Shear Modulus and Damping Relationships for Dynamic Analysis of Structures with Backfill Effect

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INTRODUCTION

Seismic events, as well as other types of dynamic loading, cause shear strain in the soil surrounding and supporting structures. Therefore the strain-dependent shear stiffness and shear damping of the soil are the required dynamic properties for dynamic analyses of structures that consider the Soil-Structure interaction effect. The dynamic properties of soil are often represented by the shear modulus, *G*, and the damping ratio *D*, which are related to spring stiffness and damper relationships used by some structural finite element programs. Many buildings include a substructure, which requires excavation and backfill to construct. A realistic soil structure interaction model may need to consider the backfill zone around the substructure as shown in Fig. 1.

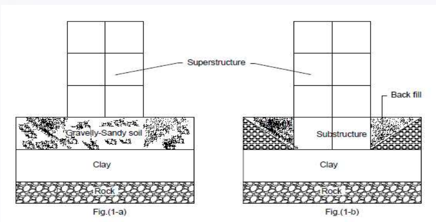

Fig. 1. SSI models with and without excavation.

OBJECTIVE

1) Summarize past research on the dynamic properties (particularly shear modulus and damping) of coarse-grained soils.
2) Develop a simple set of typical properties for coarse-grained soil, including shear modulus, the modulus reduction factor and the damping ratio, that can be used for the seismic design of the structures when the soil properties are not known.

METHODOLOGY

1) The results of many investigations of compacted or reconstituted coarse-grained soils were collected, including sand, gravel, and borderline soils with gravel contents ranged from 0 to 60%.
2) The tests results were collected with the primary purpose of finding the relationship between G_{max} and D_r over a range of different confining pressures. The relative density was provided directly by some of the studies or calculated based on the reported void ratios or dry unit weights. From the data reported by the studies, the relative density of the tested soils ranged from 5 to 100%.

RESULTS AND DISCUTION

CORRELATION BETWEEN G_{max} AND D_r

An empirical correlation was developed to estimate the value of G_{max} in situations where more detailed properties of the soil are not available. A simple linear functional form was selected to represent the dependence of the normalized G_{max} on D_r as:

$$\frac{G_{max}}{\sigma'_m{}^{0.5}} = (A\,Dr + B)P_a{}^{0.5} \qquad (1)$$

where G_{max} is the maximum shear modulus, D_r is the relative density in percent, and P_a is the atmospheric pressure. Using linear regression, the constants *A*=4.932 and *B*=615.23 were fitted to the sand data in Fig. 2(a) and A=12.22 and B=633.08 were fitted to the gravel data in Fig. 2(b). The new regressions are compared to the curves presented by [1] and [2].

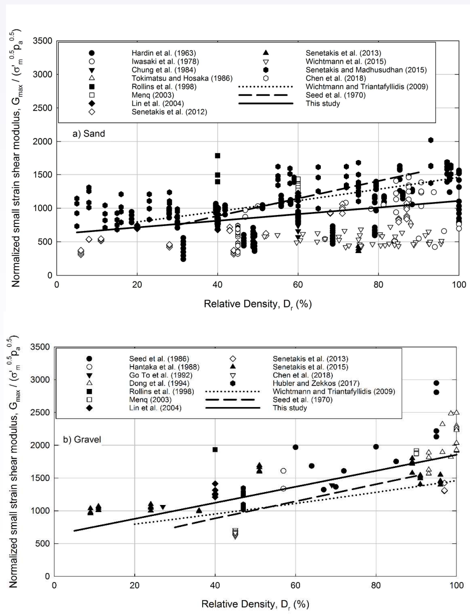

Fig 2. $G_{max}/\sigma'_m{}^{0.5}P_a{}^{0.5}$ vs. the relative density for (a) sand and (b) gravel with curves from [13] and [14].

Soils with higher gravel content, or larger particle size, tend to have higher values of normalized G_{max} as shown in Fig. 3 where the sand data has been separated by the reported gravel content of the sand.

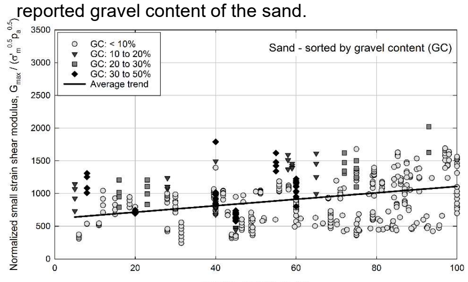

Fig 3. Effect of gravel content on the values of G_{max}.

G/G_{max} AND D VERSUS STAIN AMPLITUDES γ FOR RECONSTITUTED GRAVEL AND SAND

In numerical modeling of soil-structure interaction, the change of the soil properties with the strain is usually represented by the reduction factor of the shear modulus G/G_{max} and the damping ratio D versus strain. These curves are required input data for many programs that model the nonlinear dynamic behavior of soil in their codes. Many curves have been proposed by others (e.g., [15],[5],[6]) as shown in Fig. 4, 5, and 6. Best-fit equations Eqn. 2, 3 and 4 were found by the regression to represent the change of the shear modulus for gravelly, sandy soils and the damping ratio respectively with the strain amplitude. These equation could be used for the numerical analysis of the structures with the effect of SSI.

$$\frac{G}{G_{max}} = \frac{1}{1+1.0\left(\frac{\gamma}{\gamma_r}\right)^{0.983}} \;(Gravel) \qquad (2)$$

$$\frac{G}{G_{max}} = \frac{1}{1+1.0\left(\frac{\gamma}{\gamma_r}\right)^{0.977}} \;(Sand) \qquad (3)$$

$$D = 0.9 + 24(0.92 + 0.15\gamma^{-0.95})^{-0.95} \qquad (4)$$

Where γ is the strain and γref is the value of γ when G/G_{max} = 0.5

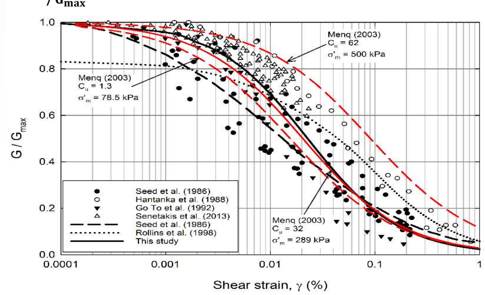

Fig 4. G/G_{max} versus γ relationship for gravelly compared typical curves from [15], [5], and [6]

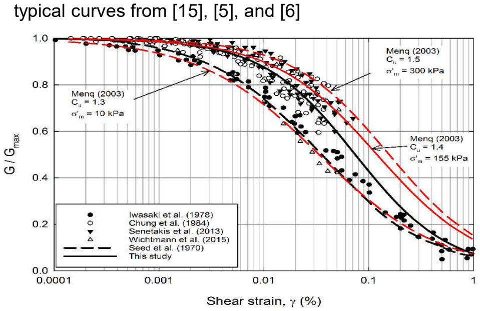

Fig 5. G/G_{max} versus γ relationship for sand compared to typical curve of [14] and [6].

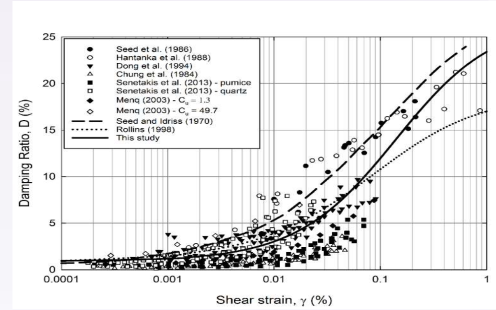

Fig 6. Damping relationship for gravelly and sandy soil compared with typical curves from [14] and [5].

CONCLUSION

1. Two simple linear correlations have been formed to distinguish between the typical behavior of the sand and the gravel using D_r as input data.
2. A modified hyperbolic equation is presented to represent the average curve of the nonlinear shear stress-shear strain behavior of coarse-grained soil for use in the dynamic analysis of structures.
3. A modified form of the damping vs. shear strain curve is proposed for reconstituted sand and gravel that better fits the available data.

REFERENCES

1. Hardin BO, Richart FE, J. Soil Mech. *Found. Division, ASCE* 89 (1963) 33-65.
2. Chung RM, Yokel FY, Drnevich VP, *Geotech. Test. J.*, 7 (1984) 60–69.
3. Iwasaki T, Tatsuoka F, Takagi Y. *J. Soils and Found.*, 18 (1978) 39-56.
4. Tokimatsu K, Hosaka Y, *J. Soils and Found.*, 26 (1986)53–64.
5. Rollins KM, Evans MD, Diehl NB, Daily WD, J. *Geotech. Geoenviron. Eng.* 124 (1998) 396–405.
6. Menq FY, Ph.D. dissertation, University of Texas at Austin, (2003).
7. Lin P, Chang C and Chang W, J. *Soil Dynamics and Earthquake Engineering*, 24(2004) 675–687.
8. Senetakis K, Anastasiadis A and Pitilakis K, *Geotech. Test. J.*, 35 (2012) 964-980.
9. Senetakis K, Anastasiadis A, Pitilakis K and Coop MR, *Soil Dynamics and Earthquake Engineering*, 45(2013)70-79.
10. Wichtmann T, Hernández MN and Triantafyllidis Th, *Soil Dynamics and Earthquake Engineering*, 69(2015)103-114.
11. Senetakis K, Madhusudhan BN, *Soils and Found.*, 55 (2015) 1196-1210.
12. Chen G, Zhou Z, Sun T, Wu Q, Xu L, Khshnevisan S and Ling D, *J. Earthquake Engineering*, (2018) https://doi.org/10.1080/13632469.2017.1387200
13. Wichtmann T, Triantafyllidis Th, *J. Geotech. Geoenviron. Eng.* 135 (2009)1404-1418.
14. Seed HB, Idriss IM, *Report EERC 70–10*, College of Engineering, University of California 1970.
15. Seed HB, Wong RT, Idriss IM and Tokimatsu K, *J. Geotech. Engng.* 112 (1986)1016–1032.
16. Hatanaka M, Suzuki Y, Kawasaki T, Endo M, *J. Soils and Found.* 28(1988)57 -68.
17. GoTo S, Suzuki Y, Nishio S, Oh-Oka H, *J. Soils and Found.* 32 (1992) 15-25
18. Dong J, Nakamura K, Tatsuoka F, Kohata Y, 1994. In: S. Shibuya, T. Mitachi, S. Miura (eds), *Pre-failure deformation of geomaterials, Rotterdam*, Balkema pp. 17–23.
19. Senetakis K, Madhusudhan BN, *Soils and Found.*, 55 (2015) 1196-1210.
20. Hubler JF, Zekkos D, *J. Geotech. Geoenviron. Eng.* 143 (2017)1-12.

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