# Chapter 1

# Introduction

## 1.1 Purpose and scope

The evaluation of a number of civil engineering problems involve the transmission of waves through soil, such as seismic response under earthquake loading, foundation response under dynamic loading and vibrations in buildings, induced by various sources. Important sources are industrial activities (looms, printing presses), building activities (pile driving, installation of sheet piles and demolition of buildings), rail and road traffic.

Mechanical waves can be divided in body and surface waves. Body waves can exist in an ideal full space or they travel in a region that is not affected by a free surface. P- (primary, compression, longitudinal) waves and s- (secondary, shear, transverse) waves are types of body waves. The particle motion of p-waves is in propagation direction; the particle motion of s-waves is perpendicular to the direction of propagation. Surface waves may only exist at the surface or the boundary, separating media of different properties. Rayleigh (vertically polarized) and Love (horizontally polarized) waves are examples of surface waves.

The prediction of elastic wave propagation from the source, through the soil to the receiver can be performed by means of numerical models. Effects of construction and renovation of traffic infrastructure or other vibration sources can already be evaluated in the phase of planning. Unreasonable nuisances to residents or damage to buildings can be avoided by design of a proper vibration isolation system. Experimental validation has shown that the estimated soil characteristics crucially affect the vibration prediction accuracy in the free field and in buildings.

The most important characteristic parameters are the velocity of s- and p-waves and the material damping ratios of these body waves. Material damping in the soil represents energy dissipation caused by friction between solid particles in the skeleton and by the relative motion between the soil skeleton and the pore fluid. Material damping must be distinguished from geometrical or radial damping. Since the velocity of p-waves is highly affected by the groundwater table, the most efforts are spent to the determination of the s-wave velocity. S-waves are transmitted in saturated soils by the soil fabric only. The dynamic shear modulus, $G_{max}$, can be calculated directly based on the s-wave velocity.

There are only a few techniques available to determine the damping ratio. Only laboratory tests, as resonant column and cyclic shear tests, but no field testing methods, can be considered as established techniques.

This work focuses on the determination of the damping ratio of shear waves by means of field and laboratory tests. Therefore extended interpretation techniques for the seismic cone penetration test (SCPT) and the bender element test (BE) are studied and evaluated.

The SCPT is an extension of the cone penetration test (CPT). The use of the CPT in the geotechnical engineering practice has increased sharply in recent years. Therefore the CPT equipment is widely spread. Since most of this equipment is also used in a SCPT the economical barriers for the transfer of technique to practice are low. The BE methods are in the focus of interests because bender elements can be mounted in various laboratory testing devices and are able to generate s-waves with very low strain amplitudes similar to those found in situ.

The research is embedded in the project "Traffic induced vibrations in buildings" initiated from the K.U. Leuven and Ghent University. Within the framework of this project soil parameters at different sites are determined for use as input parameters in a numerical model to predict the wave propagation. Five test sites in Belgium are chosen for testing: Waremme, Lincent, Retie, Sint-Katelijne-Waver and Ghent. The SCPT and the BE test are a substantial part of this exploration to measure the shear wave velocity and the damping ratio. The extensive testing campaigns offered the unique opportunity to evaluate and improve the methods on different soil materials.

## 1.2 Outline of the thesis

An introduction in Chapter 2 is devoted to the fundamentals of the dynamic soil properties: shear modulus and the attenuation parameters. This is followed by an overview of state of the art methods to determine the shear modulus and the damping ratio in Chapter 3. Laboratory testing techniques and in situ tests are considered.

The Chapters 4 to 8 provide information on the testing sites in Retie, Lincent, Waremme, Sint-Katelijne-Waver and Ghent. Apart from a general description of each site, the essential results of all performed tests are given, including free torsion pendulum and resonant column tests. The findings of the bender element resonant tests are the only exception. These are discussed in Chapter 10.

Readers primarily interested in the BE- and SCPT testing methods, which are closer investigated in this work, may at first skip the five chapters on the testing sites to come back later to certain results, if necessary.

Chapter 9 is dedicated to the SCPT. The selected test equipment and developed data acquisition tools are described. After a summary on methods to determine the s-wave velocity, the chapter focuses on possibilities to measure the damping ratio based on time recods gathered by a SCPT. The results of an evaluation of the spectral ratio slope and the attenuation coefficient method by means of a numerical simulation of the test are given. Finally the obtained results on the five testing sites are summarized.

Chapter 10 deals with the methods based on the bender element test. Procedures to measure the arrival time of the s-wave are described at first. Then methods to determine attenuation parameters are given. A resonant method is applied on samples from two of the testing sites and the results are discussed.

Chapter 11 concludes the main findings of the thesis and gives suggestions for further research.

The obtained insights in the accuracy of the testing techniques concerning the G-modulus and the damping ratio are used to compare the methods under consideration of their costs. The results of the comparison can be found in the appendix and can be considered as a conclusion of this work.