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Evaluation of the free–free resonant frequency method to determine stiffness moduli of cement-treated soil

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Abstract

The objective of this research is to validate the free–free resonant frequency method and its interpretation to determine the small-strain stiffness moduli of cement-treated soil. In this testing method, a cylindrical soil specimen is laid on top of a soft foam layer to approach fully free boundary conditions. Next, an accelerometer is placed in contact with one end of the specimen to measure vibrations, while the other end is impacted with a light hammer. Then, the small-strain moduli can be evaluated from the density, the dimensions and the fundamental frequency of the vibrations. Factors that could affect the interpretation include the actual boundary conditions of the sample, the interference of the accelerometer on the vibrational response of the sample and the aspect ratio of the sample given by the ratio diameter to length. In order to verify the reliability of the measurements, the free–free resonant frequency method was compared with a more robust technique like the laser Doppler vibrometer. Furthermore, the impact of the sample's aspect ratio was investigated through a numerical modal analysis from which correction factors were also proposed to improve the reliability of the interpretations.

Jel classifications: D07; D10; E13

Keywords: Cement; Clay; Stiffness; Resonant frequency; Laboratory testing

1. Introduction

The stress–strain behaviour of soil is complex and non-linear. Therefore, Young's modulus (E) and the shear modulus (G) of the soil are not constants, but may significantly change with the strain level. At small strains, the stiffness is relatively high, while at strains close to failure the stiffness is low. However, it has been observed that the behaviour is sufficiently constant and linear below an approximate strain level of 0.001% (Clayton, 2011). It is in such a range in strain level that small-strain moduli (E_0 and G_0) are defined. Small-strain moduli may be estimated from wave propagation-based methods that have gained popularity due to their relative simplicity.

In general, small-strain stiffness is governed by a number of factors, such as stress history, void ratio, soil fabric and interparticle contact stiffness, which will depend upon particle mineralogy, angularity and roughness, and effective stress. The small-strain stiffness is an important parameter for a variety of geotechnical design applications, including small-strain

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dynamic analyses such as those used to predict soil behaviour or soil–structure interaction during earthquakes, explosions or machine or traffic vibrations. Small-strain stiffness may also be used as an indirect indication of other soil parameters, as it (in many cases) correlates well to other soil properties. For example, when studying the hardening process of cement-treated soil, an increase in stiffness can be expected with increasing interparticle cementation and compressive strength.

The laboratory determination of small-strain stiffness is usually carried out through direct methods, such as the bender/extender elements (Åhnberg and Holmen, 2008; Verástegui-Flores et al., 2010; Seng and Tanaka, 2011; Åhnberg and Holmen, 2011). However, there are also indirect methods for measuring small-strain stiffness, such as the resonant column test (Drnevich et al., 1978). The free–free resonant frequency method is a simplified testing procedure (based on the resonant column testing concept) that has recently been used for the characterisation of cement-treated soils (Nazarian et al., 2005; Rydén, 2009; Åhnberg and Holmen, 2011; Toohey and Mooney, 2012; Schaeffer et al., 2013; Guimond-Barrett et al., 2013).

The free–free resonant frequency method (FFR) is simple to execute and can be a good alternative to the bender/extender element testing of cemented soil. In FFR testing, a cylindrical specimen is allowed to vibrate at its fundamental frequency and its stiffness is evaluated from the measured fundamental frequency, density and length of the specimen through a straightforward formula based on theories of one-dimensional wave propagation in an elastic rod. However, the interpretation of stiffness from the FFR results might be affected by uncertainties related to the boundary conditions (uncertainties of which the laboratory is not perfectly free) and also by the diameter-to-length ratio (aspect ratio) of the specimen (Åhnberg and Holmen, 2011; Schaeffer et al., 2013).

The objective of this study is to address such uncertainties of FFR testing. The correctness of the measured fundamental frequencies from the FFR testing is evaluated and compared with a reliable reference obtained with a laser Doppler vibrometer. The impact of the specimen's aspect ratio on the interpretation of the stiffness moduli, obtained from the fundamental frequencies, is studied numerically through a modal analysis in Abaqus.

Experiments were carried out on cylindrical specimens of different dimensions, consisting of cement-treated kaolin at a high water content which was selected as reference material in this research.

2. Materials and sample preparation

The cement-treated clay used in this research consists of kaolin mixed with blast-furnace slag cement of the type CEM III/B (EN 197-1, 2011) and deionized water.

A commercially processed kaolin, Rotoclay HB (Goonvean, St. Austell, UK), was used in this investigation. The clay was available as a dry powder. Table 1 summarises some properties of this material. The blast-furnace slag cement used in the experiments, CEM III/B 42.5 N LH/SR LA, consists of approximately 70% ground granulated blast furnace slag, 26% Portland clinker and 4% gypsum. It shows a minimal normalised mortar strength at 28 days, of 42.5 N/mm^2. Moreover, this cement's features improved the sulphate resistance, the low hydration heat and the low alkali content.

Table 1
Physical and chemical properties of Kaolin.

Index		Kaolin
Specific gravity	ASTM D 854 (2010)	2.64
Liquid limit, %	ASTM D 4318 (2010)	53.2
Plastic limit, %	ASTM D 4318 (2010)	31.0
Swell index, ml/2 g	ASTM D 5890 (2011)	3.5
CEC, meq/100 g		1.38

Deionized water was used for the admixture of soil and cement. The electrical conductivity (EC) and pH of the deionized water were $EC < 4$ μS/cm and pH ≈ 7, respectively.

The clay and cement were initially mixed dry in a dough mixer for about 2 min until a homogeneous cement distribution was observed. The cement dosage was fixed at 10% (in dry mass). Next, deionized water was poured in the mixing bowl to achieve a clay water content of twice its liquid limit in order to approach the consistency of clay suspensions at a high water content. The slurry of clay and cement was thoroughly mixed for approximately another 7 min. The consistency of the slurry after mixing remained liquid. Then, the fresh clay-cement mix was poured into stainless steel cylindrical moulds of different dimensions. The cylindrical moulds were lightly vibrated while filling them with the fresh mix to remove any trapped air bubbles. The bottom and top ends of the moulds were sealed with kitchen foil to prevent moisture loss. Then, the samples were allowed to cure inside the moulds for one week in a conditioned room at about 20 °C (during this period, no FFR testing could be done on the specimens). Following the 1-week curing, the samples were strong enough to be extruded from the moulds. Finally, after extrusion, the specimens were stored under water in the conditioned room and FFR testing was performed regularly at different stages of curing time. This sample preparation procedure produced uniform quality specimens with a coefficient of variation in density smaller than 0.002.

Specimens with diameter (D) and length (L) of $D = 38$ mm and $L = 85$ mm ($D/L = 0.44$), $D = 50$ mm and $L = 100$ mm ($D/L = 0.5$) and $D = 70$ mm and $L = 130$ mm ($D/L = 0.54$) were produced.

3. Methods

3.1. Free–free resonant frequency method

The free–free resonant frequency (FFR) method is an attractive alternative (due to its simplicity) for measuring the small-strain Young's modulus and shear modulus of (unconfined) cemented or cohesive soil in the laboratory (Nazarian et al., 2005; Rydén, 2009; Åhnberg and Holmen, 2011;