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Soil small strain parameters derived from wave velocity measurements

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Small-strain parameters of soil play an important role in modern civil engineering. It is common knowledge that the mechanical behaviour of soils is strain dependent. Engineering geologists should be aware of available test methods, both *in-situ* and laboratory, meeting the present day requirements in terms of the quality and adequacy of results. On the other hand, drawbacks and limitations of a particular solution force to combine different approaches. This article briefly describes two methods of determining the shear modulus of soil by means of seismic wave velocity measurement.

Key words: small strain, soil stiffness, surface seismicity, bender elements

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INTRODUCTION

Non-linear stress-strain characteristics of soils are well-known (Atkinson, 2000). The knowledge of their relation should imply methods used to determine soil parameters. Soil strain range during laboratory or field tests has to correspond with the strain range designed to be specific for a given engineering structure during its building and functioning.

An ideal solution seems to be determining a full range of stress-strain characteristics of soil with the use of many different methods and taking into consideration the results from specific ranges appropriate for the problem (Fig. 1). However, is too expensive for a widespread use.

Experience shows that very often settlement calculated on the basis of the stiffness parameters obtained with the aid of conventional tools (oedometer, traditional triaxial apparatus) takes too large values compared to real data (confirmed by real structure settlement measurements and the back-analysis of the parameters based on them). In other words, these stiffness parameters apply to strain ranges at which the structures are not usually allowed to work.

This encourages developing laboratory and field methods allowing to obtain soil parameters for the so-called small-strain range (Fig. 2). Such parameters, obtained from a reliable research, are essential for civil engineering designers while using modern techniques of design based on the computer-aided modeling approach employing the finite element method (FEM).

Two of the mentioned above methods are more and more widely used in practice by engineering geologists. One of them is considered an almost standard procedure by many laboratories. It is often referred to as the bender element method (BE). The other is an *in-situ* surface seismic method generally called SASW (Spectral Analysis of Surface Waves) with several modifications dependent on technical solutions, the number of geophones, etc. Both methods will be shortly described, and examples of soil stiffness parameters derived by them will be presented and analysed.

METHODS

Bender element system

The GDS bender element system was used by the author (Fig. 3). It enables measuring the *S* (shear, secondary) or *P* (primary) wave velocities of soil in a triaxial cell and thus calculating small-strain (in the range $10^{-6} \div 10^{-5}$%) parameters such as the maximum shear modulus *G*. The system uses pairs

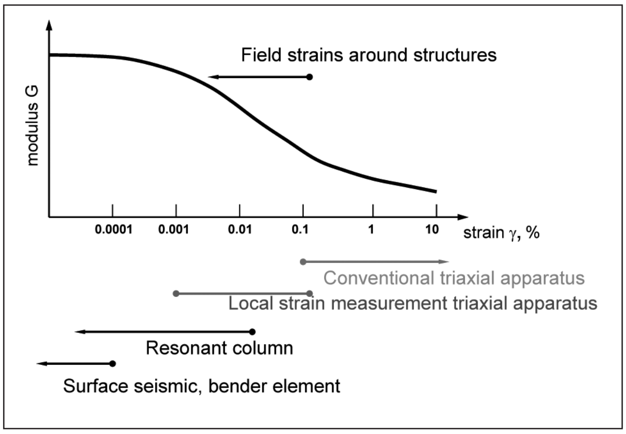

Fig. 1. Distribution of soil stiffness depending on strain level (Atkinson, 2000, modified)

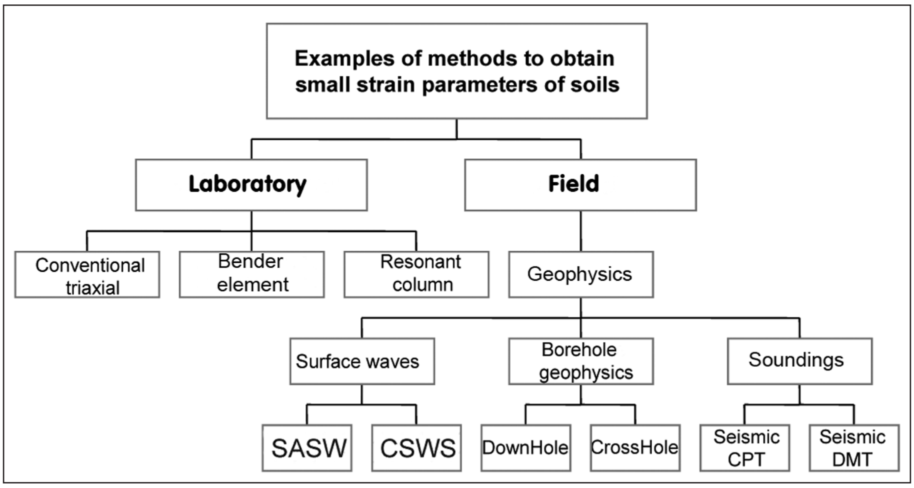

Fig. 2. Methods of soil small-strain stiffness determination

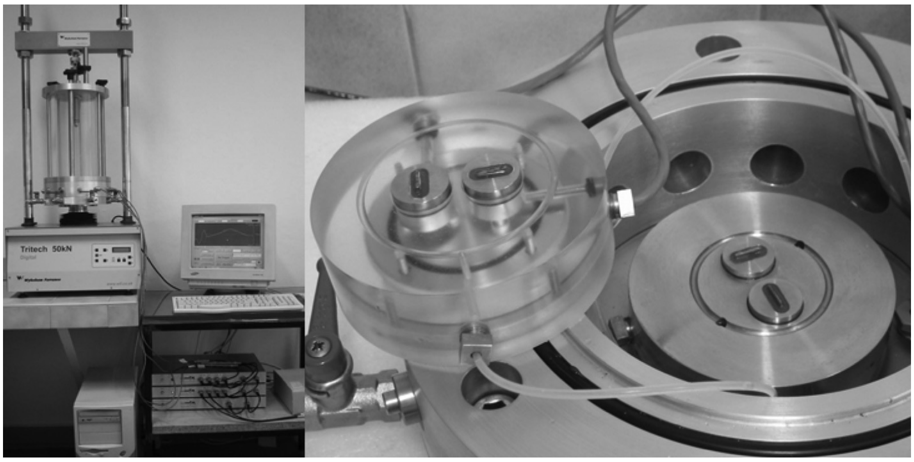

Fig. 3. Bender element system (the whole station – on the left, pedestal and topcap with BE – on the right)

of bender elements, a source and a receiver, to produce waves through the soil specimens. The elements are mounted in an adapted top cap and pedestal of a triaxial cell, and others can be additionally mounted to the sides of the sample. This allows measurements to be made across the height and diameter of a sample for both the vertical and the horizontal shear wave. Such approach enables determination of an anisotropy for the sample.

Bender elements are made from piezoelectric ceramic bimorphs. Two sheets are bonded together with a metal shim inbetween. An excitation voltage is used to produce a displacement in the source transducer, resulting in a wave sent through the sample. Depending on the polarization of sheets, *P* or *S* wave can be induced. This wave generates a displacement in the receiver, which induces a voltage that may be measured. The signal is conditioned in the external control box and sent to a computer through a high speed acquisition card. We may use any waveform of the input wave signal (sinusoidal, square, defined by the user). Through the computer software interface we can set the input wave parameters (period, amplitude), interpret, analyse and save the results. To sum up, the whole system consists of a triaxial cell with a modified pedestal and a top cap, four pairs of bender elements (two horizontally and two vertically propagating), control boxes, a computer with a high speed data acquisition card and software for test control and data acquisition for both *P* and *S* waves.

The measured *S* and *P* wave velocities may be used to calculate small-strain elastic parameters of soil as follows (Menzies, 2000):

shear modulus G_{max}:

$$G_{\max} = \rho V^2_s; \qquad (1)$$

compresion modulus *M*:

$$M = \rho V^2_p; \qquad (2)$$

bulk modulus *K*:

$$K = \rho(V_p^2 - \frac{4}{3} V_s^2); \qquad (3)$$

young modulus *E:*

$$E = 2\rho V_s^2 (1 + \nu); \qquad (4)$$

poisson ratio ν:

$$\nu = \frac{\frac{1}{2}(\frac{V_p}{V_s})^2 - 1}{(\frac{V_p}{V_s})^2 - 1}, \qquad (5)$$

where V_s is the *S* wave velocity, V_p is the *P* wave velocity, ρ is the bulk density of soil.

Surface seismicity method

The geophysical seismic surface testing has been applied in engineering geology since the 20th century and was discussed in the articles of Barański and Szczepański (2006, 2007). A group of methods using Rayleigh waves is commonly known as methods of surface waves or SASW Spectral Analysis of Surface Waves (Heisey, Stokoe, Meyer, 1982), although a variety of different modifications have been presented (CSWS, MASW).

The high potential of Rayleigh waves is based on the methods as an additional source of data and results from their non-invasive (therefore relatively cheap and fast) nature. It can serve as an additional tool to characterize the area among the study points (drillings and sounding points), at the same time verifying the variations of soil elastic parameters among the points. The soil stiffness profiles, i. e. the variation of the soil shear modulus $G_{\max}$ with depth, are obtained by the surface wave test. The results may be used in the settlement computing, the density control, the subsoil consolidation or the modelling of interaction between the construction and ground by means of programs using FEM. The advantage of this testing is the possibility of carrying them out on each stage of construction, also in deep excavations.

The investigation has been performed by using an apparatus designed and produced by the GDS Instruments Ltd (Fig. 4). There are two sub-methods used in the testing: SASW (Spectral Analysys of Surface Waves) and CSWS (Continuous Surface Wave System). In the SASW system, waves are induced by a hammer or some other object (depending on the needed range of frequency). The wide range frequency is generated. The wave spreads radiantly (similarly to the waves on the water surface) and reaches the geophones (from 2 to 6) arranged at known distances on a straight line from the source. The electric signals induced in the geophones are analysed with a computer using the FFT (Fast Fourier Transform) in order to find the wave phase difference on each of them. The CSWS system is different from the SASW; it has a vibrator with an inert mass of 63 kg. The electromagnetic vibrator is controlled by a computer, with software enabling to force vibrator frequency in the range of 6 to 600 Hz. It allows to control the investigation conditions more precisely: the lower the frequency of the surface wave, the larger the soil zone of elastic deformations. Changing the frequency of generated surface waves, a different depth of testing may be obtained.

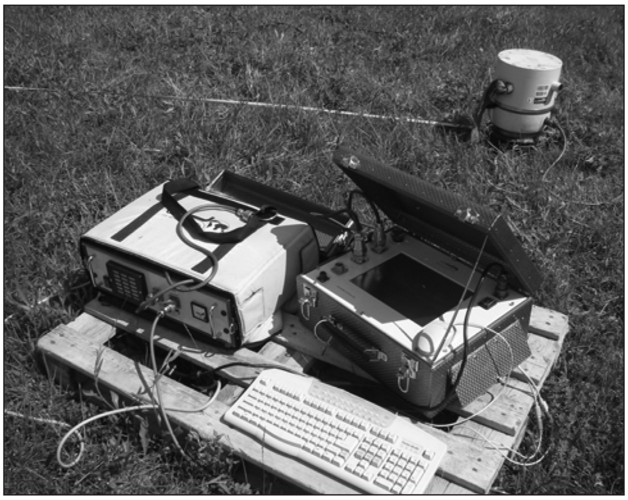

Fig. 4. Part of a seismic system. Control units (foreground), vibrator (background). Geophones not visible

The following calculations are performed: if we measure the phase difference ϕ between the geophones, with the known d, we can calculate the wavelength λ:

$$\lambda = 360d / \phi. \quad (6)$$

From the obtained wavelength λ and frequency f, surface Rayleigh V_R wave velocity is expressed as

$$V_R = \lambda f. \quad (7)$$

There is a relationship between the Rayleigh wave velocity V_R and shear wave velocity V_s:

$$V_s = PV_R, \quad (8)$$

where the parameter P is dependent on the Poisson ratio (for $\nu = 0.25$ we have $P = 1.09$, for $\nu = 0.50$ we obtain $P = 1.05$), usually the parameter P is assumed to equal 1.07.

The shear modulus may be finally determined from equation (1). Here, the following notations were introduced:

ν = Poisson ratio
v = velocity, m/s
f = frequency, Hz
λ = wavelength, m
D = geophone separation, m
ϕ = phase shift between two geophones, °
G = shear modulus, MPa
ρ = density, kg/m^3.

The above-mentioned stiffness profile of soil is obtained by applying a process called inversion to the experimental data.

There are mainly three approaches to the problem of inversion (Menzies 2000):

- factored wavelength method
- finite element method modelling
- linear models.

The first one is most commonly used, even though it is of least accuracy. Nevertheless, it allows to perform a quick data analysis even during the test. It assumes that the depth representative for a given frequency is constant, and usually the factor λ/3 is used to get a representative depth.

Others methods of inversion are far more complicated, time-consuming, demanding in terms of software tools. However, they seem to be irreplaceable in the case of intensively layered grounds with a strong diversity in the stiffness profile.

DATA AND DISCUSSION

The experimental data presented below have been gathered at sites in the Warsaw area. Three examples are shown. Site A is the Vistula River valley area, where under about 4 m of river sands Pliocene stiff clays occur. Sites B and C lay in a glacial till upland area where the soil profile generally consists of glacial till with sand layers.

The research has been aimed at checking how results of indirect geophysical tests (SASW and CSWS) will correspond with data obtained by a much more recognized test method (BES). The seismic test was performed with the use of both submethods, and the results were interpreted together.

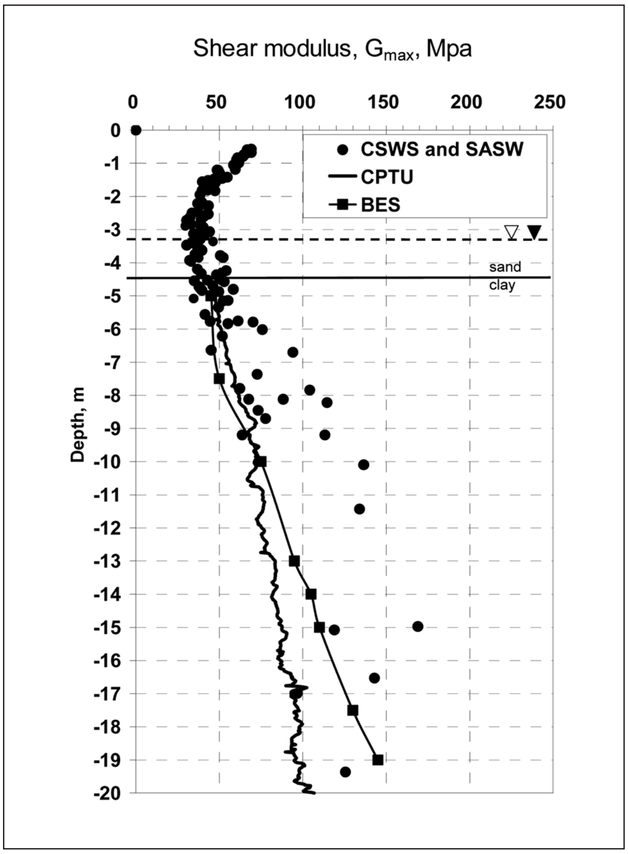

Fig. 5. Results of field and laboratory investigation (site A) (Barański et al., 2004; Barański, Szczepański, 2006). Shear modulus from CPTU test is calculated from empirical correlation (Rix et al., 1992)

Triggering the wave impulse with the use of a sledgehammer (SASW) and a vibrator (CSWS) gives different depth ranges of wave propagation, so both techniques used jointly give a better profile coverage. The BES test was performed with the use of only the best samples available, obtained with a Shelby sampler by drilling.

The results are presented in Fig. 5 and 6. The different depth of seismic wave penetration may be noticed. The depth is dependent on the soil profile and local condition, the average depth in Polish conditions being 10–15 m (Barański, Szczepański, 2006; 2007).

Figure 5 concerns results from site A, where other soundings were performed as well. One of them was a CPTU test. There is many empirical correlations in the literature to calculate the shear modulus G_{max} (among other parameters) from cone resistance and other data measured during standard soundings like CPT, DMT. One of them (from Rix et al., 1992) was used to calculate a shear modulus from the CPTU test. The calculated values in general had lower values than those obtained by other methods.

In the author's opinion, there is a reasonably good correlation between data of the surface seismic field test and laboratory BES analysis, especially if we consider undoubtedly different features of both methods, their advantages and disadvantages:

– SASW / CSWS are indirect methods inevitably averaging (as do many of geophysical methods) the properties of a number of soil layers, decreasing the spatial resolution of the data with depth;

– if the soil profile is complex, with sudden contrasts between the neighbouring layers, a simple method of interpreta-

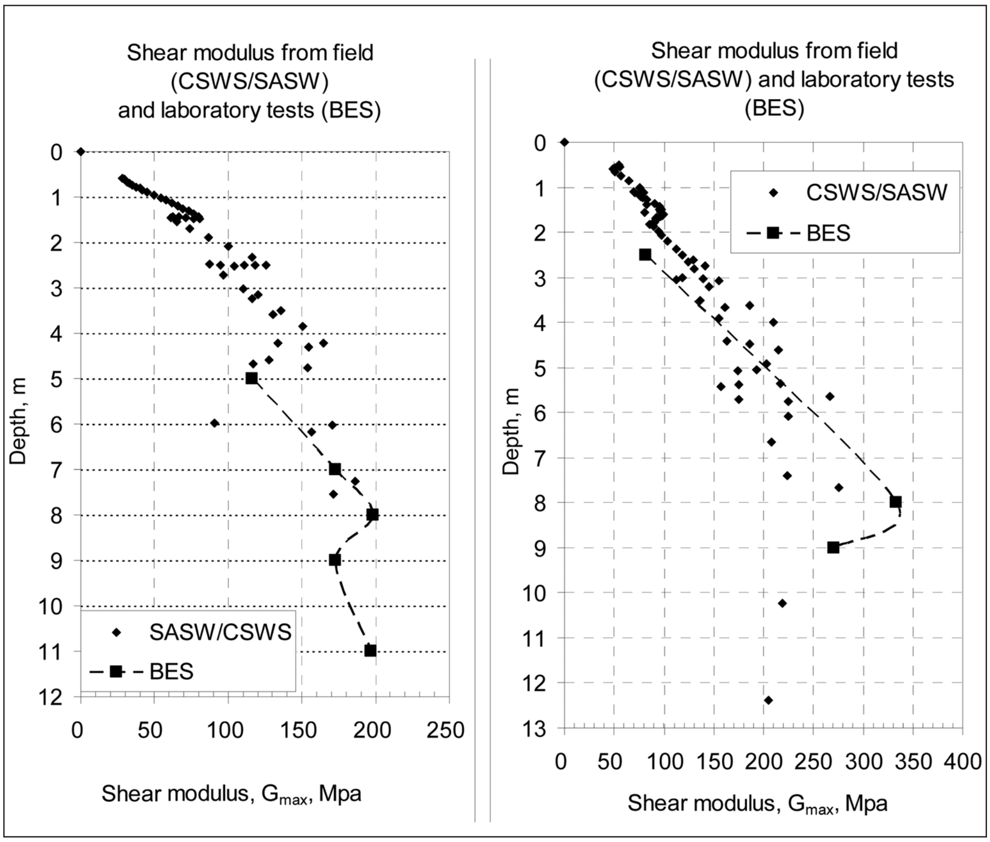

Fig. 6. Results of field and laboratory investigations (site B – left graph, site C – right graph)

tion – the factored wavelength method (FWM) – may be not sufficient for getting detailed and precise data;

– nevertheless, there is still a huge amount of data from one-surface seismic profiling as compared to good quality samples possible to get from drilling;

– the application of simple FWM can result in scattered data (as in Fig. 6) sometimes differing significantly at a similar depth. A additional information comes from such data, because it often means that there is a sudden change of parameters at that depth;

– the inherent drawbacks of laboratory testing are unrepresentative sampling and sampling disturbance (the same applies to penetration tests);

– nevertheless, a "good quality" sample gives a possibility to describe the soil in detail in the laboratory;

– both methods give the maximum value of the shear modulus for the strain level, which is not applicable to real structures. Another problem is to calibrate these values to be reliably usable for designers. The decreasing factor of 0.5 to 0.85 (based on experience and back-analysis, dependent on the type of soil) is one of the proposals (Matthews et al., 2000).

In spite of a somewhat technical character of the article, it should be emphasized that in the author's opinion, thorough knowledge of geological conditions and a proper understanding of inherently and inevitably heterogeneous natural formation – soil half-space – is crucial for the assessment of engineering-geological parameters and conditions.

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MAŽŲ DEFORMACIJŲ RODIKLIAI, GAUTI MATUOJANT BANGOS GREITĮ

Santrauka

Mažų deformacijų intervale nustatyti rodikliai vaidina svarbų vaidmenį projektuojant statinius ir vertinant jų sąveiką su gruntu. Mechaninius gruntų rodiklius galima įvertinti analizuojant gruntų deformacijas. Straipsnyje pateikiami grunto šlyties modulio nustatymo metodai naudojant seisminę bangą, gautų rezultatų pavyzdžiai.

Tomasz Szczepański

PARAMETRY GRUNTU DLA ZAKRESU MAŁYCH ODKSZTAŁCEŃ, OTRZYMYWANE Z POMIARÓW PRĘDKOŚCI FALI

Streszczenie

Parametry gruntu określane dla zakresu tzw. małych odkształceń grają istotną rolę w nowoczesnym projektowaniu obiektów inżynierskich współpracujących z gruntem. Jak powszechnie w mechanice gruntów wiadomo, parametry mechaniczne gruntu zależą od jego odkształceń. Geolog inżynierski powinien być świadomy dostępnych metod polowych i laboratoryjnych, których wyniki przystają do nowoczesnych wymogów jakości i adekwatności do badanego problemu. Z drugiej strony, wady i ograniczenia konkretnych rozwiązań zmuszają do łączenia różnych podejść razem. Artykuł charakteryzuje krótko dwie istniejące metody pozwalające określać moduł ścinania gruntu przy użyciu pomiarów przejścia fali sejsmicznej, z przykładowymi danymi z nich otrzymanymi.

Томаш Щепаньски

ПОКАЗАТЕЛИ МАЛЫХ ДЕФОРМАЦИЙ ПРИ ИЗМЕРЕНИЯХ СКОРОСТИ ВОЛНЫ

Резюме

Показатели грунтов, установленные в диапазоне малых деформаций, играют важную роль при проектировании сооружений и оценке их взаимодействия с грунтом. Механические свойства грунтов можно оценить, анализируя деформации грунтов. В статье представлены два метода определения модуля сдвига с использованием сейсмической волны. Приводятся примеры полученных результатов.