Zsolt Szilvágyi

# Dynamic Soil Properties of Danube Sands

PhD Thesis booklet

Supervisor:
Professor Dr. Richard P. Ray PhD
Department of Structural and Geotechnical Engineering
Faculty of Architecture, Civil Engineering and Transport Sciences
Széchenyi István University

Modeling and Development of Infrastructural Systems
Multidisciplinary Doctoral School of Engineering Sciences
Széchenyi István University

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# 1 Introduction

*"The finding that at small strains the ground exhibits high stiffness and, frequently, nonlinear properties, has far-reaching practical and fundamental consequences. ...nonlinearity of stress-strain response has very significant effects on soil-structure interaction, stress distributions in the soil mass, and displacement profiles around loaded areas and excavations. ...There is enormous scope for the development of improved instruments and techniques and for the experimental study of stiffness properties of soils and weak rocks at small strains."* (Burland, 1989)

# 2 Motivation, background

My PhD dissertation concerns the dynamic behavior of Danube sands. Recently in Hungary, the adaptation of Eurocode 8 standard has created a greater need to define dynamic behavior of local soils such as Danube sands. Seismicity in Hungary can be considered moderate, however expected earthquake loading could cause serious damage in structures and infrastructure, therefore engineers need to consider it in design. Since the previous design standards did not consider earthquake loading, there has not been any research focusing on soil dynamics in Hungary, and this problem not only hinders economic design and construction of civil engineering structures, but it hinders the precise assessment of local earthquake risk as well.

In the past 7-8 years, a research team has been formed at the Department of Structural and Geotechnical Engineering at Széchenyi István University under the supervision of Prof. Richard P. Ray. My PhD research focused on laboratory testing and modeling connected to small strain stiffness of granular soils, while other team members consider related topics, such as: seismic risk assessment of existing buildings (Kegyes-Brassai, 2016), pile foundations under seismic loading (Wolf & Ray,

2017) and finite element modeling of dynamic loading of trains (Koch & Hudacsek, 2017).

For the research presented in my Dissertation, the continuous development of the Geotechnical Laboratory was essential, especially the improvement of the combined Resonant Column-Torsional Simple Shear device, which was built by Prof. Ray at the University of Michigan (Ray R. P., 1983) and rebuilt, recalibrated and further developed by the author at the Geotechnical Laboratory of Széchenyi István University under the supervision of Prof. Ray.

# 3 Scope of the research

The specific scope of the research was to study and measure the very small strain stiffness, the stiffness degradation and the damping characteristics of Danube Sands as well as to obtain correlations, which describe how these parameters depend on state variables. Danube sands compose an important segment of local soils and present the geotechnical engineer with several design challenges. These soils are present at river crossings and major development parcels throughout Hungary. Although their engineering behavior can vary over a wide range, they retain some common characteristics that will help the engineer to make decisions about geotechnical and structural designs. Field and laboratory measurements are usually complex and time consuming. In practice, the designer often has to use existing correlations, which were derived from previous testing of various soils. Therefore, my research aimed to answer the following questions:

- Is there a material model available, which may be used to model the dynamic behavior of Danube Sands?
- Can existing correlations be used to obtain reliable material parameters for the model?
- How can the dynamic properties of Danube sands be quantified by laboratory

measurements?

To answer these questions, a logical order of general theory, literature review, laboratory testing methods and equipment, data interpretation and finally test results and discussion is presented in the Dissertation.

# 4 Methodology

In order to provide background to the topic of the research and to gather existing correlations for the dynamic properties of soils, a comprehensive literature review has been performed. The review focused on two main topics: the theoretical description of modeling the dynamic behavior of soils, and correlations for obtaining material model parameters for sands.

The research consisted of an extensive laboratory measurement program; two laboratory measurement methods (Resonant Column Test and Torsional Simple Shear Test) have been used to obtain information about the dynamic behavior of nine selected typical Danube sands. Both methods are considered state-of-the-art in the field of geotechnical earthquake engineering and while they are used all over the world, in Hungary this research is the first to apply them. It also has to be noted that most measurement devices use either the Resonant Column or the Torsional Shear method for testing. In contrast to them, the device used and further developed in this study is a combined one, capable of performing both tests on a single soil specimen, which makes it rather unique. The benefit of combined testing is that the soil response can be measured throughout the whole range of strains from very small strains ($10^{-4}$ %) up to large strains ($10^{-1}$ %) on one single specimen. As validation of the test methods, measurement results have been compared to an independent set of measurements performed by a fellow PhD student with the Bender Element test method at the Geotechnical Laboratory of the Slovak University of Technology. Very good agreement has been found between the results.

Analysis of the data and interpretation of results are the most important steps in the measurement procedure, hence this research focused on both of them. Visual Basic for Applications in MS Excel has been used to improve measurement result interpretation; the developed codes are presented in the Annex of the thesis.

Applying a material model to the measured set of data is also an important task and can be considered as another method of measurement data interpretation. For simple cases, this task is often done with the trial and error method, while complex models require solving an inverse problem. Some programs used for geotechnical finite element modeling (e.g. Plaxis) provide built-in tools (Soil Test module) to perform this task for commonly used laboratory tests and material models, however there is no such tool available for either of the two laboratory measurement methods or any material model which considers the small strain stiffness of soils. Therefore, in order to obtain material parameters that provide the best fit for a certain model, a procedure has been developed to solve the inverse problem and provide material parameters by regression analysis based on measured behavior. For this MS Excel Solver’s Generalized Reduced Gradient method has been used to minimize the sum of residual squares between values provided by the model and measured values.

Finally, to preview the solution of the inverse problem, a 3 dimensional finite element model has been developed and the modeling of several loading stages of the Torsional Shear Test has been performed using the Ramberg-Osgood material model. Analysis results are compared to measurement results to provide verification of the material model implemented in the computer program used.

# 5 Thesis statements

Thesis statements were obtained based on the state-of-the-art combined Resonant Column and Torsional Shear Testing of nine air dry ($w_{max}$<2%) typical Danube sands containing a small amount ((Cl+Si)<21 %) of fine particles with various plasticity (10%<$I_P$<18 %) and comprising of sub-angular and rounded grains with 0,11<$d_{50}$<0,42 mm. 69 RC tests and 19 TOSS were performed on samples with wide range of densities (0,11 < $I_D$ < 0,95) under relevant confinement pressures (80 kPa<$p'$<300 kPa). This resulted in 69 measured values of $G_{max}$, 279 measured values of $G/G_{max}$ and 261 measured values of $D$.

## *5.1 Thesis #1*

**I have shown that the further developed, combined Resonant Column-Torsional Shear Device with the testing procedure presented in this dissertation, which includes device assembly, preparation of hollow cylindrical sample, testing sequence and measurement result interpretation; is capable of measuring the very small strain shear stiffness $G_{max}$; the modulus reduction curve and the damping curve of dry sands.**

I have compared the obtained very small strain shear stiffness values to an independent set of measurements performed in a separate laboratory with the Bender Element Method by a separate researcher; and obtained acceptable agreement with 78% of the measured data within the ±15% deviation and 91% of the measured data within the ±20% deviation.

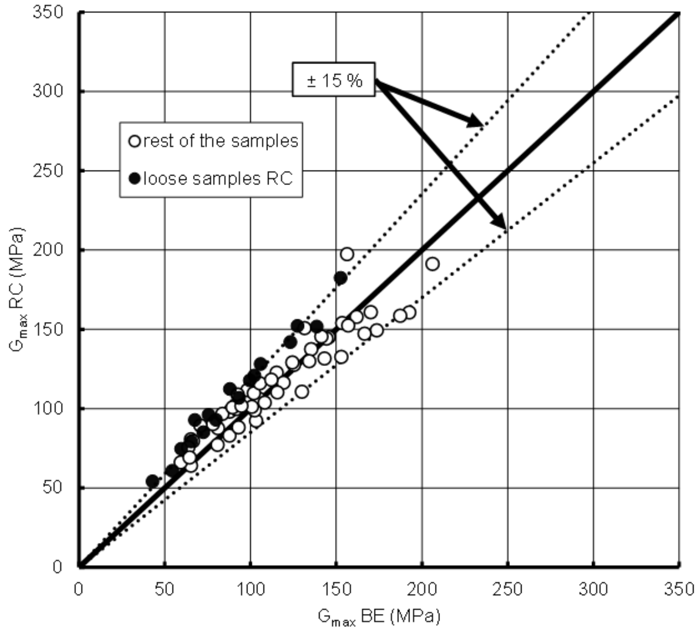


*Figure 5-1 Comparison of $G_{max}$ values measured independently. Bender element (BE) and Resonant Column (RC) results are shown for all tested soils*

References: (Szilvágyi Z. , 2012), (Ray, R. P., Szilvágyi, Z., 2013), (Szilvágyi, Z., Hudacsek P., Ray, R.P, 2016), (Szilvágyi, Panuska, & Ray, 2018)

## 5.2 Thesis #2

I have developed a procedure to obtain the model parameters for the Ramberg-Osgood material model using small strain shear stiffness, modulus reduction and damping properties of a Danube Sand measured by Resonant Column and Torsional Shear Testing methods, by solving the inverse problem using MS Excel Solver's Generalized Reduced Gradient Method for minimizing the sum of squared errors between predicted and measured values of a hysteresis loop.

**I have created a three dimensional finite element model of the Torsional Shear Test and verified that the Ramberg-Osgood material model implemented in the software Midas GTS NX v2014 is capable of modeling the static Torsional Shear Test performed on a hollow cylinder sample with representation of the nonlinear material behavior concerning modulus reduction with increasing strain.**

The verification by the back analysis of the Torsional Shear Test has not been done before with a nonlinear material model and indicates that the Ramberg-Osgood material model can be used in practical calculations requiring the modeling of stiffness degradation.

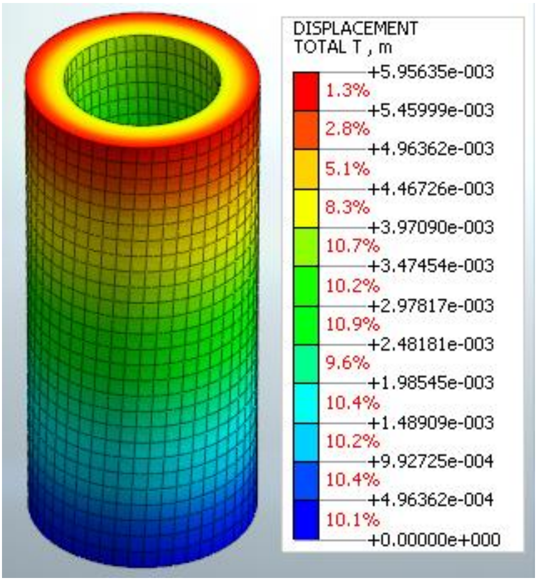


*Figure 5-2 3D finite element model of the Torsional Shear Test*

References: (Szilvágyi Z. , 2010), (Szilvágyi & Ray, 2018)

### *5.3 Thesis #3*

I have compared the very small strain stiffness ($G_{max}$) of typical Danube sands at a wide range of densities and relevant confinements obtained by the Resonant Column method to correlations from literature and confirmed that out of the presented correlations the correlation given by (Carraro, Prezzi, & Salgado, 2009) gives the best estimate for $G_{max}$.

I have confirmed based on my measurement results with the Resonant Column method, that correlations which have been obtained for sands with non-plastic fines, such as the correlations given in (Iwasaki & Tatsuoka, 1977) and (Wichtmann, Navarrete Hernández, & Triantafyllidis, 2015), could underestimate $G_{max}$ of sands with plastic fines by 30-35%.

This suggests that over the content of fine particles, their plasticity has an even more dominant effect on $G_{max}$.

**I have measured the very small strain stiffness ($G_{max}$) of typical Danube sands at a wide range of densities and relevant confinements with the Resonant Column method and obtained the following correlation for $G_{max}$:**

$$G_{max}\ [\text{MPa}] = 62\ \frac{(2.17 - e)^2}{1 + e}\left(\frac{p'}{p_{atm}}\right)^{0.45} \qquad \textit{Equation 5-1}$$

where $e$ is void ratio, $p'$ is the mean effective stress in [kPa], and $p_{atm}$ is the atmospheric pressure in [kPa]. The applicability of the most commonly used void ratio function in literature has been confirmed by my measurement results and has been used in the above equation. Coefficient of determination is $R^2$=0.71.

This correlation can be used in practical calculations for the estimation of $G_{max}$ of typical Danube sands, in the absence of measurements.

References: (Szilvágyi Z. , 2012), (Ray, R. P., Szilvágyi, Z., 2013), (Szilvágyi, Z., Hudacsek P., Ray, R.P, 2016), (Szilvágyi, Panuska, & Ray, 2018)

### *5.4 Thesis #4*

**I have measured the stiffness degradation (*$G/G_{max}$*) of typical Danube sands over a wide range of densities and relevant confinements with the combined Resonant Column and Torsional Shear test methods and obtained the following degradation curve formulated in the Ramberg-Osgood material model:**

$$\frac{G}{G_{max}} = \frac{1}{1+0.8334\left|\frac{\tau}{0.6386\,\tau_{max}}\right|^{1.142}} \qquad \textit{Equation 5-2}$$

where $G$ is the secant shear modulus, $G_{max}$ is the very small strain stiffness, $\tau$ is shear stress, $\tau_{max}$ is shear strength. Coefficient of determination $R^2$ is 0.89.

This degradation curve can be used in practical calculations to describe the stiffness degradation behavior of typical Danube sands.

References: (Szilvágyi Z. , 2012), (Ray, R. P., Szilvágyi, Z., 2013), (Szilvágyi, Z., Hudacsek P., Ray, R.P, 2016), (Szilvágyi, Panuska, & Ray, 2018)

### *5.5 Thesis #5*

**I have measured the damping (*$D$*) increase with strain of typical Danube sands at a wide range of densities and relevant confinements with the Resonant Column and Torsional Shear test method and obtained the following correlation for damping:**

$$D\text{ [-]} = 0.1667\left(\frac{G}{G_{max}}\right)^2 - 0.3932\left(\frac{G}{G_{max}}\right) - 0.2165 \quad \textit{Equation 5-3}$$

where $G/G_{max}$ is the stiffness degradation value at a given strain level. Coefficient of determination is $R^2$=0.82.

This correlation can be used in practical calculations for the estimation of $D$ of typical Danube sands, in the absence of measurements.

References: (Szilvágyi Z. , 2012), (Ray, R. P., Szilvágyi, Z., 2013), (Szilvágyi, Z., Hudacsek P., Ray, R.P, 2016), (Szilvágyi, Panuska, & Ray, 2018)

# 6 Summary and future research

In my dissertation I have shown, how small strain stiffness of Danube sands can be described and modeled based on state-of-the art laboratory measurements. A detailed literature review on the modeling of small strain stiffness of soils has been presented to provide insight into the most commonly used model parameters; and their determination based on correlations has also been investigated. A comprehensive laboratory testing program has been performed on nine selected typical Danube Sands with the combined Resonant Column-Torsional Shear device. Measurement results have been compared to an independent set of measurements performed by a fellow PhD student at a different laboratory with the Bender Element test method and a very good agreement has been found between the results.

Besides testing, data interpretation has also been developed by solving the inverse problem of choosing most suitable model parameters which provide the closest behavior with the used material model as the measurements. For this, the 3D finite element model of the Torsional Shear Test has been developed and the modeling of a TOSS test has been performed with use of the nonlinear Ramberg-Osgood material model. Finally measurement results have been presented and new correlations have been obtained for the most important parameters which can be used to estimate them in the absence of measurements.

It has been emphasized, that some features of this complex behavior still need investigations. Some of these topics can be further investigated in laboratory; some can be modeled with the presented FEM modeling process.

Laboratory testing should focus on the effects of irregular loading, especially RC testing after TOSS prestraining and perhaps a more precise measurement method of void ratio could be developed. Comparison of laboratory measurements to in-situ testing is another difficult task in this topic and needs further research. Effects of uneven distribution of density, imperfections due to sample preparation could be investigated by further modeling.

An additional topic concerns the application of dynamic soil parameters in modeling, especially in ground response analysis, which can be used to assess the specific value of the earthquake load, based on local soil conditions. Our first studies in this field (Kegyes-Brassai, Wolf, Szilvágyi, & Ray, 2017), (Szilvágyi, et al., 2017) confirmed, that the nonlinear behavior of surface near soil layers have a major effect on earthquake loading and if the profile is not homogeneous or nearly so, a substantial degree of amplification can be expected.

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