Soil testing using a Chirp RC

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Abstract – **The Resonant Column (RC) test is the standard to determine dynamic and static parameter of soils and rocks under different shear strain and confining conditions. The test consists of vibrating a cylindrical specimen in torsion establishing a fundamental mode, measuring the resonant frequency and amplitude of vibration with a frequency search.**

In order to minimize the spectral content beyond the used frequency range, borrowing a radar technique, a "Chirp" is used. This continuous modulation improves the system measurement performances, minimizing the effect of the number of cycles, reducing the test time and increasing the frequency resolution.

I. INTRODUCTION

Dynamic tests of material characteristics have been a very important part in the engineering of machines and structures. Progresses in laboratory methods for dynamic tests have become routine. It has made possible to solve complex problems of dynamic nature in regards cooperation of structure with soil.

Dynamic properties of the soil can be also used to analyze static geotechnical problems. For very small deformations, soil parameters demonstrating its stiffness are comparable in dynamic and static conditions [1].

The correct description of the soil behavior in the range of small deformations is an important element in the prediction of the movement of structures and has a great impact on the quality of the evaluation of the internal forces in the structural system of buildings and its foundations.

Stiffness modules for very small deformations are recognized as the fundamental properties of the soil to solve problems of interaction with the building. In geotechnical engineering, information obtained from advanced laboratory dynamic tests, are used often even if not sufficiently to deal with static problems.

In terms of soil dynamics and geotechnical earthquake engineering, the response of the geotechnical material to shearing motions is of most concern focusing on G according to the following equation:

$$G = \rho \cdot V_S^2 \qquad (1)$$

where: ρ soil volume density; V_S transverse wave velocity

The module at very small deformations is called primary (G_0 or Gmax). Direct laboratory measurements of this parameter are done changing the shearing strain rate, the shearing amplitude, the level of confining stress and the number of cycles applied to the soil sample.

The RC test is considered the most consistent estimation method of the initial modulus. It is a well-known technique for determining the dynamic shear modulus, dynamic modulus of elasticity and the damping coefficient of soils and rocks.

The main objective of this technique is to analyze the properties of materials subjected to harmonic vibrations representing seismic interaction.

The sample is placed in a triaxial stress chamber, and its ends are loaded with torque. In this device, the base of the soil specimen is fixed against rotation and the free end is excited in torsion. The stress is generated by an electromagnetic motor operating up to a range of frequencies in which inertial forces are not as negligible as in static conditions.

Measurement of the resonant frequency and vibration amplitude of the sample using elastic wave propagation theory, allows for estimation of the wave speed and the damping in the sample.

The resonant column testing technique has been known in geotechnical engineering since the 1930's ideated by the Japanese engineers Ishimoto and Iida [2, 3].

In the 1960's, the resonant column was already used in studying the dynamic behavior of the soil and was already well known among geotechnicians.

The device originally developed by professor Stokoe's team at the University of Texas, Austin is widely known as the RCTS. It can function both as a resonant column and as a torsional shear testing system allowing large deformations as well as small deformation.

Currently, the RCTS method is considered one of the most reliable, effective and pragmatic laboratory methods for the determination of the shear modulus, damping ratio of soil[4]. This can be also used for other materials.

II.   THEORETICAL BACKGROUND

The resonant column test is based on the links between the dynamic deformation modulus G and the resonant frequency of the soil material.

The sample subjected to harmonic torsional waves may be described by physical models, such as a twisted rod with one degree of freedom, including in the analysis the effects of external loads and taking into account the equations of propagation generated in the material of elastic deformation waves.

The torsional shear test is used to measure cyclic stress-strain properties of soil at low frequencies applying a torque and measuring the resulting angle of twist. The shear modulus and the hysteretic damping are measured from the stress-strain curve. Hysteretic and viscous damping both assume that soil is a linear, viscoelastic material.

In the RCTS apparatus, drive system inducing torque has a quite significant inertia (Ip). The drive head mass polar moment of inertia is calculated using a metal rod subjected to a RC test in two different configurations, with and without adding a known mass.

The calculation of the searched velocity V_S is achieved from the solution of the following equations:

$$\frac{I_0}{I_P} = \beta \cdot \tan \beta \qquad (2)$$

$$V_S = \frac{2 \cdot \pi \cdot f_R \cdot L}{\beta} \qquad (3)$$

where: f_R resonant frequency, L specimen height, Io sample polar inertia, Ip drive system polar inertia.

Changes in specimen length and volume are monitored to adjust sample mass polar moment of inertia.
The above derivation does not include the damping, effect of absorption of energy by the vibrating material and associated with the viscosity of the material.
Material damping is calculated in a simple manner by using the SDOF model.

The frequency is gradually increased to find the maximum response amplitude that is the resonant frequency, from which one can determine Gmax and the frequency f1 and f2, which allow for specification of the value of the damping coefficient using the "half-power bandwidth method" [9].

The shear stiffness and shear damping are the key dynamic properties and in the strain ranges exhibit linear and nonlinear changes generally presented in semi-logarithmic plots.

A typical scheme shows a decreasing trend of shear modulus and an increasing trend of material damping as strain increases.
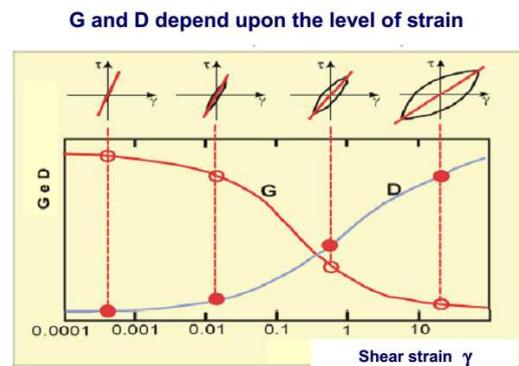Above a level of strain the curve is also a function of the number of loading cycles.

Fig.1 Shear stiffness and shear damping vs. γ

Material damping in soils is caused by hysteretic and viscous dissipation. Hysteretic damping is best measured at low frequency and viscous damping is best measured in the resonant column test.

III.   APPARATUS DESCRIPTION

The sample is placed in a triaxial stress chamber and is loaded with torque and isotropic load with the assumption of base fixidity and a free head
The stress is generated by an electromagnetic motor operating up to a range of frequencies in which inertial force are important.

The described apparatus has been designed and built to determine the static and dynamic deformation characteristics of soil samples or weak rocks in the small and medium-sized amorphous deformation range (up to 0.1%).
Megaris has been developing and manufacturing a number of RCTS apparatus for sample diameters ranging from of 38 mm to 100 mm and max torque levels ranging from 1 to 15 Nm.
The sample in a sealed rubber membrane, is placed on a pedestal fitted with a porous stone. Changes in sample volume are measured using a volume gauge.
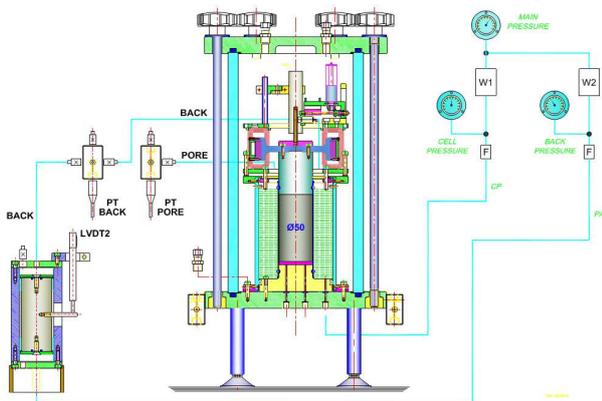
Fig.2 Scheme of RCTS apparatus

The main component of the apparatus is the electromagnetic drive system, whose task is to load the upper free end of the sample.

The drive system includes a four arm cross equipped with permanent neodymium magnets (Fig.3).

The cross is attached to the head on the upper surface of the sample. The four NdFeB magnets are placed between the four pairs of driving coils fixed to a ring forming the stator of the motor.

Each coil is shaped so that the magnets can move as the soil specimen shortens or bends during consolidation.

The support cylinder is in the form of a rigid transparent polycarbonate that is also the chamber for the liquid surrounding the sample.
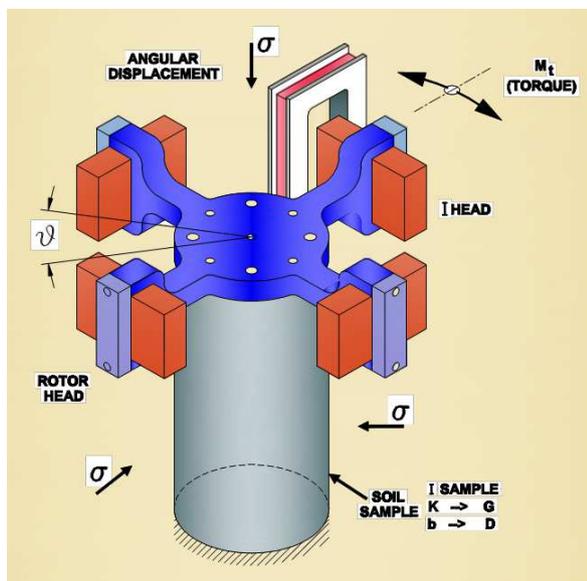

Fig.3 The drive system and the specimen

The torque applied to the top free sample end is proportional to the current circulating into the coils.

A current amplifier minimizes the effect of counter EMF [10, 11].

The electronics enable control of applied load and tracking of the response of the soil sample using direct measurements of the following sample parameters:

- confining pressure,
- pore water pressure,
- axial displacement,
- volume change,
- head angle of rotation,
- head acceleration.

The measuring system of angular movement is composed by an accelerometer and a couple of proximity sensors. An innovative micro positioning unit provides a zeroing of the proximity sensors.

The torque is proportional to the current flowing in the coils, which is controlled directly by a high accuracy electronic amplifier. A control and data acquisition system supervises the entire test system.

After the preparation and consolidation, the soil sample is subjected to a torque with constant amplitude and variable frequency. The range should include the induced resonant frequency.

IV. THE CHIRP

The main objective of this paper is to evaluate the use of a rise and fall Chirp (R-F Chirp) to run a RC test.

Direct comparison of results from the R-F Chirp method and the standard RC method has been applied to a calibration rod of a WF8500 RCTS machine by Controls/WF.

According to the standard RC test, the frequency is gradually increased in discrete steps with a defined sequence. The specimen resonant frequency is the one with the maximum response amplitude.
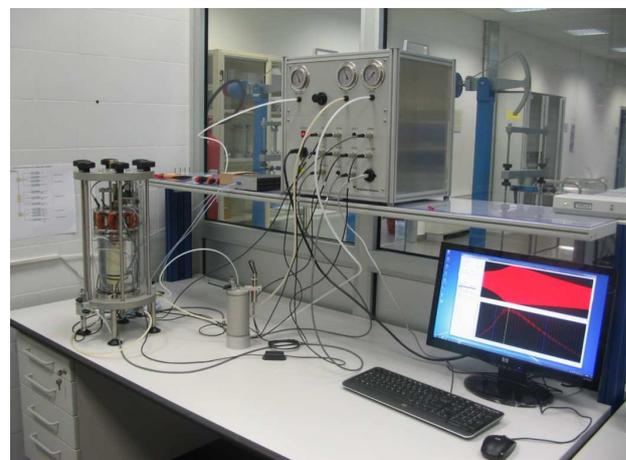

Fig.4 The RCTS WF 8500 by Wykeham Farrance

The test is usually conducted in two steps, one with a large range and the following with a small one around the resonance. Each frequency is applied for a fixed number of periods.

In order to minimize the effect of the number of cycles and time spent, we introduced a Chirp modulation [12, 13]. Chirp linear frequency modulation has been used for digital communication and was patented by Sidney Darlington in 1954.

The Chirp is a continuous modulation where the frequency increases within the limits set by the user.

It is characterized by the time-bandwidth product T.Δf with T time duration and Δf frequency change interval.

There is very little spectral content beyond the used frequency range, especially where the time-bandwidth product is large as in our application.

For example, with a start frequency of 30 Hz and a final one of 40 Hz (Δf = 10 Hz) using a time duration T of 25 s, the time-bandwidth product is 250 and only about 1% of the total power resides at frequencies outside the sweep range.

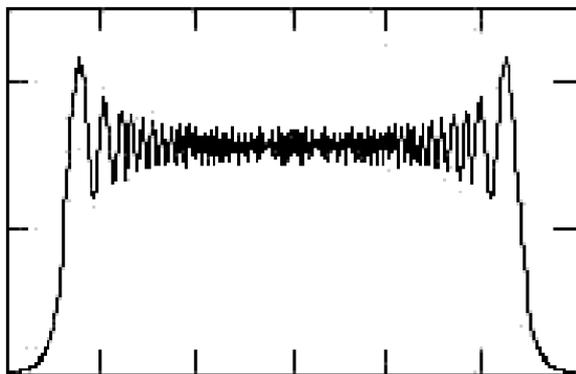Frequency resolution is improved being proportional to 1/T once fixed the Δf and the sampling rate.

Fig.5 The Chirp power spectra with T.Δf =250

To improve the performance, the spectrum ripple levels can be reduced introducing short rise and fall times (R-F) at the signal ends [14, 15]. The rise and fall profile is a linear slope lasting 4% of the time duration.

Fig.6 shows the spectra of a linear R-F Chirp with a time-bandwidth of 250 showing a marked reduction in ripple amplitude compared to the spectra of unmodified linear Chirps of Fig.5.
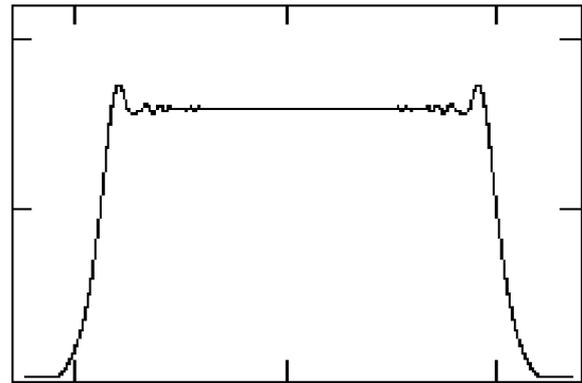

Fig.6 The Chirp spectra with T.Δf =250 and 4% R-F

To further improve the Chirp ripple it's possible to shape it symmetrically in the time domain [16].

This idea brought us in using a up/down Chirp with rise/fall control to get max performance from each test.
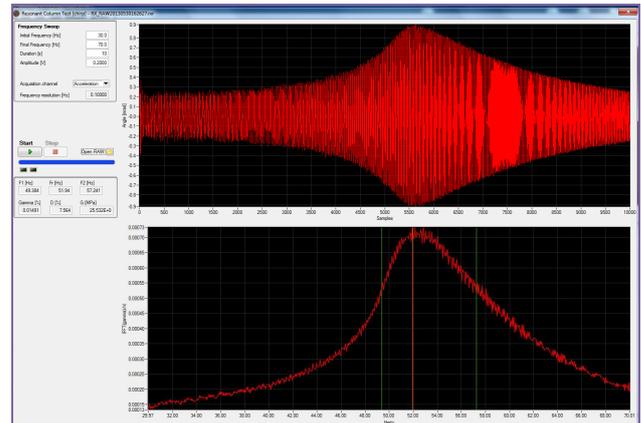

Fig.7 Software screen shot after a Chirp RC

A series of 20 tests have been carried out elaborating the relevant spectrum content using the two excitation methods on a stainless steel rod.

Those tests are made under the assumption that the uncertainty is normally distributed.

The used frequency range for the Chirp was from 40 Hz to 60 Hz (Δf=20 Hz) using a time duration T of 20 s. The same range has been used for the standard RC with a 0.5 Hz step and 20 periods each.

The resonance of the rod resulting into the test is about 52 Hz and the ξ (i.e. the damping) is about 0,2%.

The algorithm used to evaluate the quality of the resulting spectrum is based on the ripple measurement.

The principle is to compare each spectrum with the closest second order system amplitude shape (Fig.8).

The mismatch of the curves has been calculated with the least square regression as a synthetic indicator of the

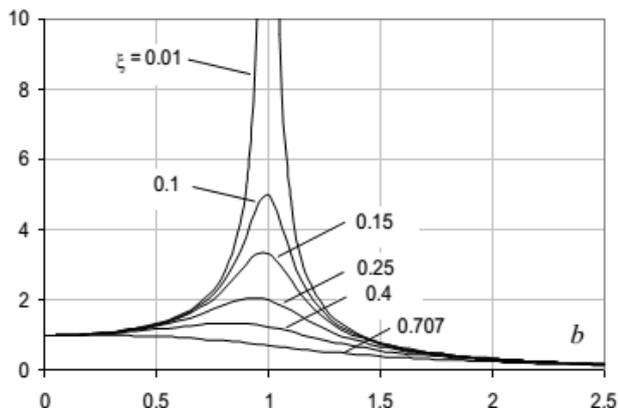percent quality improvement between the R-F Chirp vs. the standard RC.

Fig.8 Non-dimensional second order system

The results of the test series are synthetized in the following table indicating estimated average (μ) and standard deviation (σ) of percentage.

Table 1. Standard RC - R-F Chirp RC comparison

RC mode	M	σ
Standard	21,5	10,2
R-F Chirp	6,5	2,6

V. CONCLUSION

The minimized spectral content beyond the used frequency range with the rise/fall control of the Chirp RC is able to improve the system measurement performances minimizing the effect of the number of cycles reducing the test time with an increased frequency resolution.

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