Numerical evaluation of shear modulus degradation and damping curves of Algerian soils using geophysical tests

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SUMMARY:
The purpose of this paper is to evaluate the shear modulus reduction curve $G/G_{max}(\gamma)$ and the increase of damping $D(\gamma)$ with the cyclic shear strain amplitude of some Algerian soils, using data resulting from geophysical and geotechnical investigations. It consists on numerical identification of these curves using FLAC code. The non linear elastic model proposed by Ramberg–Osgood and limited by the Mohr-coulomb criterion is used. The experimental curves given by Seed and Idriss (1970) for granular materials and Vucetic and Dobry (1991) for the fine grained soils are used to calibrate the parameters of the model.

Keywords: Shear modulus, hysteretic damping, non linear model, geophysical tests

1. INTRODUCTION

The design of geotechnical structures, located on regions subjected to cyclic loading due to earthquakes, requires considering the cyclic shear strength. These structures founded on such soils must be able to withstand cyclic shear stress from a large number of different amplitude seismic acceleration, during their life time. The dynamic behavior of structures during an earthquake is correlated with the behavior of the ground underneath. Therefore, the evaluation of the dynamic response of a soil or structure founded on soil requires knowledge of the dynamic properties of the foundation soil, particularly the determination of two important parameters, the shear modulus and the damping of the soils. During the last 30 years, several investigations have been made in order to understand the behaviour of soils during cyclic loading (Atkinson et al., 1991; Tatsuoka et al., 1997). It has shown that the stress strain behaviour of soils is non linear and hysteretic, characterized by a shear modulus and damping ration varying significantly with the amplitude of shear strain. The evaluation of dynamic soil properties is based either on laboratory and in situ test. Geophysical methods are often used to characterize the dynamic soil properties of the subsurface.
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In Algeria, because the Algerian Para-seismic Rules (RPA 2003) allows the use wave velocity for different soil classes, which is selected based on the average shear wave velocity of the top 30 m of the site profile, and geophysical investigations are imposed at high seismicity region. Cross hole and down hole seismic surveying methods are being used increasingly in geotechnical investigations to classify the sites and to evaluate dynamic properties, particularly the dynamic shear modulus of soils and rocks, required before any geotechnical design. Thus, one of the obstacles found in design phase of projects is no experimental shear modulus degradation and damping curves are available for the Algerian soils, because the cost of laboratory and in situ test is quite expensive; a complete geotechnical description of a site is very rare.

This paper presents an analysis to evaluate the shear modulus degradation curve $G/G_{max}(\gamma)$ and the increase of damping $D(\gamma)$ with the cyclic shear strain amplitude of some Algerian soils, using data resulting from geophysical and geotechnical investigations. It consists on numerical identification of these curves using FLAC code. The non linear elastic model proposed by Ramberg–Osgood and limited by the Mohr-coulomb criterion is used (Bagagli, 2010). The empirical curves given by Seed and Idriss (1970) for granular materials and Vucetic and Dobry (1991) for the fine grained soils are used to calibrate the parameters of the model.

2. G/G$_{MAX}$ RELATIONSHIPS

The model used in this study is an elastoplastic model with a no linear elasticity. Several simple mathematical functions have been proposed to take into account the hysteretic behaviour of the soils. Ramberg-Osgood (1943) formulation is adopted and limited by Mohr coulomb criterion which contains a few parameter. This criterion usually accepted in the literature as a simple model and enough precise. Ramberg-Osgood (RO) class models are hysteretic models that take into account energy dissipation within soil under cyclic loadings (see Fig. 2.1). The relationship between shear stress τ and strain γ can be written:

$$\gamma - \gamma_c = \frac{1}{G_{\max}} \left[1 + \alpha \left(\frac{|\tau - \tau_c|}{n \tau_y} \right)^{r-1} \right] (\tau - \tau_c) \tag{2.1}$$

α and r are constants. γ_c and τ_c are the coordinates of the tips of the loop (see Fig. 2.1). G and τ describe the hysteresis loop (Fig. 2.1). n is equal to 1 in the first loading and then is equal to 2. The constitutive stress-strain relationship using the Ramberg-Osgood (RO) formulation is fully specified be the shear modulus at very small strains, G_{max}, a reference strain γ_y, and constants α and r. The limit shear stress t_y is related to the reference strain, γ_y by the relationship (see Fig. 2.1):

$$\tau_y = G_{\max} \gamma_y \tag{2.2}$$

Values of the secant modulus, G_s, and the equivalent damping ratio, D, and taking into account the Mohr-Coulomb criterion, from this (RO) formulation can be explicitly expressed as functions of these parameters as follows:

$$G = \frac{d\tau}{d\gamma} = \frac{G_{\max}}{1 + \alpha \left(\frac{|\tau - \tau_c|}{n \tau_y} \right)^{r-1}} \tag{2.3}$$

$$D = \frac{\Delta W}{4\pi W_e} = \frac{2}{\pi} \left(\frac{r-1}{r+1} \right) \left(1 - \frac{G_s}{G_{\max}} \right) \tag{2.4}$$

The hysteretic damping ratio can be calculated by equation (2.4) where ΔW is the energy dissipated in one cycle of loading, and W_e is the maximum strain energy stored during the cycle. As noted in Figure 2.1, the area inside the hysteresis loop is ΔW, and the area of the triangle is W_e. The described model is implemented in FLAC software. The seismic response of soil behaviour is performed using computer program FLAC^{2D} taking into account the Ramberg-Osgood hysteretic model with the Mohr Coulomb criterion.

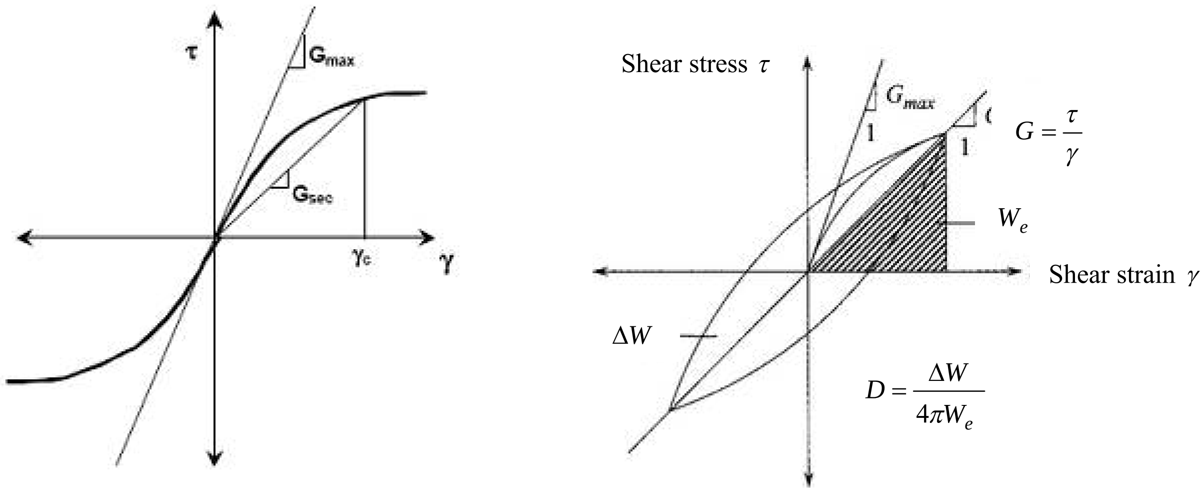

Figure 2.1. Typical stress strain relationship.

3. NUMERICAL SIMULATION AND IDENTIFICATION METHODOLGY

In seismic analyses, the degradation curve of shear modulus G(γ) and the evolution of damping D(γ) measured in shear test are largely used for the material identification. The objective of the soil identification is to obtain the elastoplastic model parameters from these experimental curves. The model's parameter identification methodology proposed in this study is:

In the first step, the parameters of the Ramberg Osgood law, r and α, are identified by means of a practical procedure developed by comparing the curve G/G_{max} given by this law and the experimental curve G/G_{max}. The evaluation of maximal shear modulus is determined from geophysical methods, often used to characterize the dynamic soil properties of the subsurface, in particular down hole test. Because no experimental of these curves G(γ) and D(γ) are available for Algerian soils, the identification of the model parameters, r and α, is based on the empirical curves proposed by Seed and Idriss (1970) for granular materials and Vucetic and Dobry (1991) for clays. In second step, a cyclic behavior of a soil profile is simulated using the numerical code FLAC, taking into account Ramberg-Osgood law limited by the Mohr Coulomb criterion. The angle of friction φ, the cohesion c, and the effective mean stress p' are defined from geotechnical investigations.

Dynamic site response analysis is performed considering a 2D finite difference model. The soil deposit is assumed to be made of several horizontal layers, which are horizontally homogenous and of infinite horizontal extent soil column extending from the ground surface to bedrock. The soil layers are characterized by their physical and mechanical properties of the model taking into account in this study. The mesh of the soil profile is 30 rectangular elements of one meter in thickness and width. The mesh size for soil column model is selected to ensure accurate wave transmission. Earthquakes or mono-harmonic sinusoidal functions are assumed to generate only horizontal motion at the soil-bedrock interface, and to result into shear waves that propagate vertically in the soil layers. Figure 3.1 shows the model prediction for four acceleration amplitude. The results illustrate the potentiality of the model to fit the non linear stiffness of soil. It can be noted that with the increase of the amplitude of the loading loops are more and more tilted towards the horizontal what brings to light the degradation of the shear modulus. The area of the hysteresis loop on the other hand increases proportionally with the development of the amplitude of loading, what explains the increase of the damping ratio D according to the distortion γ.

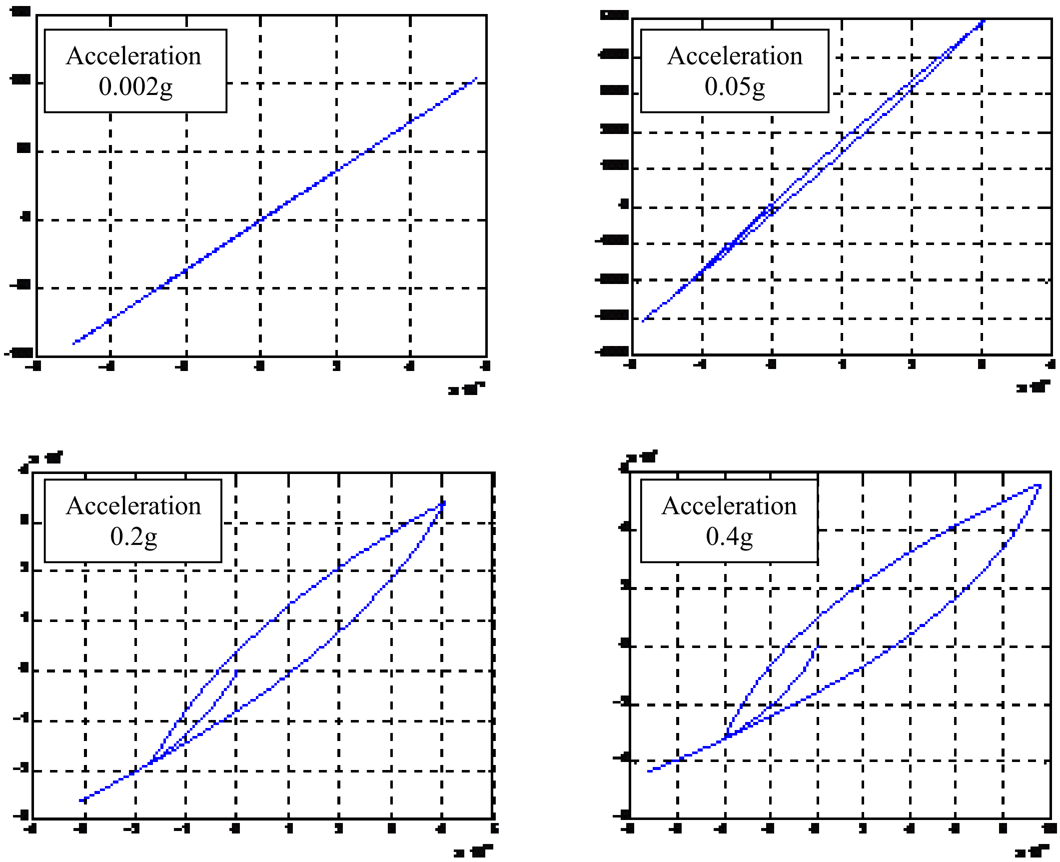

Figure 3.1. Numerical hysteresis loop curves τ=f(γ) according acceleration.

4. DEGRADATION SHEAR MODULUS AND DAMPING CURVES FOR ALGERIAN SOILS

Northern Algeria is a highly seismic area, as evidenced by the historical (1365–1992) seismicity (Benouar, 1994). During the last two decades, it experienced several moderate to strong destructive earthquakes. Therefore, Design of geotechnical engineering problems that involve dynamic loading of soils and soil-structure interaction systems requires the determination of two important parameters, the shear modulus and the damping of the soils. Many geophysical and geotechnical investigations are performed to characterise the Algerian soils, but few dynamic tests and no experimental of the G (γ) and D (γ) curves are available. The aim objective of this study is to propose these curves by means a numerical analysis based on empirical curves proposed by Seed and Idriss (1970) for sands and Vucetic and Dobry (1991) for clays.

4.1. Harbor zone of Bejaia

The alluvial plain of Bejaia is a depression, located between two mountains, Gouraya to the north and Sidi Boudraham to the southwest. It covers an area of approximately 750 hectares. The depression has been filled by fine alluvium of the Soummam and the Seghir rivers and interpenetrated in transgressive marine deposits. It consists of sedimentary soil deposits of quaternary age. The geologic formations found in the region are: the old alluvia represented by marl gravel, pebble and sand enveloped in silt matrix; the swamp alluvia consisted of fine elements represented by silt and mud with of fine sand intercalations; the recent alluvia which are deposits slightly muddy and cover the most of the plain and fill composed of heterogeneous soil represented by gravelly clay with a presence of few blocks. The geological history indicates that the harbor area extending the alluvial plain is composed of more or less muddy fine materials (silt, clay) and sand deposited on a bedrock encountered at approximately 30 to 40 m depth, likely marl and limestone of cretaceous age. Many geotechnical surveys are carried out in the harbor area to evaluate the resistance of soils and their degree of constructability. It appears that the surface layers of alluvial nature, predominantly sandy clayey and sometimes heterogeneous have not yet reached a sufficient degree of consolidation, therefore their bearing capacity is low and their compressibility is high. Typical soil profile and engineering properties of the soil layers are shown in Figures 4.1, Figure 4.2 and Table 4.1. For this site, the Ramberg-Osgood constants are identified using the empirical curves of Seed and Idriss (1970). The best fit gives r equal to 2.2 and α vary between 0.7 and 1.4 (see Table 4.3). Then, a simulation with FLAC program is performed taking into these parameters for the RO law and the Mohr Coulomb criterion. Figures 4.3 and 4.4 shows the best fit Ramberg-Osgood curve and compares the calibration curve to those obtained by numerical calculation using FLAC code. The soils are fine sand and muddy sand.

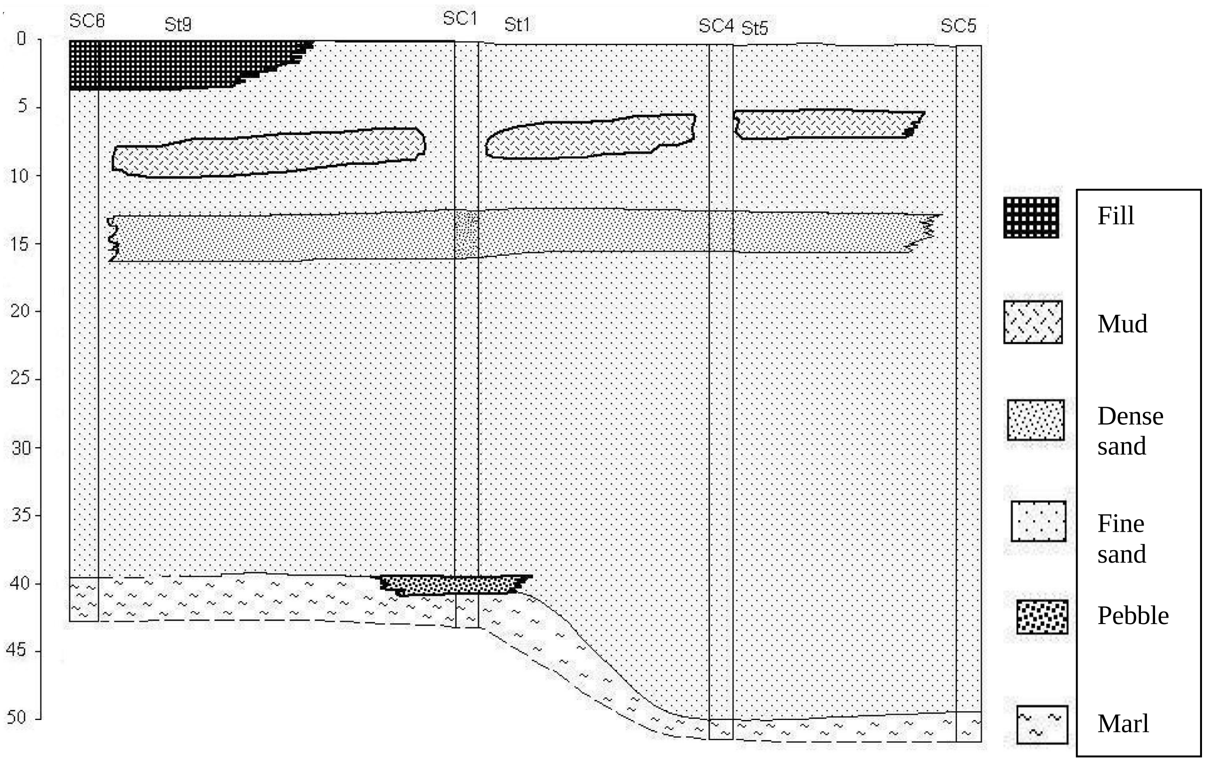

Figure 4.1. Typical soil profile (Sadaoui, 2006).

Table 1.1. Physical and mechanical characteristics.

Characteristics of soil	Fine muddy sand	mud	Marl
Dry density (kN / m^3)	14.90 - 17.50	13.60 – 16.80	16.60 – 17.10
Wet density (kN/m^3)	18.80 - 21.00	18.20 – 20,40	20.40 – 20.50
Natural moisture content w (%)	19.80 - 32.00	21.90 – 33,50	19.50 - 23.40
Degree of saturation Sr (%)	88 - 99	91 – 96	90.7 - 100
Liquidity limit w_L (%)	34 - 43	47 - 48	46 - 48
Plasticity index Ip (%)	20 - 24	23 - 24	24 - 25
Angle of friction (°).	10 - 24	5 - 8	18 - 20
Cohesion c (kPa)	20 - 105	10 - 39	16 - 32
Pressure of preconsolidation p’ (kPa)	238-344	76 –215	271-337
Compression index Cc (%)	9.05 – 17.42	10.40-26.40	16.94-18.27
Swelling index Cg (%)	0.99 – 2.26	1.91-3.86	4.10-10.91

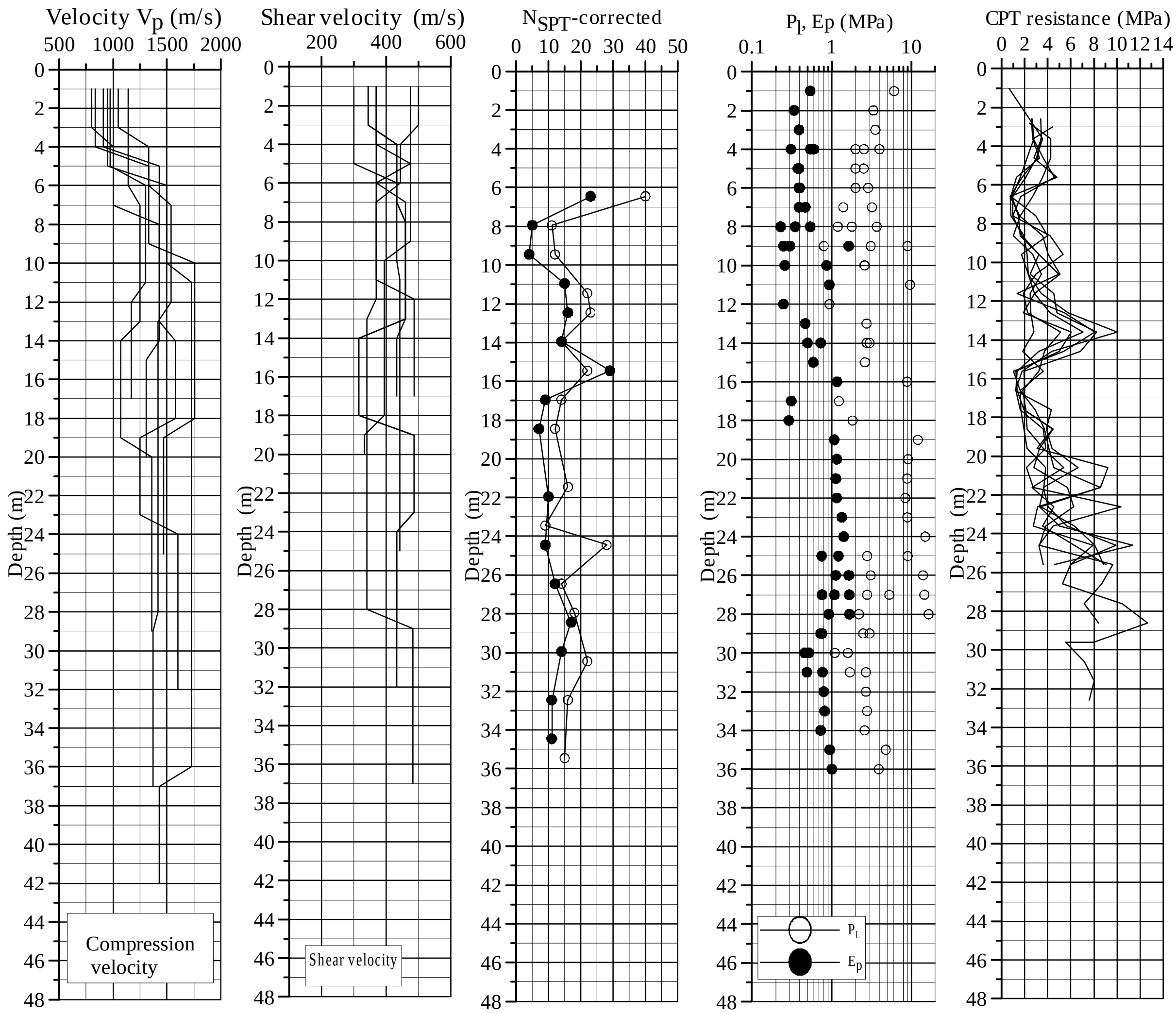

Figure 4.2. In situ soil characteristics.

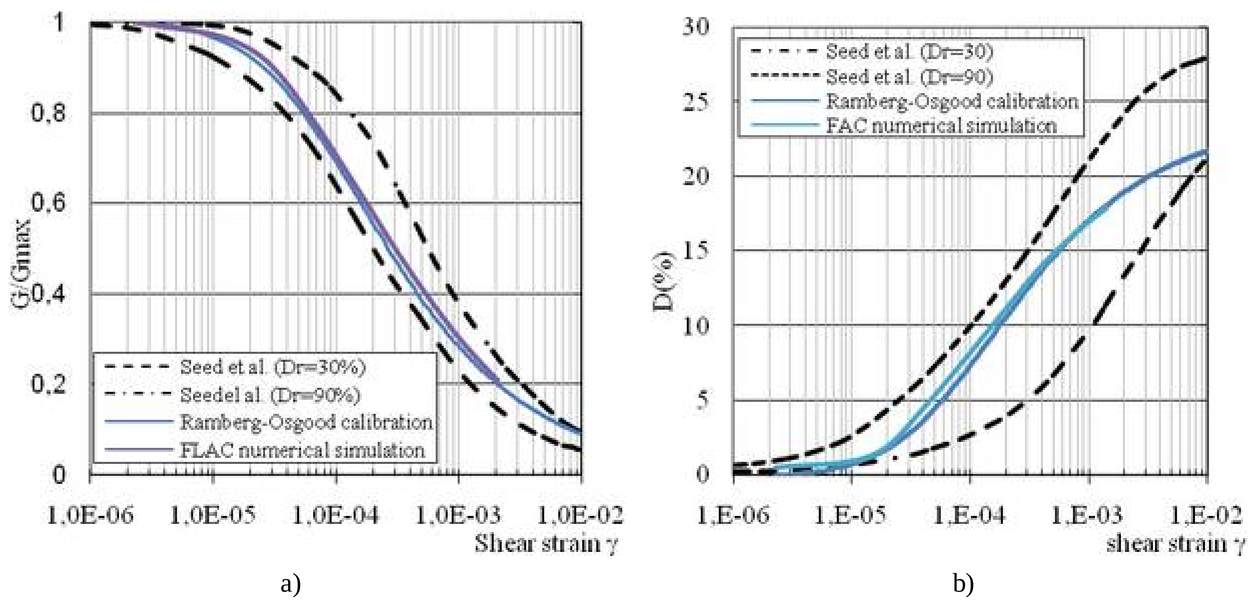

Figure 4.3. Degradation of shear modulus (a) and evolution of damping ratio (b) curves for fine sand.

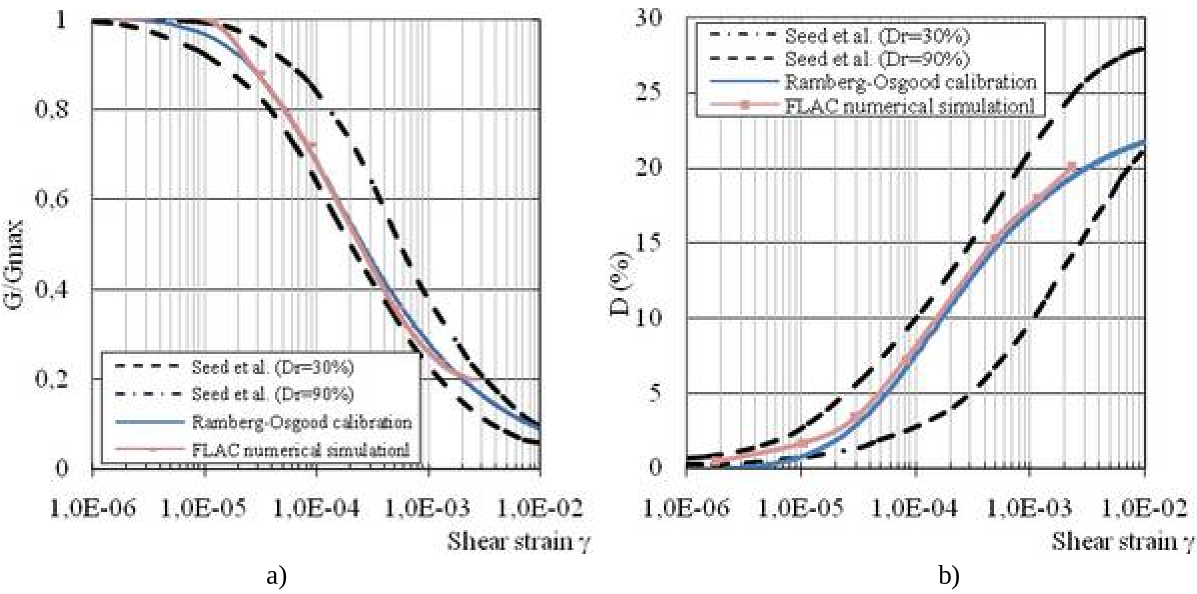

Figure 4.4. Degradation of shear modulus (a) and evolution of damping ratio (b) curves for muddy fine sand.

4.2. Bab Ezzouar site

The site is located in Algiers. The soil stratigraphy encountered on the site consists on stiff to very stiff clays, which overlies a layer of sandstone material. The thickness of the clay is about 15 to 18 m. The clay is saturated. The natural water content w_n varied between 7% and 21%. The plasticity index varied between 22% and 27%. The shear strength parameters derived from consolidated undrained triaxial tests with pore pressure measurement range from 7° to 21° for the friction angle and from 14 kPa to 126 kPa for the cohesion. A conventional limit pressure ranging from 500 kPa to 2600 kPa and pressuremeter modulus ranging from 4700 kPa to 44000 kPa characterizes the clay. Consolidation testing indicates that the soil is normally consolidated to slightly overconsolidated with medium compressibility, C_c ranging from 10% to 17%.

The parameters used in the calculations are given in the Table 4.2. The curves of evolution of the shear modulus and the damping are given by Vucetic and Dobry (1991) are used for the identification of the parameters of the law of Ramberg-Osgood. The results are presented in the Figure 4.6.

4.3. Curves G (γ) and D (γ) for other Algerian sites

Within the framework of the realization of projects and the study of microzonation of the Algiers region, several geotechnical and geophysical investigations were made on different area and type of soils. The approach proposed previously is used to predict the curves of the shear modulus degradation and the evolution of the damping. Similar test data for these soils are shown in Figures 4.7, 4.8 and 4.9. The best fit Ramberg-Osgood curves gives the parameters shown in Table 4.3. The obtained results show clearly that the RO model reproduces an acceptable behavior of the granular and fine soils under cyclic load.

Table 4.1. Physical and mechanical characteristics.

Wet density (kN/m^3)	19.6
Shear velocity Vs (m/s)	1170
Maximal shear modulus G_{max} (MPa)	2680
Angle of friction (°)	20
Cohesion (kPa)	100
Ramberg-Osgood parameters	R= 2.0 a=0.15

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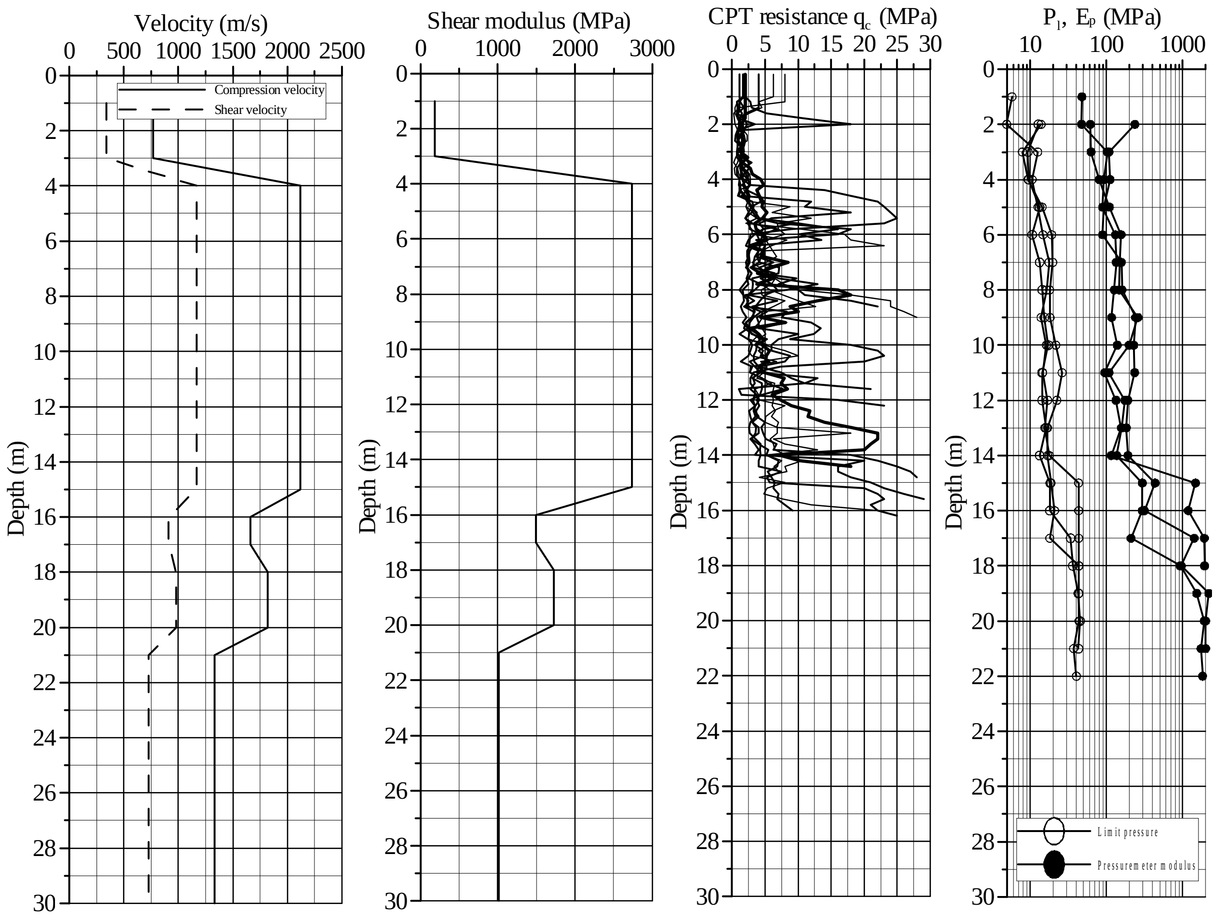

Figure 4.5. Characterics of soils.

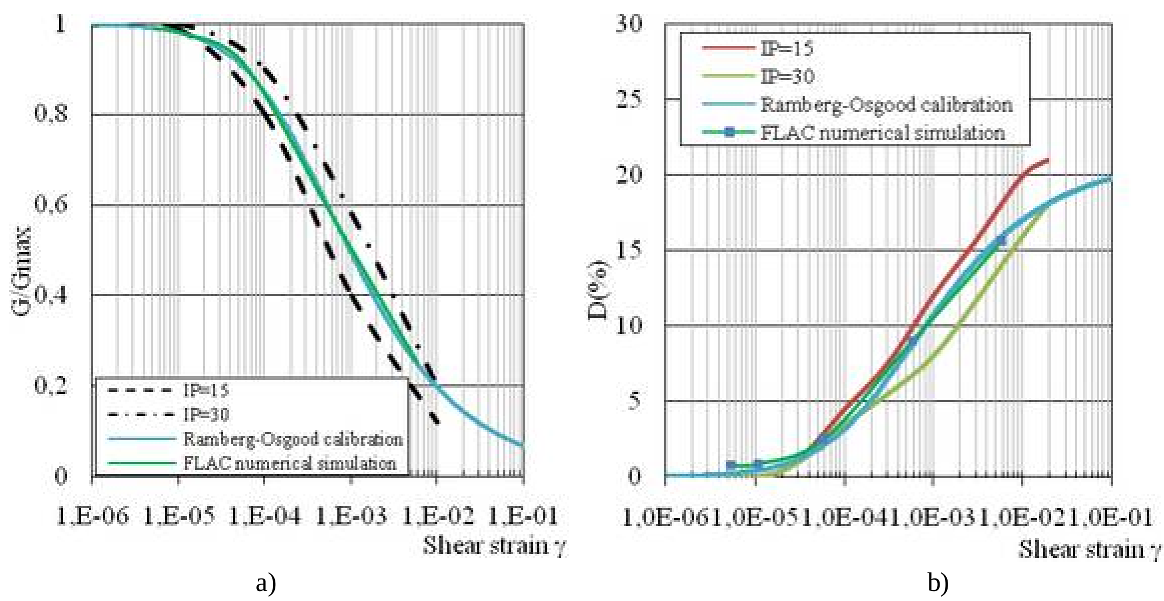

Figure 4.6. Degradation of shear modulus (a) and evolution of damping ratio (b) curves for clay.

Table 4.3. Ramberg-Osgood parameters giving the best fit.

Sand sites	α	r	Gravel sites	α	r	Clay sites	α	r
Bab Ezzouar	2.1	2.5	Rouiba	2.05	9	Dar El Beida	2.2	0.5
Souidania	2.1	3	Badjarah	2	10	El Biar	2	1.2
El Biar	2.1	1.2	Bourouba	2.1	17	Bab Ezzouar	2	0.15
El Mouradia	2.2	3.1	Gue de Constantine	2	3	Hydra	2.05	1.2
Casbah	2.2	3	Hammamet	2.1	0.9	El Mouradia	2	1.1
Bordj El Bahri	2.2	2.6	Oued Koreich	2.03	6	Baraki	2.1	3
Dar El Beida	2.1	2.3	Kouba	2	7	Beni Messous	2	0.7
Bordj El Kiffan	2.15	2.33	Alger Centre	2.5	5.5	-	-	-
Bejaia	2.2	0.7-1.4	El Mouradia	2.05	6	-	-	-
Boumerdes	2.2	0.5 – 1.3	El Harrach	2	20	-	-	-
Zemmouri	2.2	2 -4.5	Bordj El Kifan	2.0	3	-	-	

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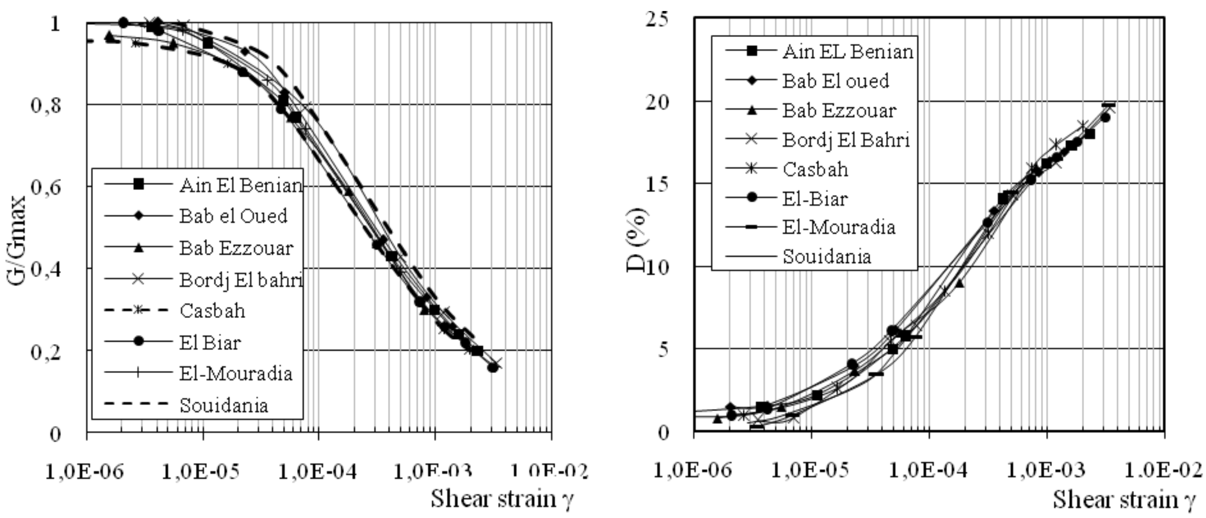
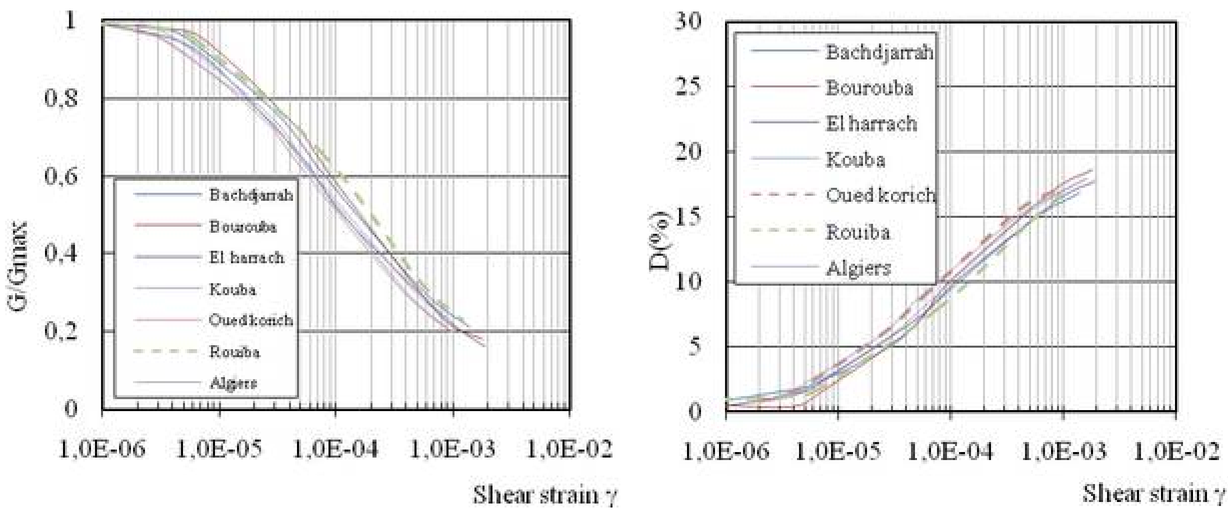


a) b)

Figure 4.7. Degradation of shear modulus (a) and evolution of damping ratio (b) curves for sands.



a) b)

Figure 4.8. Degradation of shear modulus (a) and evolution of damping ratio (b) curves for gravels.

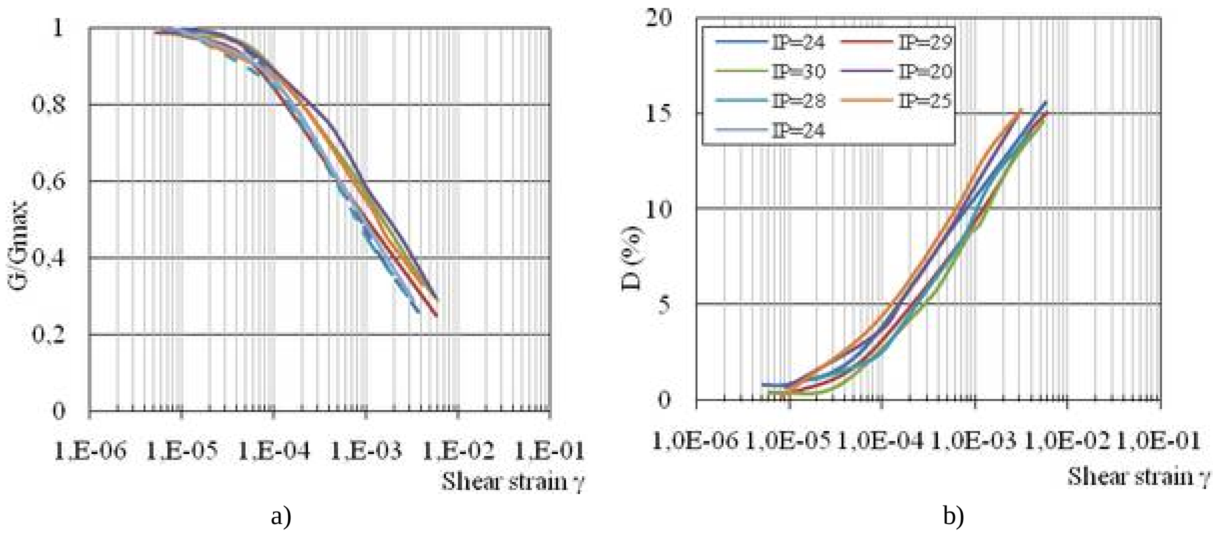


Figure 4.9. Degradation of shear modulus (a) and evolution of damping ratio (b) curves for clays.

5. CONCLUSION

Using the empirical curves of shear degradation modulus and damping curves proposed for soils in the literature, the dynamic analysis performed using FLAC code point out the potentiality of Ramberg-Osgood model, limited by the Mohr Coulomb criterion, to evaluate the degradation of the shear modulus and damping ratio curves for Algerian soils. This study can form the preliminarily basis to give these curves when no experimental data is available or to be used as the starting point for cases where geotechnical measurements are not sufficient.

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