Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-154

ECSMGE 24
XVIII EUROPEAN CONFERENCE ON SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The influence of clay and silt content on reducing stiffness of soil in a small range of strains

L'influence de la teneur en argile et en limon sur la réduction de la rigidité de sol dans une petite gamme de souches

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ABSTRACT: Stiffness parameters are defined as the ratio of stress to strain and depend on many factors, e.g. on soil type, stress conditions, stress history. The stress–strain behaviour of soil is highly non-linear. Therefore, the moduli - i.e. parameters characterizing soil stiffness - are not constant and, in addition to the previously mentioned factors, also depend on the deformation level. The initial soil stiffness is assumed as moduli values for strains smaller than approximate $1x10^{-4}$%. It can be determined on the basis of shear wave velocity measurement or tests in a resonant column. It is assumed that these are non-destructive tests, carried out in the range of very small soil strains. Resonant column test allows to determine the shear modulus in the range of shear strains $10^{-4}\div10^{-1}$%. As the deformation increases, the soil stiffness decreases. The change in stiffness occurs faster for less cohesive soils than for very cohesive soils. The paper presents the analysis of resonant column test results in terms of soil stiffness reduction along with deformation for different soils. The authors of the paper proposed a relationship between shear modulus and values of shear strains based on the initial stiffness and basic soil index properties.

RÉSUMÉ: Les paramètres de rigidité sont définis comme le rapport entre la contrainte et la déformation et dépendent de nombreux facteurs, par exemple du type de sol, des conditions de contrainte, de l'histoire de la contrainte. Le comportement contrainte-déformation du sol est fortement non linéaire. Par conséquent, les modules - c'est-à-dire les paramètres caractérisant la rigidité du sol - ne sont pas constants et, en plus des facteurs mentionnés précédemment, dépendent également du niveau de déformation. La rigidité initiale du sol est supposée correspondre aux valeurs du module pour des déformations inférieures à 1x10-4%. Elle peut être déterminée sur la base d'une mesure de la vitesse des ondes de cisaillement ou d'essais dans une colonne résonante. On suppose qu'il s'agit d'essais non destructifs, réalisés dans le domaine des très petites déformations du sol. L'essai sur colonne résonante permet de déterminer le module de cisaillement dans la plage de déformations de cisaillement 10-4÷10-1 %. À mesure que la déformation augmente, la rigidité du sol diminue. Le changement de rigidité se produit plus rapidement pour les sols moins cohérents que pour les sols très cohérents. L'article présente l'analyse des résultats des tests de la colonne résonante. Les résultats des tests ont été analysés en termes de réduction de la rigidité du sol ainsi que de déformation pour différents sols. Les auteurs de l'article ont proposé une relation entre le module de cisaillement et les valeurs des déformations de cisaillement, basée sur les propriétés de rigidité initiale et d'indice de base du sol.

Keywords: Soil stiffness; resonant column tests; small strains.

1 INTRODUCTION

In the resonant column device, it is possible to determine soil stiffness expressed by shear modulus (G) also called Kirchoff's modulus, in the range of small strains; γ: $10^{-4}\div10^{-1}$% (Atkinson and Sallfors 1991, Mair 1993). According to ASTM D4015, ASTM D8295 the value of modulus obtained in the range of strains γ: 10^{-4} is taken as the maximum value (G_0 or G_{max}). This value is called the initial soil stiffness and can also be determined from the shear wave velocity propagation in soil. The studies on the soil stiffness concept in the range of small strains, based on laboratory results, have led to the development of empirical formulae to estimate the maximum values of shear modulus G_{max} in an indirect manner (e.g. Hardin and Black, 1968; Kim and Novak, 1981). The empirical equations describing the reduction of shear modulus (G) with shear strains (γ) were proposed by among others, Ishibashi and Zhang (1993); Darendeli (2001); Zhang et al. (2005); Kallioglou et al. (2008); Vardanega and Bolton (2013). The computational formulae proposed in the literature allow the approximation of small strain behaviour of soil considering: selected soil index properties, expressed by plasticity index (PI) and void ratio (e), stress history, expressed by overconsolidation ratio (OCR), effective stress, applied to the soil sample tested, correction factors, adopted in the individual calculation formulas.

The scope of application of the formulae developed so far may be limited to specific soil types. The formulae described in the work of Vardanega and Bolton (2013) allow reliable distributions of G/G_{max} values as a function of shear strain γ for cohesive soils of plasticity index (10-150%); and void ratio, (0.480-6.150). The equations proposed by them predicted over 90% of the G/G_{max} ratios within a margin of +/-30% across the full range of values from 0 to 1.0 for all soils, with the exception of certain London Clay data. Ishibashi and Zhang (1993) analysed available in literature experimental data and attempted to establish unified formulas for shear moduli to cover wide variety of soils ranging from sands to highly plastic clays such as Mexico City clay. Empirical relationships to evaluate reduction of the normalized stiffness (G/G_{max}) together with the shear strains (γ) are also formulated for non-cohesive soils (e.g. Oztoprak & Bolton (2013)). The parameters such as effective stress, plasticity index PI, void ratio (e) and overconsolidation ratio OCR are the components of most of the proposed equations describing G/G_{max} vs. γ relations. However, it should be noted that these parameters are determined indirectly and in extreme cases their values may be subject to considerable error or, in case of plasticity index, may be completely impossible to determine (soils bordering on fine- and coarse-grained soils - ISO 17892-12). In this study, a formula is proposed to predict the reduction of the normalised stiffness (G/G_{max}) together with the shear strains (γ) taking into account the changes in clay and silt fractions content. (fines content FC<0.063mm). The proposed relationship applies to cohesive, pre-consolidated soils.

2 CHARACTERISTIC OF TESTED SOILS

The tested soil samples came from the area of Poland, also from the areas located in the Baltic Sea. The basic index properties of the tested soils are presented below (Table 1). Index properties tests were performed in accordance with ISO 17892 group of standards. The analysed soils are mainly clay with sand and silt. (see Table 1).

Table 1. Index properties of tested soils

Sample	Depth	Gravel	Sand	Silt	Clay	Silt+Clay	Type of soil according to PN-EN ISO 14688-2:2006	Natural water content	Plastic limit	Liquid limit	Plasticity index	Liquidity index	Consistency index
								w	w_p	w_L	PI	LI	I_C
	m	[%]	[%]	[%]	[%]	[%]		[%]	[%]	[%]	[%]	[-]	[-]
1	5.4	1	25	46	28	74	sasiCl	31.4	15	38	23	0.71	0.29
2	28.8	4	41	32	23	55	saCl	12.9	15	25	10	-0.26	1.26
3	30.4	0	28	47	25	72	sasiCl	25.1	32	48	16	-0.43	1.43
4	33.8	0	33	44	23	67	sasiCl	20.4	20	42	22	0.02	0.98
5	35.1	4	50	28	18	46	sasiCl	8.8	12	24	12	-0.27	1.27
6	35.2	4	20	43	33	76	Cl	21.9	15	31	16	0.43	0.57
7	40.6	0	46	33	21	54	sasiCl	20.2	27	35	8	-0.85	1.85
8	41.1	1	24	45	30	75	saCl	19.2	15	30	15	0.29	0.71
9	44.0	0	41	39	20	59	sasiCl	19.2	23	40	17	-0.22	1.22
10	58.1	0	3	41	56	97	Cl	21.3	29	54	25	-0.31	1.31

3 RESONANT COLUMN TESTS

The tests were performed in a resonant column manufactured by GDS Instruments (Stokoe Type – Figure 1). According to ASTM D4015, this is a Fixed-Base - Type 1 (DT1) column where the passive end platen is connected to the fixed base (no torque transducer). The test comprised three stages: back pressure saturation, isotropic consolidation (overload), isotropic consolidation (unload) and a resonant test for several different vibration amplitudes. Based on the resonant frequencies, the moduli of elastic strain (G) were calculated for elastic strains in the variation range of approx. $5x10^{-5}$ to 10^{-1}%. The stress conditions under which the tests were carried out are shown below in Table 2. The results of the resonant column tests are shown in Figure 2 as a plot of the reduction of normalised shear modulus against shear strain.

Figure 1. Fixed-Base - Type 1 Resonant Column made by GDS Instruments

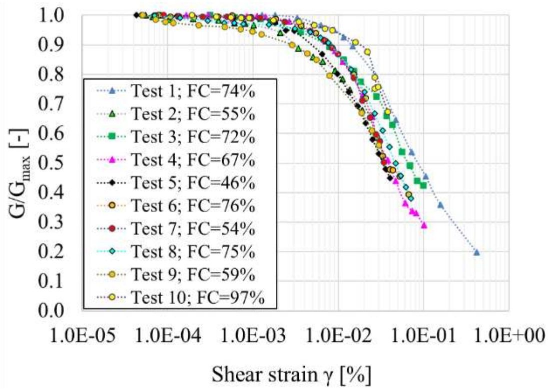

Figure 2. G/G_{max} reduction curves from resonant column tests.

Table 2. Values of consolidation stress applied during resonant column tests.

Sample	Test name	Consolidation stress	
		I Stage overloading	II Stage unloading
		[kPa]	[kPa]
1	Test 1	40	30
2	Test 2	900	360
3	Test 3	900	340
4	Test 4	900	330
5	Test 5	900	490
6	Test 6	900	380
7	Test 7	900	500
8	Test 8	900	480
9	Test 9	900	480
10	Test 10	900	540

4 ANALYSIS OF TEST RESULTS

The test results confirm that reduction of soil stiffness with deformation is more pronounced for low-cohesive soils than for very cohesive soils (e.g. Vutecic and Dobry 1991). In Figure 3, the relationship between G/G_{max} and fines content is presented on the basis of the obtained test results. The relationship is described by the linear equation:

$$\frac{G}{G_{max}} = a \cdot FC + b \tag{1}$$

where: a – slope, b – intercept, FC – fines content (<0.063 mm)

As it can be seen in Figure 3 for some tests no G/G_{max} value was obtained for a strain of 0.04%. The results for this strain value were not considered for further analyses. Both parameter 'a' and 'b' vary with the shear strains. The following equations describing the relationship are proposed (Figure 4).

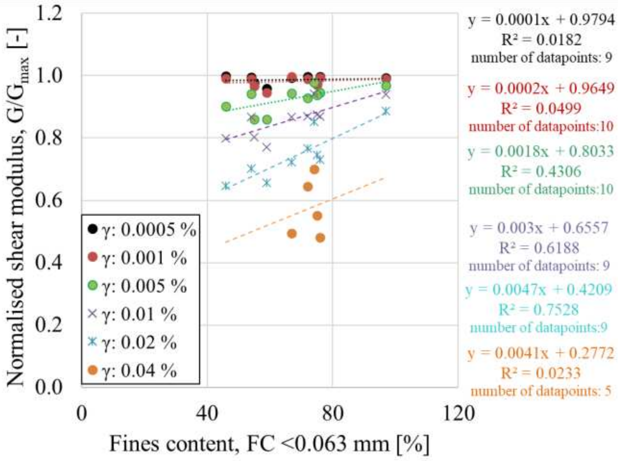

Figure 3. Relationship between G/G_{max} and fines content.

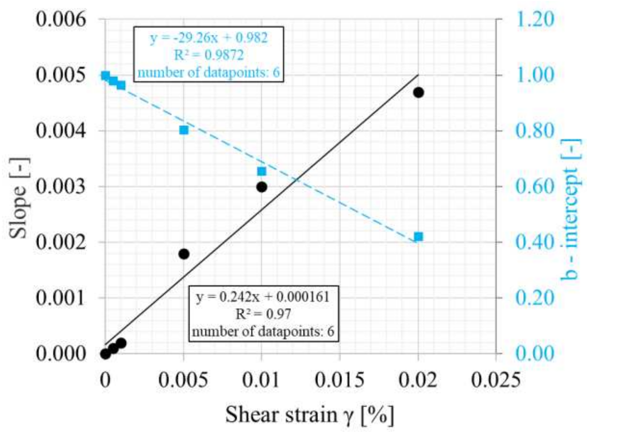

Figure 4. Relationship between parameters a,b and shear strain.

Using the above relationships, the following equation was proposed from which the value of G/G_{max} can be estimated.

$$\frac{G}{G_{max}} = (0{,}242\gamma + 0{,}000161) \cdot FC - 29{,}26\gamma + 0{,}982 \tag{2}$$

The comparison of the G/G_{max} values obtained directly from the tests and based on the proposed equation for the three selected tests is shown below in Figure 5. Soils with different fine fraction contents were selected for comparison. The next figure (Figure 6) presents the compatibility of obtained values depending on the shear strains. The largest scatter of results was obtained for shear strains of 0.04%. This can be concluded to represent the limit of applicability of the proposed formula.

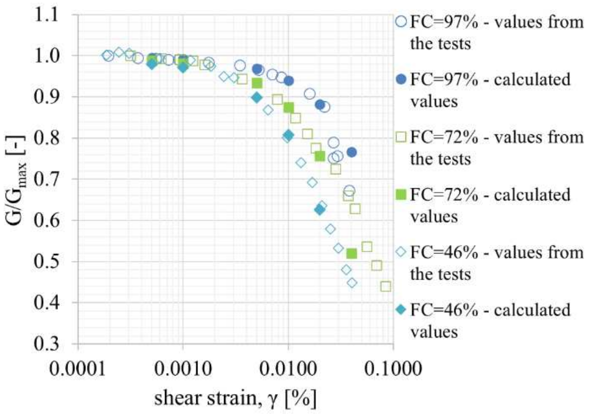

Figure 5. $G/G_{max} - \gamma$ curves obtained directly from the tests and from the proposed equation.

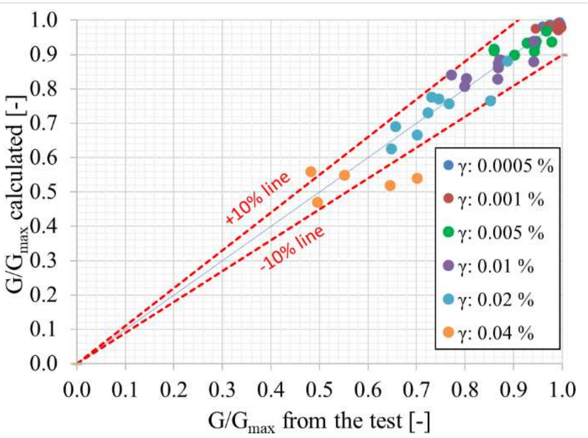

Figure 6. Comparison of G/G_{max} values obtained from the tests and from the proposed equation.

5 CONCLUSIONS

The following conclusions can be drawn from the tests carried out:

- The results of the normalised shear modulus (G/G_{max}) obtained directly from laboratory tests and from the proposed empirical formula are comparable. According to the authors, the proposed formula can be used to estimate (G/G_{max}) values for different cohesive preconsolidated soils.
- Calculated values of normalised shear modulus for shear strains above 0.04% differ significantly from the results obtained from the tests. Therefore, the value of shear strains 0.04% is a limitation of the applicability of the proposed formula.
- The G/G_{max} values calculated from equation (2) do not differ from the measured values by more than +/- 10% of the measured value (Figure 6).
- The proposed formula is based only on fines contnent. The soil stiffness depends on many other factors (effective stress, stress history, void ratio, soil cementation), and the given solution can be used for preliminary estimation of G/G_{max} values.

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