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On correlations between "dynamic" (small-strain) and "static" (large-strain) stiffness moduli – An experimental investigation on 19 sands and gravels

T. Wichtmann*, I. Kimmig, T. Triantafyllidis

Karlsruhe Institute of Technology (KIT), Institute of Soil Mechanics and Rock Mechanics, Engler-Bunte-Ring 14, 76131, Karlsruhe, Germany

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ABSTRACT

Correlations between "dynamic" (small-strain) and "static" (large-strain) stiffness moduli for sand are examined. Such correlations are often used for a simplified estimation of the dynamic stiffness based on static test data. The small-strain shear modulus $G_{dyn} = G_{max}$ and the small-strain constrained modulus $M_{dyn} = M_{max}$ have been measured in resonant column (RC) tests with additional P-wave measurements. Oedometric compression tests were performed in order to determine the large-strain constrained modulus $M_{stat} = M_{oedo}$, while the large-strain Young's modulus $E_{stat} = E_{50}$ was obtained from the initial stage of the stress-strain-curves measured in drained monotonic triaxial tests, evaluated as a secant stiffness between deviatoric stress q=0 and $q = q_{max}/2$. Experimental data for 19 sands or gravels with specially mixed grain size distribution curves, having different non-plastic fines contents, mean grain sizes and uniformity coefficients, were analyzed. Based on the present data, it is demonstrated that a correlation between M_{max} and M_{oedo} proposed in the literature underestimates the dynamic stiffness of coarse and well-graded granular materials. Consequently, modified correlation diagrams for the relationship $M_{max} \leftrightarrow M_{oedo}$ are proposed in the present paper. Furthermore, correlations between G_{max} and M_{oedo} or E_{50}, respectively, have been also investigated. They enable a direct estimation of dynamic shear modulus based on static test data. In contrast to the correlation diagram currently in use, the range of applicability of the new correlations proposed in this paper is clearly defined.

1. Introduction

It is well known that soil stiffness decreases with increasing magnitude of strain [1,7,8,10,14,15,20–22,24–29,33–35,37,38,43,48,49]. In many practical problems dealing with dynamic or cyclic loading (except soil liquefaction problems [18,19,23,36]) the strain amplitudes generated in the soil are relatively small. Furthermore, dynamic measurement techniques like resonant column (RC) tests or wave propagation measurements are frequently applied to determine the small-strain stiffness in the laboratory [3,5-7,11,12,16,28,34,35,47]. Therefore, the stiffness at small strains is often also denoted as "dynamic" stiffness. For the stiffness moduli applied in deformation (e.g. settlement) analysis of foundations, usually oedometric compression or triaxial tests with monotonic loading are conducted. The stiffness moduli resulting from these "static" tests have been found significantly lower than the dynamic stiffness. Initially, this has been attributed to the different loading rates applied in the static and dynamic tests. However, it has been recognized soon that the material response of sand is approximately rate-independent and that those differences are due to the different strain levels.

For the design of foundations subjected to dynamic loading, the small-strain shear modulus G_{max} of the subsoil is a key parameter. For final design calculations in large or important projects it will be usually determined from dynamic measurements in situ, e.g. surface or bore-hole measurements of the wave velocities. However, for feasibility studies, preliminary design calculations or final design calculations in small projects the small-strain shear modulus is often estimated from empirical formulas, tables or correlations with static stiffness values.

For design engineers in practice it is attractive to estimate the dynamic stiffness based on static stiffness data, because static tests are less elaborate than dynamic ones. While the dynamic experiments are conducted by specialized laboratories only, even small soil mechanics laboratories are usually equipped with devices for oedometric testing. Furthermore, for many locations experienced data for the static stiffness moduli are available. Without any further testing these data can be used to estimate the dynamic stiffness.

A diagram providing a correlation between static and dynamic stiffness moduli is incorporated e.g. in the "Recommendations of the working committee Soil Dynamics" of the German Geotechnical Society

* Corresponding author.
E-mail addresses: torsten.wichtmann@kit.edu (T. Wichtmann), ivo.kimmig@kit.edu (I. Kimmig), theodoros.triantafyllidis@kit.edu (T. Triantafyllidis).

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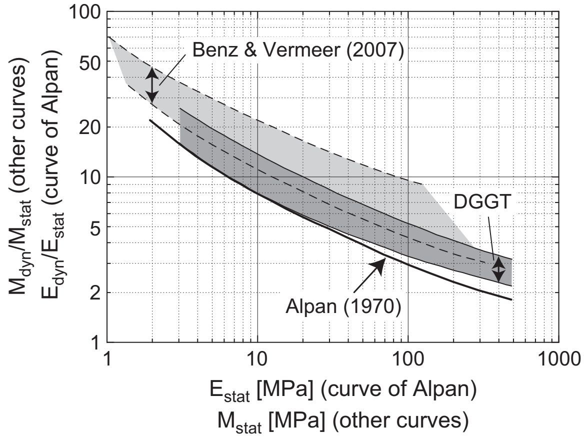

Fig. 1. Correlation between M_{dyn} and M_{stat} according to the "Recommendations of the working committee Soil Dynamics" of the German Geotechnical Society (DGGT) [9] versus correlation proposed by Benz and Vermeer [4]. The original relationship between E_{dyn} and E_{stat} according to Alpan [2] is also shown.

(DGGT) [9]. It is shown in Fig. 1 (area marked by the dark gray colour). The diagram is entered with the large-strain constrained modulus $M_{stat} = M_{oedo}$ (stiffness on the primary compression line obtained from oedometric compression tests) on the abscissa and delivers the ratio between small-strain and large-strain constrained moduli $M_{dyn}/M_{stat} = M_{max}/M_{oedo}$ on the ordinate. The small-strain shear modulus $G_{dyn} = G_{max} = M_{max}(1 - \nu - 2\nu^2)/[2(1 - \nu)^2]$ can be obtained with an assumption regarding Poisson's ratio ν. Note, that the indices $\sqcup_{dyn}$ and $\sqcup_{max}$ are equivalent, i.e. both denote the small-strain stiffness. The DGGT diagram is based on the correlation between static and dynamic Young's moduli proposed by Alpan [2]. This original correlation is also presented in Fig. 1 (black solid curve). Benz and Vermeer [4] have proposed another correlation between static and dynamic constrained moduli (see the area marked by the light gray colour in Fig. 1). It is also based on Alpan [2], but in comparison to [9] different assumptions were used when converting the E data into a diagram in terms of M. However, the experimental basis and the range of applicability of all correlations shown in Fig. 1 is not clear [4,45,46].

A first inspection of the correlations in Fig. 1 for four sands with different grain size distribution curves has been presented in [44,46]. It has been found that the dynamic stiffness of a coarse and a well-graded granular material was significantly underestimated by the range of the DGGT correlation. In consideration of the fact that this correlation is frequently used in practice (at least in Germany), it has been decided to undertake a closer inspection, based on experimental data collected for a wider range of grain size distribution curves. The present paper reports on that new study.

2. Tested materials

The grain size distribution curves of the specially mixed sands or gravels tested in the present study are shown in Fig. 2. These are the same mixtures that have been already investigated in [39–43]. The raw material is a natural fluvially deposited quartz sand obtained from a sand pit near Dorsten, Germany, which has been decomposed into 25 gradations with grain sizes between 0.063 mm and 16 mm. The grains have a subangular shape and the grain density is $\varrho_s = 2.65$ g/cm^3. The sands or gravels L1–L8 (Fig. 2a) have the same uniformity coefficient C_u=1.5 but different mean grain sizes in the range 0.1 mm $\leq d_{50} \leq$ 6 mm. The materials L4 and L10–L16 (Fig. 2b) have the same mean grain size d_{50}=0.6 mm but different uniformity coefficients $1.5 \leq C_u \leq 8$. The inclination of the grain size distribution curve of the fine sands F2 and F4–F6 (Fig. 2a) is similar to that of L1 (C_u=1.5) but these sands contain between 4.4% and 19.6% silty fines (quartz powder). The sands F1 and F3 have not been tested in the present study but the numbering of the sands chosen in [39] has been maintained herein. The index properties of all tested materials are summarized in Table 1.

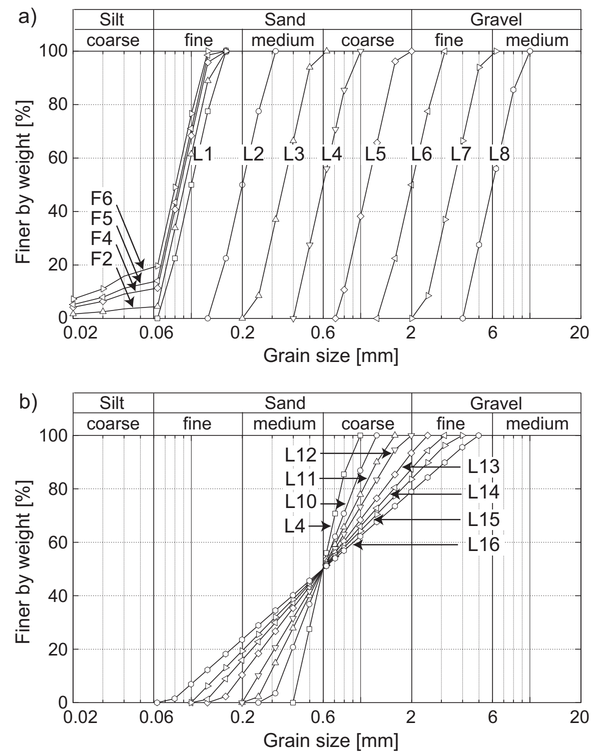

Fig. 2. Tested grain size distribution curves.

Table 1
Index properties (non-plastic fines content FC, mean grain size d_{50}, uniformity coefficient $C_u = d_{60}/d_{10}$, minimum and maximum void ratios e_{min}, e_{max}) of the tested granular materials.

Mat.	FC [%]	d_{50} [mm]	C_u [–]	e_{min} [–]	e_{max} [–]
L1	0	0.1	1.5	0.634	1.127
L2	0	0.2	1.5	0.596	0.994
L3	0	0.35	1.5	0.591	0.931
L4	0	0.6	1.5	0.571	0.891
L5	0	1.1	1.5	0.580	0.879
L6	0	2.0	1.5	0.591	0.877
L7	0	3.5	1.5	0.626	0.817
L8	0	6.0	1.5	0.634	0.799
L10	0	0.6	2	0.541	0.864
L11	0	0.6	2.5	0.495	0.856
L12	0	0.6	3	0.474	0.829
L13	0	0.6	4	0.414	0.791
L14	0	0.6	5	0.394	0.749
L15	0	0.6	6	0.387	0.719
L16	0	0.6	8	0.356	0.673
F2	4.4	0.092	1.5	0.734	1.107
F4	11.3	0.086	1.9	0.726	1.117
F5	14.0	0.084	2.6	0.723	1.174
F6	19.6	0.082	3.3	0.746	1.091

3. Small-strain stiffness from RC tests with additional P-wave measurements

The small-strain stiffness moduli G_{max} and M_{max} were obtained from resonant column tests with additional P-wave measurements, using piezoelectric elements integrated into the end plates of the RC device. The test device, the testing procedure and the test results are