics of the behaviour of the substrate in the full spectrum of stresses and deformations, obtained from different types of tests, which, as in the case of soil stiffness degradation, together allow the correct determination of the necessary parameters.

Keywords: deformation tests, degradation curve, fine grained soils, loess, microstructures, soil stiffness

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1. Introduction

Facing the challenges and needs related to geotechnical designing, essential parameters have to be determined for the substrate described on the behavioural (and not only granulometric) level, according to the rule introduced by Robertson [1] – Soil Behaviour Type. Moreover, when determining, e.g. the strain modulus in soil, it is vital to consider the structure's real work, i.e. the moduli values should be quoted in the stress and strain range that the structure's interaction belongs to. Determining soil parameters always suffers from certain "indeterminacy". In this sense, indeterminacy means the effect of several factors we can influence (collecting and storing of samples, test method accuracy, interpretation of results) and independent factors resulting from natural variability of the soil characteristics (non-homogeneity of the material, degree of weathering, sedimentation conditions, consolidation conditions, the influence of glaciotectonic structures and deep frost penetration, etc.). Most of the unknown data in geotechnical designing is epistemological and results from a lack of knowledge, but other are random and reflect the intrinsic and co-existing soil features such as randomness and natural variability [2–4].

Generally, major uncertainties in geotechnics are caused by the inherent variability of features in the subsoil, limited information (related to identification) and incomplete information (related to methodological constraints) [5]. The dominant uncertainty related to the variability of the soil medium is typically imposed by the variability of nature caused by soil and rock formation processes and can be analysed for different rocks, from microstructures to regional forms and geological structures. Moreover, additional uncertainties occur in the case of problematic soils (e.g. swelling, thixotropic or settling soils) sensitive to environmental changes or if non-typical behaviour occurs because of changes resulting from cyclic loads or exposure to dynamic impacts. These items apply to designing when data uncertainties are accompanied by model uncertainties [6]. Currently, the analyses of building structure foundations are oriented to specific reliability levels and must include adequate parameters such as physical and mechanical properties, loads and intrinsic uncertainties. Although complex numerical analyses have become increasingly popular (and welcome), more straightforward and reliable engineering rules often turn out more reliable than scientifically advanced methods [7], especially once used in practice. It happens because the expected parameters for advanced models are not quoted based on dedicated research tools. Developing research methods (especially in situ and advance complex laboratory tests) in geotechnics entails a long-lasting implementation and validation process based on own (i.e. local) field experiences.

A proper characterization of behavior of fine-grained soils has significant practical implications for a number of geotechnical design problems. While laboratory tests are often preferred for the assessment of geotechnical parameters in controlled conditions, their statistically representative quantity is seldom available as they are relatively expensive and time-consuming. Therefore, the use of a database, as a complementary source of information, may be an interesting alternative for implementation in engineering practice. Although it cannot be treated as a substitute for the site-specific tests, it can significantly increase the reliability of parameter estimation and offer an additional guidance in selection of their characteristic values [8].

A triaxial apparatus is used as one of the preferred laboratory methods for obtaining soil strength and stiffness parameters of the soil. However, as such tests are relatively expensive and time-consuming, especially tests conducted for fine grained soils in drained conditions, the scope of testing program is often limited in the case of standard geotechnical investigation. As a consequence, a statistically representative number of tests may not be available to offer sufficiently reliable prediction of soil parameters without a reference to prior knowledge and comparable experience. In geotechnical practice, this is often done implicitly; however, a use of a database of previous test results can allow explicit comparison, and it is justified when parameter variability assessment is needed. Therefore, in limit state design framework, it can help in the selection of characteristic values based on derived ones [9]. Whereas, establishing databases for different types of parameters and various geographical locations can be used for benefit of probabilistic analysis in reliability based design (RBD) framework [10, 11].

The actual soil behavior depends on geological processes related to the original sedimentation and other post-genetic processes, as well as stress history, physical and chemical processes (e.g. age and cementation) [12]. Estimation of deformation parameters for natural normally consolidated (NC) soils from in situ tests is very well described, e.g. by Robertson [13] with many extensive publications attempting to address this issue (e.g. selected studies: [14–17]) and to give some proposals for interpretation (e.g. Annexes to Eurocode 7 Part 2 [18]). In the case of overconsolidated cohesive soils, a number of studies have been conducted to characterize various aspects of their behavior and variability (e.g. selected studies focused on overconsolidated soils) or directly on stiff clays and glacial tills (e.g. selected studies: [19–23]), and loess (e.g. selected studies [24–26]). However, these correlations between the results of borehole measurements and geotechnical parameters require regional determination or adaptation to local conditions in order to accurately estimate soil parameters [27, 28].

In Poland, Neogene clays (very similar with London clays) and Ouaternary glacial clays (tills) have been investigated for many years, but using an advance methods (with seismic instrumentation), to some extent mostly based on a limited number of laboratory tests, and recently on various in situ tests (e.g. selected studies: [28–32]). The results of parameters for loess can be found in the works [33, 34]. The majority of these studies, including laboratory and in-situ tests, aimed to establish some new correlations or validate existing ones that can be used in practice for parameter estimation. Additional difficulties refer to many other factors that have an influence on the soil properties [12]. One of them is the problem of estimating correctly deformation characteristic for overcosolidated (OC) soils.

Determination of soil-structure interaction demands that properly determined parameters should be used with a particular design method [35, 36]. In the case of deformation modulus determination, it is essential to take into consideration the moduli at corresponding stress-strain range of the particular construction together with possible dynamic loads. It means that these moduli should correspond to the so-called small strain, semi-elastic range of deformations. The realisation of the non-linearity of the stress-strain relationship has led to the need to measure soil stiffness over a range of small strains ($10^{-6} \div 10^{-3}$) and utilization of many methods for this purpose [37]. As described by (e.g. [38–40]), several in-situ and laboratory test methods are employed to determine the maximum shear modulus G_0 (from the shear wave velocity, Vs): Down-Hole (DH) and Cross-Hole (CH) seismic methods, Seismic Dilatometer Test (SDMT) and Seismic Cone Penetration Tests (SCPT), Spectral Analysis of Surface Waves (SASW), Bender Elements Test (BET), Resonance Column (RC). The Dilatometer test (DMT), Pressuremeter Test (PMT), Triaxial Test (TRX), Oedometer test (OET) are also performed to allow assessment of the stiffness of soils at moderate to large strains. It's mean that non-linear behavior of the soil can be determined by many in-situ and laboratory tests, but to get shape of this curve its necessary to make complex research (in situ and laboratory tests). In the case of overconsolidated fine grained soils, a number of studies have been conducted to characterize various aspects of their behavior and variability; majority of them focused on the area of the United Kingdom [41–45]. In Poland, these soils have been investigated to some extent, mostly based on a limited number of data points or based on various in situ tests, however [46–49]. Majority of these studies aimed to establish new or validate existing transformation models used for parameter estimation.

The paper focuses on the presentation of the overview of the database of triaxial test results conducted for soil samples taken in various regions of Poland. Three soil types were investigated, namely: clays, glacial tills and loess. Due to limitations of the paper, the presentation and the analysis of the results contained in the database has been limited mainly to small-strain stiffness.

Since the provisions of Eurocode 7 were implemented along with general global trends in geotechnical practice in Poland, field tests have become more popular, focusing primarily on cone penetration tests. CPT and laboratory tests combined with geophysical methods have been disseminated for over a decade. The application of these modern methods enables a much better (*complete*) description of the subsoil properties than in previous practices, but the tools require broad experience in interpreting the results.

The discovery of non-linearity of the strain modulus in the low strain zone ($\gamma_s = 10^{-6} \div 10^{-3}$) marked a significant step forward in soil mechanics [50]. The non-linearity phenomenon of shear characteristics and dilatancy was studied by many scientific centres where laboratories had long observed a decrease in the soil stiffness in the samples' shear tests for a broad range of non-dilatational and axial strain (e.g.). Observing the non-linearity of soil behaviour in the low strain zone, owing to local strain measurements (*on-sample sensors* according to [51]) in triaxial tests and then using bender elements and tests in resonance columns, helped discover the phenomenon and describe the characteristics of the modulus variability within the entire strain range (constant modulus values were previously used) – Fig. 1. The knowledge was disseminated owing to studies by [41, 52, 53]. Soil stiffness tests using different test methods and techniques were described, e.g. by [12, 16, 30, 39, 49, 54–60].

"Non-linearity of the modulus in the low strain zone" has become one of the essential terms used in contemporary soil mechanics, next to "effective stress" and "critical condi-

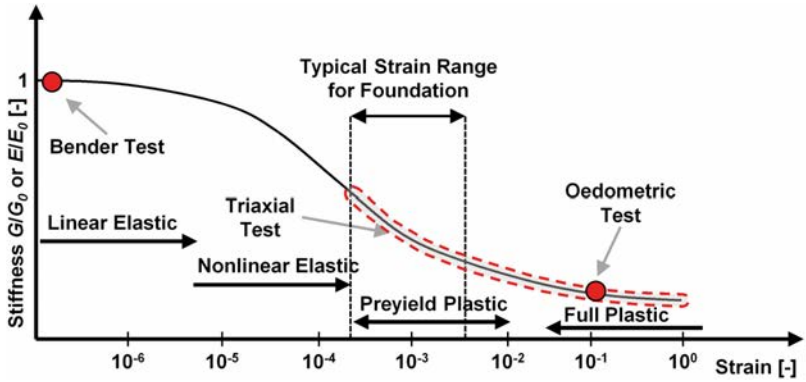


Fig. 1. Soil stiffness – degradation curve based on [14]

tion". They were implemented into advanced constitutive models to describe soil behaviour (*Typical elastic-plastic kinematically reinforced models*). This way, the need to obtain adequate parameters to describe the models gave grounds for developing state-of-the-art measuring apparatuses and new testing methods.

2. Material and metodology

Pleistocene glacial tills, Pliocene clays and loess were used; these soils can be encountered in most areas of Poland and they often are the main subject of investigation and laboratory tests conducted during standard geotechnical investigations. The geographical and geomorphological distribution of sampling locations is related to geological history of the investigated strata and the three major glaciation periods that resulted in their significant preconsolidation (clays and tills), loess are normal consolidated. To assess the properties of small-strain stiffness, a database for clays and tills described in detail in the work [61] was used. Against this background, the characteristics of loess as a problem soil due to the phenomenon of collapsed subsidence are presented.

Loess subsoil is the analysed subject. Loesses cover ca. 7% of Poland's territory [62, 82]. Wind significantly contributed to the formation of the loess cover. This soil type is considered peculiar and problematic as its structure often causes collapse settlement – some of the formations are macroporous. The findings presented in this article apply to soils from the Nałęczów Plateau near Lublin. The behaviour of loesses in other regions of Poland and the world can be identical, but regional specificity cannot be excluded since the behaviour of loesses formed in different periods and regions and with a contribution of other phenomena can vary significantly. Loesses are usually silt formations and transition soils on the borderline of cohesive and non-cohesive soils. It is reflected in the test parameters. Despite the silty fraction content of ca. 5÷10%, the soils usually behave like non-cohesive soil. The "sand-like" behaviour is revealed by SBT (Soil Behaviour Type) nomograms for CPTs (low R_f value and high q_c value) and the ID material index from the DMT ($ID > 1.8$). Typical loesses are characterised by zero readings of u_2 or by low vacuum. It comes from the unsaturated nature of their work. The q_c value decreases through diluvial or alluvial layers, and the u_2 water pressure in the pores increases. The R_f coefficient increases, and its waveform is typically highly diversified [33].

The term "loess" is generic and includes formations of purely eolicaeolian origin as well as loess-like formations that have developed or been partially transformed with the contribution of other factors. Considering all protogenetic, syngenetic and epigenetic processes related to loesses, facies characterised by diversified features are identified [63, 64].

Surveys were carried out using two triaxial testing devices. Tests were carried out on undisturbed soil samples of 70 mm diameter and 140 mm height or 38 mm diameter and 75 mm height. The triaxial chamber used in the tests featured internal rods, which enabled maintaining axisymmetrical test conditions. After mounting the chamber, placing the membrane and attaching the on-sample sensors, the samples were saturated using a compensating pressure method [65].

The pressure in the chamber and the back pressure increased simultaneously, which enabled maintaining constant effective stress in the sample. Each saturation step was maintained until the water stopped flowing into the sample and the water pressure in the soil pores became stable. After each saturation stage, the sample's saturation degree was checked by marking the Skempton B parameter. The specimens were saturated with an automatic pressure control algorithm. The final value of parameter B was less than 0.95. At the next stage, the soil samples were isotropically consolidated at four effective stress values of 50, 100, 200 and 400 kPa. Moreover, an additional sample was consolidated in several stages to the effective stress values of 25, 50, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000 and 1100 kPa. The consolidation process was completed when no more water flowed out of the sample and excess pressure dissipated in the soil pores. After the isotropic consolidation ended, the sample's shearing with the drained method was initiated. The sample's shear rate amounted to 0.07%/min.

After the saturation phase, the isotropic consolidation stage was carried out, followed by the S-wave transition measurements with bender element tests (BET). In the case of 38 mm diameter samples, both the shear wave and the compressional wave (P-wave) velocities were measured [66]. Five specimens were tested. Four of these had on-sample sensors and bender elements (BET) mounted. Encoder sensors were used for the tests [67]. The sensors were derived from Hall effect sensors [68]. Two sensors were used to measure the sample's axial strain and one radial sensor in a system proposed by [69]. The sample consolidated in many stages was intended only for studying the seismic wave velocity at the increasing value of effective stress. In the analysis of the signal, a method of visual interpretation of the signal was applied, where the main signal "peak" transition measurement was focused on the major first peak method [70, 71].

For the measurement of stiffness parameters in the small deformation range, the test rig used a test sensor system developed at ITB based on a magnetic linear encoder. A schematic of the test rig is shown in Fig. 2.

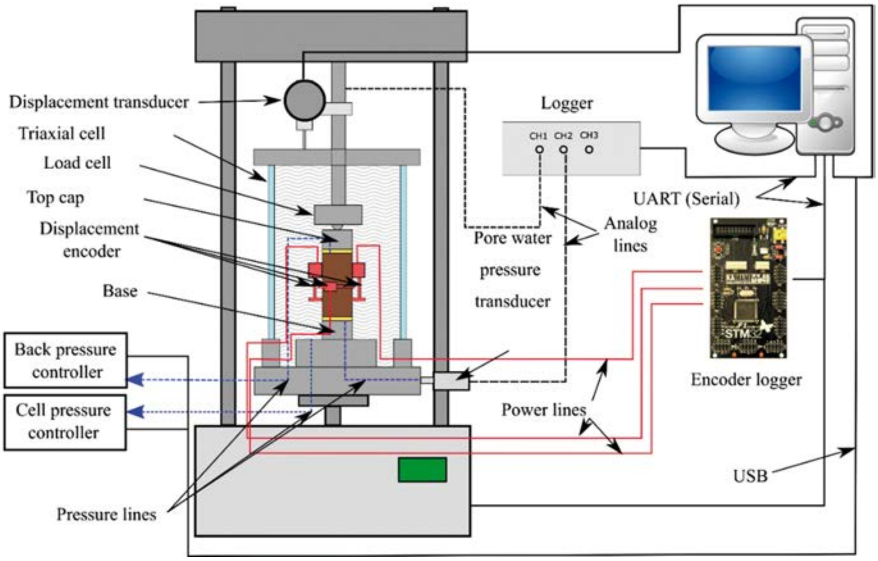


Fig. 2. A schematic of the test rig with triaxial cell and all measurement equipments [81]

3. Results

Together with the use of local displacement transducers developed in-house [67], during shearing, detailed results over the entire range of stiffness degradation were obtained for each sample. However, despite the availability of such detailed data, at this stage, basic soil parameters and obtained wave velocities are the primary concern of the current study, in relation to resulting small-strain stiffness characterization. More detailed analysis of other parameters (e.g. shear strength, stiffness at intermediate strains and its degradation) will be the subject of future studies as more data points are acquired.

The dataset presented in the paper consists primarily of the measured shear wave velocities in relation to the stress-state and the basic parameters of the soil. The properties expected to significantly affect the obtained results are: the effective confining pressure, natural water content (w_n), initial void ratio (e_0), plasticity index (PI) and bulk density. The measured local axial strain ε_a and radial strain ε_r were used to determine the shear strain ε_s:

$$\varepsilon_s = \frac{2}{3}(\varepsilon_a - \varepsilon_r) \tag{3.1}$$

Under axisymmetric test conditions, the response of the soil to a given load can be described by the shar strain modulus G. The secant of this modulus was determined from:

$$G = \frac{\Delta q}{3\Delta\varepsilon_s} \tag{3.2}$$

where: q – deviatoric stress.

Figure 3 shows the values of the shear wave velocity obtained during the tests and the values of the initial shear modulus derived from these values (Fig. 4). As can be seen, the values of both parameters for loess are between those obtained for clay and till.

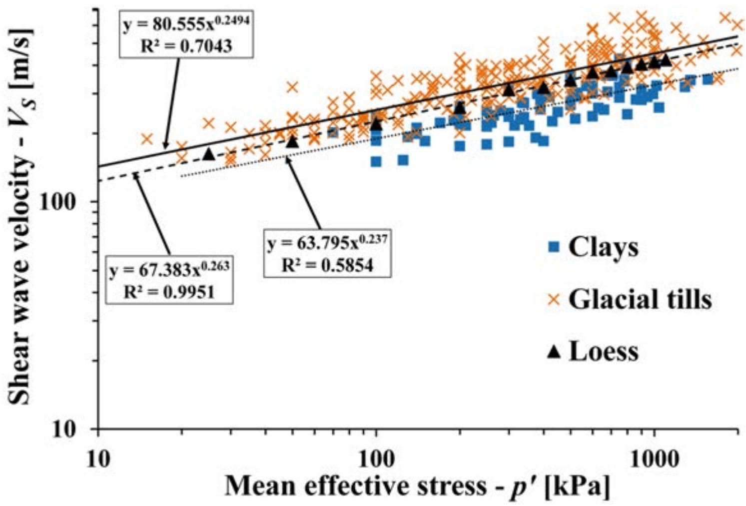


Fig. 3. Relation between shear wave velocity and mean effective stress for analysed soils

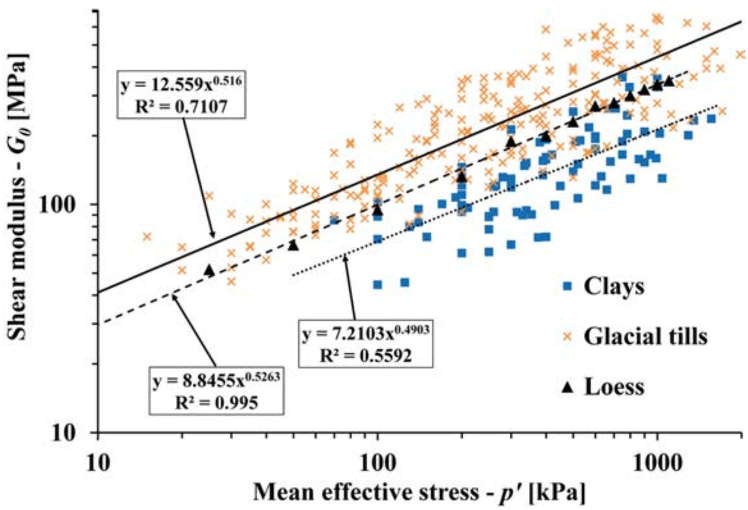
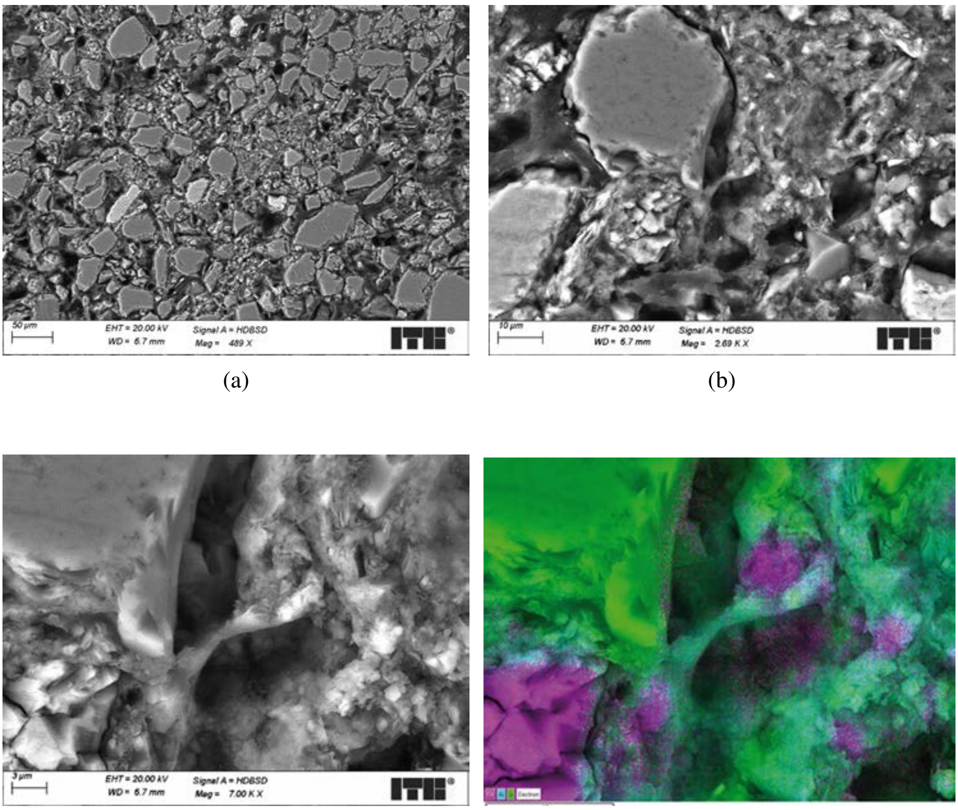


Fig. 4. Relation between shear modulus and mean effective stress for analysed soils

The following diagrams (Fig. 4) show the stiffness degradation characteristics for the three investigated soils. All samples were tested at similar values of effective stress.

The clay samples are characterised by the smallest horizontal spread compared to the other soils which may be mainly due to their internal structure (Fig. 4). The obtained shear wave velocity values were applied to the diagram showing the transverse wave velocity's dependence in the function of mean effective stress (Fig. 3). In general, the shear wave values for loess correspond to the results obtained for silts and glacial clay, and fall between the values obtained for these soils [61]. This is also due to their specificity, which is manifested at the level of microstructure.

The aerometric and sieve analysis authorises the statement that silty fraction with an 88% share dominates in the studied loess, followed by silty particles with an 11% share. One per cent share of sand is negligible, which leads to the conclusion that the studied loess is mainly composed of silty and silt fractions. This shows that the studied loess is in the context of classification proposed by [24]. According to the diagram, the referenced soil represents the silty loess category. For better illustration, a photo of the studied soil was taken with a scanning electron microscope Fig. 5. The method of preparing samples for



(a) (b) (c) (d)

Fig. 5. SEM micrographs showing an overall structure of the studied loess: (a) 500×, (b) 2700×, (c) 7600×, (d) EDS mapping 7600× (The green colour is due to the prevailing dominance of silicon (Si) atoms, the purple colour is from calcium (Ca) atoms and the light blue colour is from aluminium (Al) atoms)

testing and the techniques used during microstructural analyses using scanning microscopy were similar to those described in earlier publications [72, 73].

Structure observations were made using a scanning electron microscope (SEM) model Sigma 500 VP. The silty fraction's dominance is visible – its large particles are surrounded by several times smaller silty particles (Fig. 5a). Subsequent magnifications (Fig. 5b, c) show connections within the macroporous structure called silty bridges that determine the collapse settlement. The "chemical" image (Fig. 5d) obtained based on EDS mapping shows a distinct structure – connections between silty packets built of calcium aluminosilicates occur within the silt grains mainly built of silicon.

A similar granulometric composition and internal structure occur in loesses in central China, whose series stratigraphically belongs to a younger Lishi unit [26]. Moreover, the obtained values of plasticity index correspond to the results obtained for loesses occurring in western Europe, where the soils are characterised by a similar value of this parameter [25].

Loess samples for the non-dilatational strain of 0.002% revealed the shear modulus values between 50 and 200 MPa at the effective stress increase from 50 to 400 kPa (Fig. 6). It should be noted that the point at which the shear modulus value decreases significantly shifts as the effective stress rises. For 50 and 100 kPa stress, it occurs at 0.002%, for 200 kPa, it is observed at ca. 0.006% strain, while at the last stress stage – at ca. 0.01% strain. The diagram also shows the data obtained for similar soils w (I_P = 12÷14%, w_L = 25÷30%, w_P = 13÷15%) consolidated to the effective stress values of 404 kPa [74]. As can be seen, the soils in the Lublin area are characterised by the shear modulus value for the same non-dilatational strain twice higher than soils with a similar structure described in the literature. Moreover, the waveform of the degradation curve is convergent in the studies and literature results for soils.

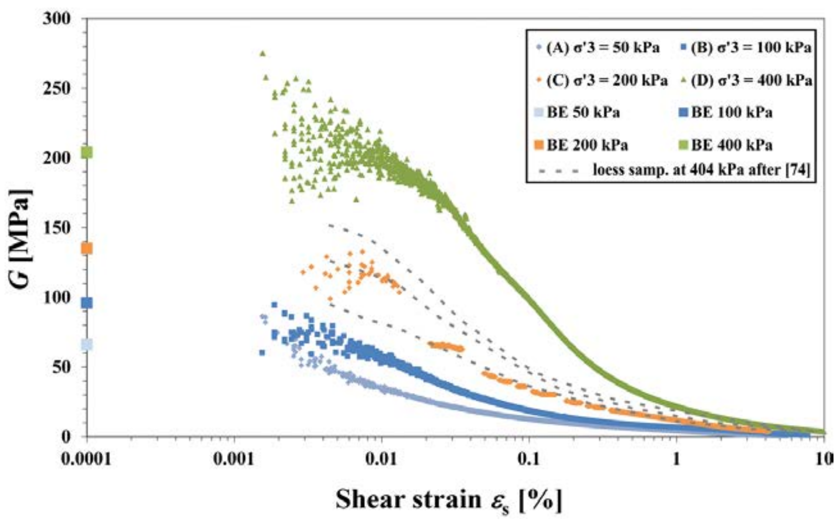


Fig. 6. Shear modulus degradation

4. Discussion

Knowing the value of the maximum shear modulus obtained in BET tests, the shear modulus value waveform was normalised in the function of shear strain (Fig. 7). As can be observed, the increase in the effective stress value causes the shift of the plot representing stiffness reduction to the right, which corresponds to the results obtained for other natural soils [75]. Again, the data for similar soils were compared with the locally obtained data. The stiffness reduction values are moved to the right against the values obtained for comparative soils, despite a lower value of the porosity index and effective strain, which are among the essential factors affecting the stiffness characteristics [76, 77]. It can also be seen that above 0.2% strain, stiffness degradation is higher than in other soils.

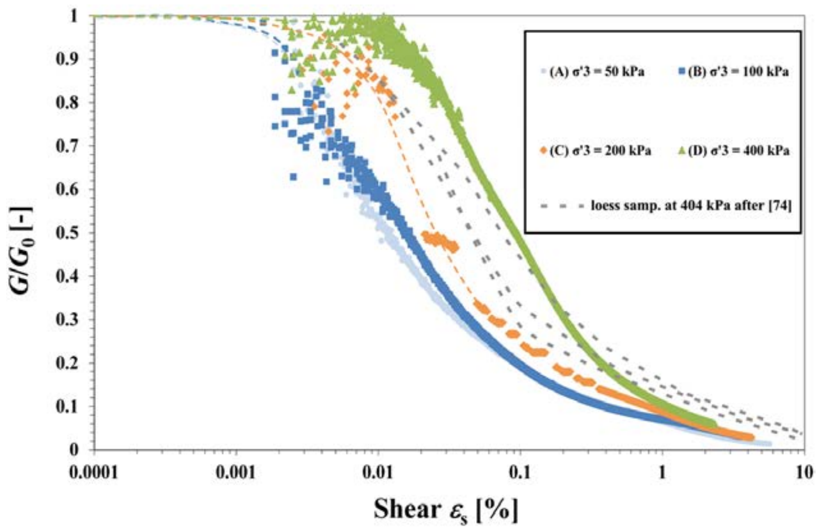


Fig. 7. Degradation curves for analysed soils

5. Conclusions

The relation between shear wave velocity and mean effective stress is presented in Fig. 3, and as expected, the increase in V_S velocity is visible along with the increase in effective stresses. Data showing V_S velocities for glacial tills are generally in line with data published by other researchers for similar soils from Poland as well as other regions [30, 78]. Furthermore, Fig. 4 presents the relation between initial (small-strain) shear modulus, calculated based on the measured shear wave velocities, and bulk density. Results obtained for glacial tills exhibit larger scatter than in the case of clays and loessess. Such results are to be expected considering the variability of soils generally classified as glacial tills.

Finally, analysis of relationship between small-strain shear stiffness and confining pressure normalized by atmospheric pressure (p_a), based on the identification algorithm presented by [79] was carried out. Obtained gradients of linear regression lines represent the stiffness exponents at small-strains, which can be used to describe stiffness-dependence of non-linear constitutive laws, e.g. parameter m for Hardening Soil model [80]. Values obtained for clays ($m = 0.490$), glacial tills ($m = 0.516$) and loessess (0.497) are in line with values observed for soils of various origins in other countries (0.400÷0.850), which were summarized by [79]. Obviously, for calculation purposes, such generalized values should be used with caution and only as a first rough calculation.

The paper presented the overview of a data containing advanced laboratory test results obtained for clays, glacial tills and loessess from various locations. The information on some of the parameters contained in the database was presented as well as relations between selected results. Due to the limitation of the paper and still initial stages of the study, the presented results are focused especially on small-strain shear stiffness.

Observed higher variability in initial shear stiffness for glacial tills can probably be attributed to broader definition of those soils than in the case of clays and loessess. Conversely, its stress-dependence, when defined as a power-law exponent, shows unanticipated resemblance.

Generally, the soil parameters presented herein should not be used as a substitute for proper geotechnical investigation; they can be referenced as a baseline for comparison or used as a supplementary understanding in the process of parameter selection.

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Charakterystyka sztywności gruntów drobnoziarnistych na podstawie zaawansowanych metod badań laboratoryjnych

Słowa kluczowe: badania odkształcalności, grunty drobnoziarniste, krzywe degradacji sztywności, lessy, mikrostruktura

Streszczenie:

Nieliniowość modułu w strefie małych odkształceń stała się jednym z trzech podstawowych pojęć we współczesnej mechanice gruntów, podobnie jak "naprężenia efektywne" czy "stan krytyczny". Tym samym konieczne jest pozyskiwanie odpowiednich parametrów do opisu tych zjawisk poprzez rozwój nowoczesnej aparatury pomiarowej i nowych metod badawczych. Ograniczenia w dostępności terenu badań czy aparatury badawczej wskazują na potrzebę tworzenia zbioru danych, w formule zestawień o charakterze regionalnym. W artykule przedstawiono kompilację danych w zakresie charakterystyki odkształceniowej dla gruntów zajmujących ok. 75% powierzchni kraju, stanowiących najczęstsze podłoże obiektów budowlanych. Przedstawiono opisy, obrazy mikrostruktur oraz zapis parametrów mechanicznych dla różnowiekowych glin polodowcowych i iłów zastoiskowych oraz lessów. Główny nacisk zostałpołożony na parametry uzyskane z badań "trójosiowych", w tym oznaczenia modułu ścinania przy małych odkształceniach uzyskane z pomiarów sejsmicznych metodą BET. W połączeniu z opatentowanym rozwiązaniem napróbkowego pomiaru odkształceń uzyskano pełne przebiegi odkształcalności badanych próbek wskazując modelowe krzywe referencyjne opracowane dla ww. typów gruntów. Istotna statystycznie ilość zebranych danych pozwoliła na stworzenie swoistego portfolio dla wybranych gruntów, jako punkt wyjścia do oceny zdolności deformacyjnych. Spełnia to obecne oczekiwania odnośnie charakterystyk zachowania podłoża w pełnym spektrum naprężeń i odkształceń, uzyskiwanych z różnego typu badań, które tak jak w przypadku degradacji sztywności gruntu zebrane razem pozwalają na poprawne wyznaczenie niezbędnych parametrów.

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