

**UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ**

**Colegio de Ciencias e Ingenierías**

**A comparison between shear modulus degradation curves**

**Lucía Soledad López Yépez**

**Ingeniería Civil**

Trabajo de fin de carrera presentado como requisito

para la obtención del título de

Ingeniera Civil

Quito, 16 de abril de 2020

# **UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ**

**Colegio de Ciencias e Ingenierías**

## **HOJA DE CALIFICACIÓN DE TRABAJO DE FIN DE CARRERA**

**Comparación entre curvas de módulo de degradación**

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Quito, 16 de abril de 2020

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## RESUMEN

El propósito de este trabajo es obtener las curvas del módulo de degradación y los parámetros dinámicos de la relación de amortiguamiento del suelo de muestras con diferentes índices de plasticidad utilizando un Rheómetro AR2000 a deformaciones controladas y mostrar la influencia de las técnicas de sujeción entre la muestra y el equipo. Las curvas de degradación de cortante y relación de amortiguamiento se obtendrán en una sola prueba, evitando la necesidad de combinar los resultados de otro tipo de pruebas dinámicas del suelo como columna resonante y pruebas de cortante torsional. Los resultados experimentales se comparan con aquellos obtenidos con pruebas dinámicas tradicionales de muestras consolidadas al mismo esfuerzo para validar estos resultados experimentales. La comparación demostró que esta técnica permite obtener resultados exactos en una sola prueba para muestras con altos índices de plasticidad. Sin embargo, para muestras con bajo índice de plasticidad, los resultados mostraron que las técnicas de sujeción tienen un gran impacto.

Palabras clave: Relación de amortiguamiento, módulo de degradación, reómetro, índice de plasticidad, técnicas de sujeción.

## **ABSTRACT**

The aim of this work is to obtain degradation modulus curves and damping ratio soil dynamic parameters of different plasticity index samples using an AR2000 rheometer at controlled strains, and to show the influence of coupling techniques between samples and the equipment. The shear degradation and damping ratio curves will be obtained in a unique soil test, avoiding the need to combine results coming from other kind of soil dynamic tests such as resonant column and torsional shear tests. Results obtained are compared to the ones obtained with traditional dynamic tests of samples consolidated at the same stress value, in order to validate the experimental results. Comparison demonstrated that this technique permits to obtain accurate results in just one test, for high plasticity index soils. However, for low plasticity soils, results showed a great impact that coupling techniques could have.

**Keywords:** Damping ratio, degradation modulus, rheometer, plasticity index, coupling technique.

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### **Disclaimer**

This capstone project consists of a short academic paper written by myself. It contains the procedure and results of an investigation that was conducted during the last two semesters of Civil Engineering. It was intended to be presented in the 5<sup>th</sup> International Conference on Geotechnical Research and Engineering (ICGRE'20), who accepted the submission of the paper. This Conference was scheduled to be carried out by April 2020 in Lisbon, Portugal, but due to the epidemic circumstances of COVID-19, it was rescheduled to be held by October 2020.

The paper titled “A comparison between shear modulus degradation curves”, presented below, will be published after the Conference takes place. The DOI for the paper will be registered as 10.11159/icgre20.131. It is important to emphasize that the presentation of the information included in this capstone project was authorized by the conference administrator. This authorization and the acceptance of submission of the paper are included at the end, as part of the document.

# A COMPARISON BETWEEN SHEAR MODULUS DEGRADATION CURVES

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**Abstract** – The aim of this work is to obtain degradation modulus curves and damping ratio soil dynamic parameters of different plasticity index samples using an AR2000 rheometer at controlled strains, and to show the influence of coupling techniques between samples and the equipment. The shear degradation and damping ratio curves will be obtained in a unique soil test, avoiding the need to combine results coming from other kind of soil dynamic tests such as resonant column and torsional shear tests. Results obtained are compared to the ones obtained with traditional dynamic tests of samples consolidated at the same stress value, in order to validate the experimental results. Comparison demonstrated that this technique permits to obtain accurate results in just one test, for high plasticity index soils. However, for low plasticity soils, results showed a great impact that coupling techniques could have.

**Keywords:** Damping ratio, degradation modulus, rheometer, plasticity index, coupling technique

## 1. INTRODUCTION

Soil dynamic behavior is one of the key factors to take into account, in order to understand and to predict seismic behavior of structures. When there is a cyclic load, such as

earthquakes, soil acts as another kind of structure and dissipates energy. This energy dissipation depends on the damping coefficient (Lin, Ni, Wright & Stokoe, 1988). Damping is a measure of the dissipated energy due to vibration or cyclic loadings. This energy loss often occurs in the form of heat (Ashmawy, Salgado, Guha & Drnevich, 1995). Another dynamic soil property that is critical in the soil response is the shear modulus that degrades with strong cycles (Hardin & Drnevich, 1972). Experimental methods that are commonly used to measure these soil properties are resonant column and torsional shear equipment tests. Through these methods, it is possible to obtain soil degradation curves within a wide range of strains (using the resonant column for low strain levels and the torsional shear test for larger strains). The results of both techniques are then combined to obtain the total degradation curve.

Nevertheless, the fact that different techniques are used to construct a single curve creates doubts on the reliability of the resulting degradation curves (Karray, Hussien, Chekired & Ethier, 2016). A possibility to obtain shear modulus and damping ratio curves in a unique soil test using a rheometer is the aim of this study. Results of two fine-grained soil sample curves completed with a dynamic shear rheometer will be compared with those obtained in the literature. This comparison is carried out to verify the effectiveness of the measuring method.

## **2. EQUATIONS**

The dynamic shear modulus and phase angle were obtained experimentally for these calculations by using a rheometer. The phase angle is the lag between deformation and

applied torque. To carry out the data processing and the comparison between the experimental test and literature, the following equations were used.

Damping ratio was calculated with equation (1) provided by Kelly (Kelly, 2013) as the ratio of dissipated energy and elastic stored energy.

$$D = \tan\left(\frac{\delta}{2}\right) \quad (1)$$

Where:

D is the Damping ratio.

$\delta$  is the phase angle in degrees.

The experimental values of degradation modulus were normalized by using equation (2)

$$\text{Normalized } G = \frac{G}{G_{max}} \quad (2)$$

Where:

G is the shear modulus of the sample obtained with the rheometer at different strains.

$G_{max}$  is the maximum experimental value of the shear modulus.

### 3. MATERIALS

Two soil samples were fabricated in order to analyze the influence of coupling agent in the measuring of soil shear modulus degradation curve. The samples were constructed using two types of soils (i.e. Kaolin and Bentonite). These soils were mixed in different proportions to obtain samples with different index properties. The first sample was 100% Kaolin with a liquid limit of 86% and plastic limit of 31%, resulting in a plasticity index of 55. The second sample was 48% Kaolin and 52% Bentonite. This sample has a liquid limit of 202% and a plastic limit of 20% resulting in a plasticity index of 182. Soil index properties

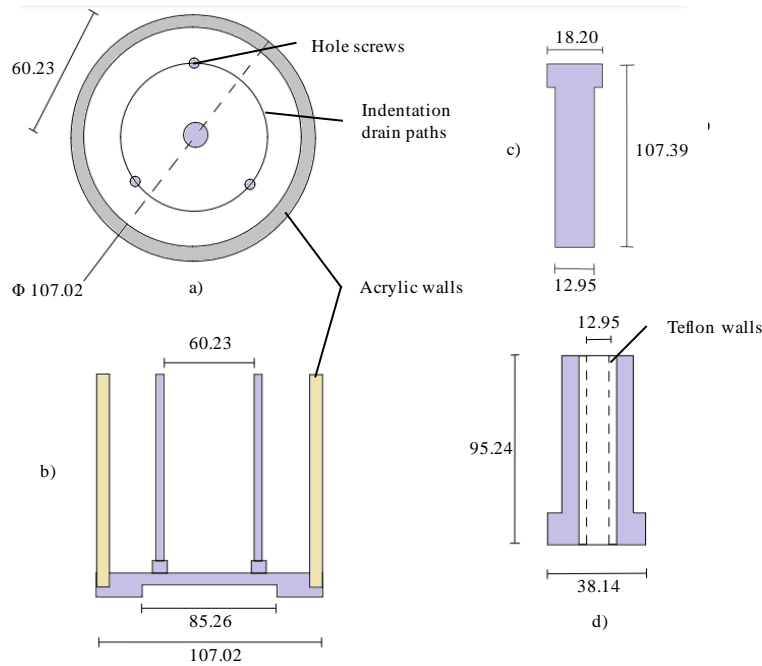
were determined according to ASTM D4318-84 (ASTM D4318-84, 1984). Additionally, specific gravity of the soil mixtures was determined (ASTM D854-14, 2014). The measured values of soil specific gravity for soil mixtures are 2.54 and 2.61 for Sample1 and Sample2, respectively. Properties are summarized in Table #1.

*Table #1: Samples' properties*

Sample	Content		Liquid limit (%)	Plastic limit (%)	Plasticity index	Specific gravity
	Kaolin (%)	Bentonite (%)				
1	100	-	86	31	55	2,54
2	48	52	202	20	182	2,61

#### **4. EQUIPMENT**

A special cylindrical mold was built for the preparation of the soil samples. It consists of two main parts. The first part is a cylinder with acrylic walls and a stainless-steel base. In this element, water is poured to saturate the soil sample for the consolidation process. The second part is a stainless-steel cylinder with a teflon coating in the inside to avoid any friction stress that can affect the sample. The soil is poured in this second element for consolidation. The dimensions of the mold are summarized in Figure 1. The diameter of the acrylic container is 107.02 mm, and the separation between hole screws inside is 60.23 mm. It can be seen in Figure 1 a) and b). The piston (i.e. Figure 1 c)) has a length of 107.39 mm and radius of 12.95 mm, and the mold with Teflon coating shown in Figure 1 d) has an inside diameter of 12.95 mm.



*Figure #1: Sample preparation mold: a) acrylic container plan view and b) lateral view, c) piston and d) mold*

The consolidation process took place in a conventional oedometer. The used equipment corresponds to ASTM D2435 M-11 (2011). The load was incremented until the samples reach a consolidation stress of 100 kPa. A piston was built to load the samples and to remove them from the mold. One end of the piston was enlarged to ensure a proper load transfer between the oedometer and the piston.

A rheometer was used to measure shear modulus for a range of strains (Villacreses, Caicedo, Caro & Yépez, 2020). In this study the AR 2000 was used (TA Instruments, 2007). The main specifications of the apparatus are: torque range that goes from 0.1  $\mu\text{N}\cdot\text{m}$  to 200  $\text{mN}\cdot\text{m}$ , its frequency range goes from  $7.5 \times 10^{-7}$  – 628  $\text{rad/s}$ , and the equipment is able to test solid samples (TA Instruments, 2007). The coupling devices were modified and adapted to test cylindrical solid samples.

## 5. PROCEDURE

The procedure seeks to study the influence of the coupling technique between the sample and the equipment on determining the degradation modulus over a range of strains. To achieve this objective, two soil samples were made with a controlled plasticity index. The soils used for sample fabrication were mixed with water at 1.8 times their Liquid Limit. Then, the samples were consolidated within a sequence of loads that produced stresses of 10, 20, 40, 80, 100 kPa in a lapse of two days. The end of the consolidation was monitored using Taylor Square root of time (Taylor, 1948). The samples' heights were 46.03 mm and 40.75 mm for samples 1 and 2, respectively. The sample diameter was kept constant to 12.95 mm because of the fixed teflon coating.

The samples were tested in the AR 2000 rheometer to obtain the degradation moduli curve. The experimental measurements were compared to the results obtained by Vucetic (Vucetic & Dobry, 1991). The used test was a strain controlled procedure, where the torque for each strain steep was recorded. The test begun with a strain of  $5 \times 10^{-6}$ , computed as conventional torsional procedures (i.e. ratio of deformation arc length by the height of the sample). The strain was twice the previous one until reaching a deformation of  $2 \times 10^{-2}$ . The frequency of the strain deformation was 1 Hz throughout the test.



## 6. RESULTS

The experimental results and the data taken from Vucetic (1991) are shown in Figures 2 and 3.

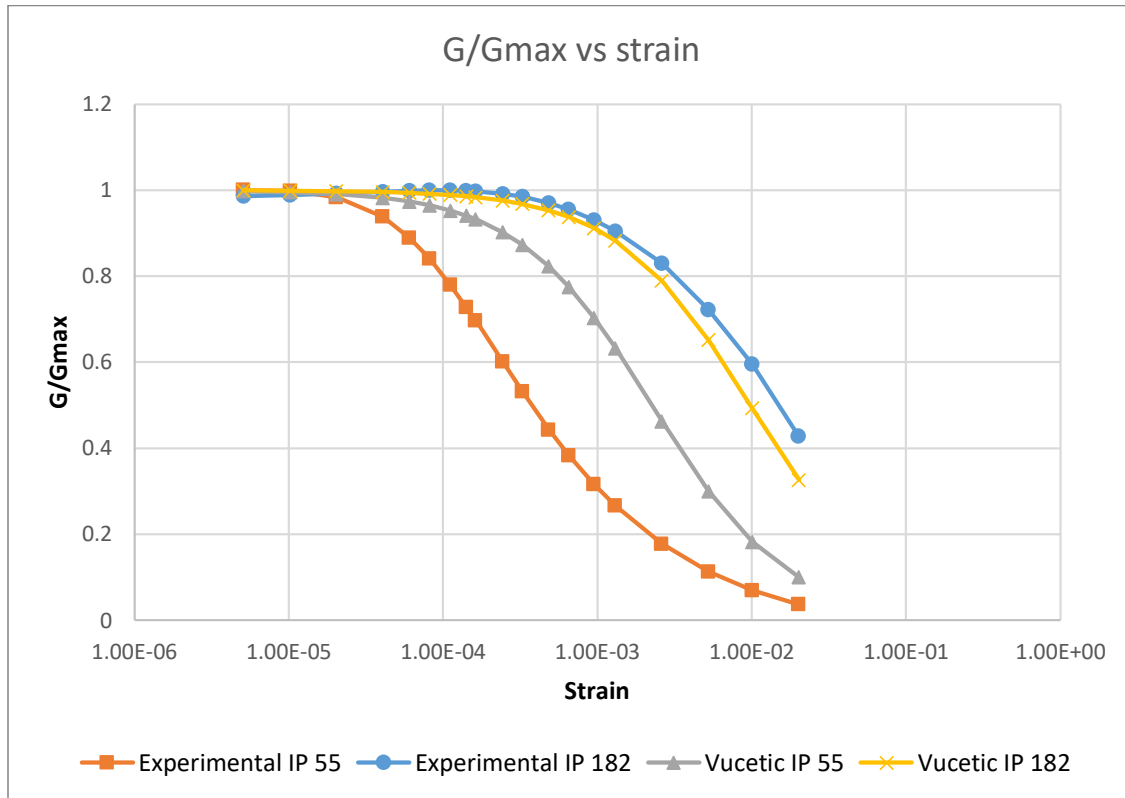
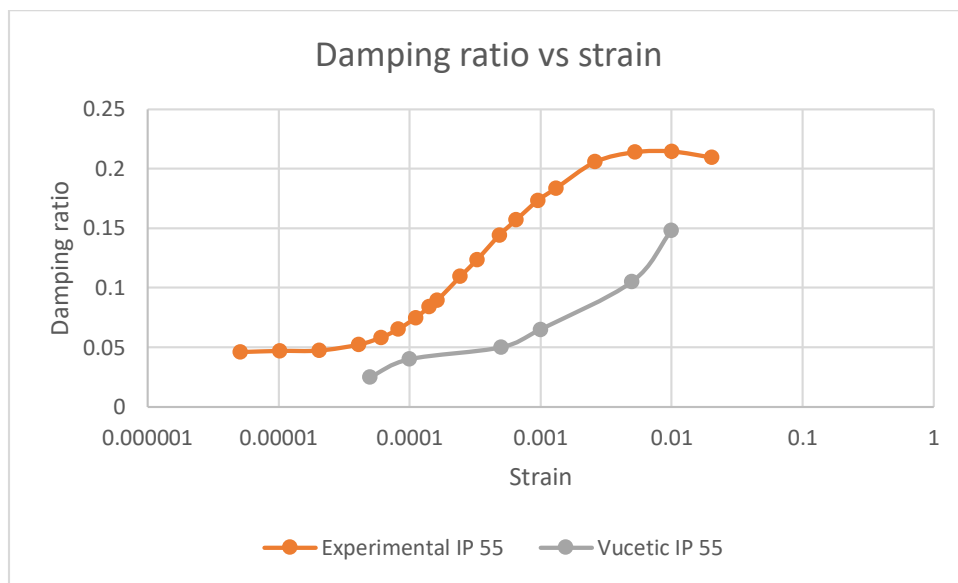


Figure #2: Degradation modulus curves

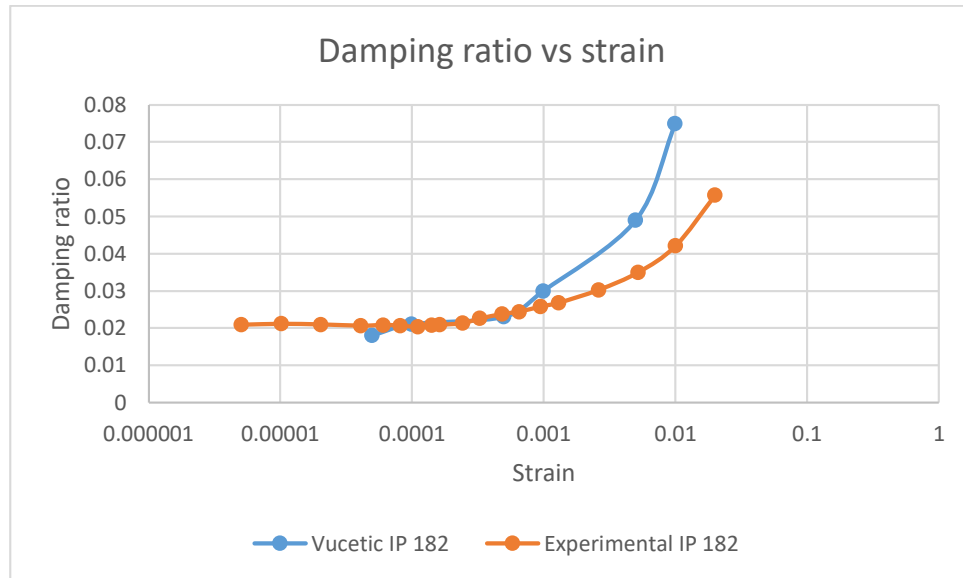
Figure 2 shows the normalized degradation modulus curve of both, experimental samples tested with the rheometer and the degradation modulus curves found in literature (Vucetic & Dobry, 1991). The figure shows that the beginning of the material degradation for the sample with plasticity index of 182 is found at a strain value of  $2 \times 10^{-4}$ . This strain value matches the theoretical results (Vucetic & Dobry, 1991). On the other hand, for the sample with plasticity index of 55, the experimental data shows that the material degradation begins at a strain of  $2 \times 10^{-5}$ , while reference data show it begins at  $4 \times 10^{-5}$  (Vucetic & Dobry,

1991). These numbers suggest that for low plasticity index, the adhesion quality between the sample and the testing instrument influences the start of the degradation of the material.

For samples with high plasticity index, the percentage difference between the experimental data and literature results is less than 5.0% at strains below  $1 \times 10^{-3}$ . Percentage difference at strains greater than  $1 \times 10^{-3}$  increased significantly up to 31.3% at a strain of  $2 \times 10^{-2}$ . On the contrary, for samples with lower plasticity index, percentage differences exceed 10.0% at strains of  $8 \times 10^{-5}$ , and they reach a percentage difference of 63.6% at the maximum strain.



(a)



(b)

*Figure #3: Damping ratio for (a) plasticity index 55 soil sample and (b) plasticity index 182 soil sample*

Figure 3 contains the data of damping ratio of the two samples compared to the theoretical information (Vucetic & Dobry, 1991). Figure 3(a) presents the results of sample 1, and it shows an evident difference between the results obtained in the test and the ones given by the bibliographic reference (Vucetic & Dobry, 1991). Picornell (2013) explains the influence of the coupling techniques in these measurements when samples are tested on the torsional Resonant Column. This can be the reason for the discrepancy between the experimental results and theory (Vucetic & Dobry, 1991). A different outcome is observed in the sample with a higher plasticity index. In this case, the difference between the test results and the theoretical ones (Vucetic & Dobry, 1991) at low damping ratio is minimal, and it increases with the increasing values of damping.

## 7. CONCLUSIONS

This paper presents the degradation modulus curves and damping ratio of two soil samples of kaolin and bentonite with different plasticity index (i.e. 55 and 182). These samples were consolidated at the same stress by using an oedometer and a special mold built with stainless steel and teflon. They were tested in the AR 2000 rheometer, and the resulting data was compared to the information found in professional literature (Vucetic & Dobry, 1991). The graphs showing the degradation modulus and damping ratio suggest that the coupling technique influences the measurements of the samples. Figures show that the role that the coupling technique plays in these measurements affects more in samples with low plasticity index. The beginning of plastification in the sample with low plasticity index is different between the experimental results and the reference data (Vucetic & Dobry, 1991), and the percentage difference at different strains is higher for this sample than it is for the high plasticity index sample. The results obtained from this test support the conclusions described in literature (Picornell, Nazarian & Almadhoun, 2013), who compares various coupling techniques and demonstrates its influence in damping measurements.

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## 9. ANEXO A: AUTHORIZATION OF USE OF INFORMATION



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If your answer is positive, I would like to know what policies I should follow, and what acknowledgements I should include.  
I look forward to hearing from you.

Sincerely,  
Lucía López.



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We look forward to seeing you at the conference.

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