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SOILS NONLINEARITY EVALUATION FOR SITE SEISMIC MICROZONATION

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This paper presents a method for evaluating the nonlinear characteristics of the soils material from a certain layer which was investigate only by *in situ* methods using the nonlinear dynamic function experimentally determinate from the same material but situate in another layer. Such method is needful for microzanation studies.

1. INTRODUCTION

The strong dependence of the soils dynamic properties on strain or stress level produced by external loads is very well known. A large volume of investigation concerning dynamic stress-strain characteristics of soils in dynamic load conditions have been performed so far [10 – 13]. These studies show that main characteristics for the choice of a dynamic constitutive equation, is the strain dependency and dissipative capacity.

In the previous first author's papers [1], [5], [6] this dynamic nonlinear behavior was modeled assuming that the geological materials are nonlinear viscoelastic materials. This model describes the nonlinearity by the dependence of the linear mechanical parameters: shear modulus G and damping ratio D in terms of shear strain invariant γ: $G = G(\gamma)$, $D = D(\gamma)$. Due to this two dynamic functions – one for material strength modeling and another including material damping - this model can be regard as an extension in the nonlinear domain for the non-viscous linear Kelvin-Voigt model [7], [13] and for this reason, in the next, we will use the denomination - the nonlinear Kelvin-Voigt model (NKV model).

This model can be used for soil dynamic response calculations and was successful employed in earthquake engineering for nonlinear site response computations [8], [14].

The material function of the NKV model, $G = G(\gamma)$ and $D = D(\gamma)$, can be quantified by laboratory tests (especially in resonant column tests) performed upon soil samples obtained from site boring correlated with directly *in situ* measurements of the S-wave velocity which can offers the pertinent estimation of the initial values G_0. However, the damping evaluation and the nonlinearity of both material functions can be obtained only by laboratory tests.

This full description of the dynamic soil behaviour, by combining the field and laboratory data are needful for finally site studies for a certain building emplacement.

The microzonation studies regards a large territory not integral covered by site – laboratory experimental studies. Usually, one can perform some seismic refraction survey for the wave velocity but due to the drilling costs, the full data acquisition is not accessible. However, neglecting the nonlinear behaviour of the geotechnical materials situated between base rock and free surface can discredits the microzonation result. However, full emplacements evaluation is not the purpose of the microzonation, which must give only a seismic qualification for a relative large zone regarding preliminary design data.

For this reason, an approximate method for nonlinear soil evaluation seems as adequate. Missing data for a certain material situated at a certain depth into a certain layer (denominate in the next as *target layer*) can be substitute by extension using known material functions obtained by laboratory tests performed upon the same material but situated in another layer (denominate as *provider layer*). Certainly, the result accuracy is more reduced by comparison with the accuracy of direct determination but this approximate method can satisfy the microzonation demand.

The extending of the known data for cover an unknown place is a difficult operation due to inherent differences between soil characteristics of the same material type but situated in different layers. All of these differences must be prior carefully evaluated by experimental studies and for each case, the needful correction functions must to determine. Thus, for example, if there are the material functions determined from a clay sample obtained from a layer situated at certain depth and we wish to use these functions for another clay situated at another place at another depth we must prior evaluate the influences give by physical properties differences (such as material humidity or density) and then we must evaluate the influences of the different stress condition between provider and target layer.

In the next, we exemplify this correcting technology by showing some correction functions intended for attenuate the effects. give by different conditions.

2. INFORMATIONS ABOUT *in situ* CONDITIONS

First steps of the extension depend on *in situ* measurements, which must give as soon as complete image for the physical and mechanical condition of the soil materials from the layer. Geological survey must provide the current stratification and for each layer must give minimal informations as: shear wave velocity v_s, primary wave velocity v_p, specific gravity G_s or mass density ρ, water level, humidity w_0, a.s.o.

These preliminary data enable us to evaluate the soil mechanical condition, in the first place the confining stress condition, which have a major weight in dynamic response.

The *in situ* measurements are performed under reduced load levels when the soil behaviour are nearly linear and for this reason for all *in situ* evaluations one can use the linear elasticity relationships. Also, the modulus value *G* obtained from *in situ* data using the well-known relationship:

$$G_0 = G(\gamma)\big|_{\gamma=0} = \rho v_s^2 \tag{2.1}$$

may be assumed as initial value G_0 of the nonlinear modulus function $G(\gamma) = G_0 \cdot G_n(\gamma)$.

Prior to dynamical loading, the soil material are subjected *in situ* to the confining stress state σ_0, which can be evaluated in terms of physical and mechanical characteristics as:

$$\sigma_0 = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \tag{2.2}$$

with:

$$\begin{aligned} \sigma_1 &= p_v \\ \sigma_2 &= \sigma_3 = K_0 p_v \end{aligned} \tag{2.3}$$

where p_v is the vertical lithological pressure and K_0 is the coefficient of the earth pressure at rest, dependent on Poisson's coefficient υ:

$$K_0 = \frac{\upsilon}{1-\upsilon} \tag{2.4}$$

Thus, eq. (2.2) becomes:

$$\sigma_0 = \frac{1+\upsilon}{3(1-\upsilon)} p_v \tag{2.5}$$

Vertical lithological pressure can be connected with depth *z* as:

$$p_v = \gamma_v z \tag{2.6}$$

where γ_v is the volumetric weight:

$$\gamma_v = \rho g \tag{2.7}$$

where ρ is the mass density and *g* is gravitational acceleration. Thus, eq. (2.5) becomes:

$$\sigma_0 = \frac{(1+\upsilon)}{3(1-\upsilon)}\rho g z \tag{2.8}$$

Starting to the definition relationships of the wave velocities:

$$v_p = \sqrt{\frac{\lambda + 2G}{\rho}} \quad ; \quad v_s = \sqrt{\frac{G}{\rho}} \tag{2.9}$$

and using the relationship between Lamé's coefficient λ and Poisson's coefficient υ:

$$\lambda = \frac{2G\upsilon}{1-2\upsilon} \tag{2.10}$$

one can obtain the Poisson's coefficient in terms of wave velocity:

$$\upsilon = \frac{v_p^2 + 2v_s^2}{2v_p^2 + 6v_s^2} \tag{2.11}$$

Now, from eq. (2.8) one can obtained the confining stress value σ_0.

3. THE EFFECTS OF THE PHYSICAL PROPERTIES VARIATION

It is possible that the physical properties of the tested material will differ from the same properties of the soil material from target layer, where are intend to use the experimentally material functions. The differences between physical properties values can yield significant modifications of the mechanical values that govern the dynamic soil response. Although all of physical properties affect the mechanical properties in the extending operation one can keep accounts only the physical characteristics that can be evaluated by *in situ* methods – the mass density and the water contents, and in this latter case the *in situ* methods can only specify if the layer is under or over water level.

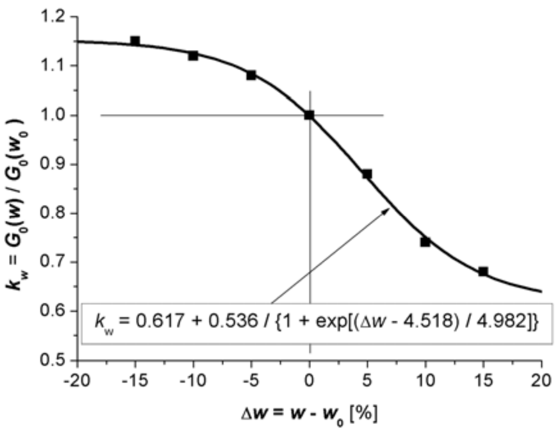

Fig. 3.1

The mass density has an important weight on modulus values determination. Because the modulus values determinations are based on the known formula $G = \rho v_s^2$ the density differences affects in the same proportion the modulus values. From this reason, the existing modulus-function $G = G(\gamma)$ must be "translated" by a certain amount give by density difference.

It is experimental evidence that the modulus values G and the water content *w* are in inverse ratio – increasing humidity leads to decreasing modulus values. Such relationship can be experimentally mark out by resonant column tests performed upon the samples processing from the same soil material but with the different humidity. As an example, in fig. 3.1 are given such humidity correction obtained by using the clay samples [2].

4. DEPTH CORRECTION

The confining stress conditions supported by soil material in the emplacement layer have a major weight on dynamic response. The modulus-function values are in direct ratio with the confining stress values σ_0, the increase of the confining stress leads to the estimable grow of the modulus values. For this reason the same soil material become stiffened when the confining stress increases, that is when the depth increases.

We mention that the experimental evaluation of the modulus values dependence in terms of confining stress σ_0 is often necessary not only for extension purpose and for depth correction of the material functions experimentally evaluated. Usually, in the resonant device a sample is tested under pressure chamber until to 0.3 – 0.35 MPa, much under many in situ confining stress conditions from the profound layers [18].

The depth correction have two stages – first, one must evaluate the confining stress effects on initial values G_0 of the modulus-function and then the effects of the confining stress on strain dependence of the material functions, that is the effect on function curvature. Both objectives can be reached using resonant column tests performed upon the soils samples from the same material but tested under different cell pressure. Thus, for each confining stress σ_0 one can obtain the material functions $G = G(\gamma) = G_0 \cdot G_n(\gamma)$ and $D = D(\gamma)$ and then one can obtain the dependences of these material functions in terms of σ_0 variable.

In the next, we exemplify this procedure by resonant column results obtained from some sand sample subjected to the usual tests but prior consolidated under different cell pressures. As can see from figs. 4.1 and 4.2 these material functions differ not only by modulus values and by their nonlinear curvature.

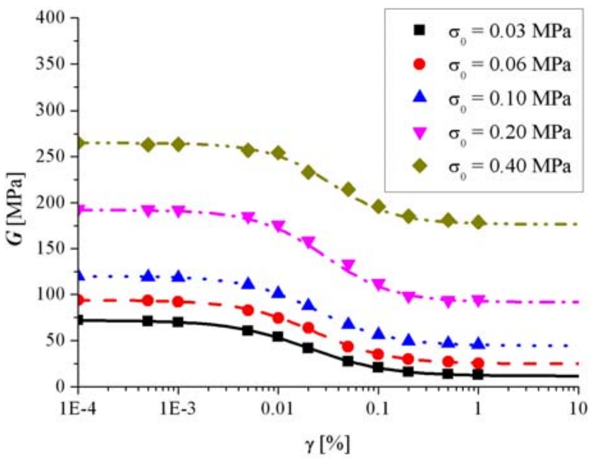

Fig. 4.1

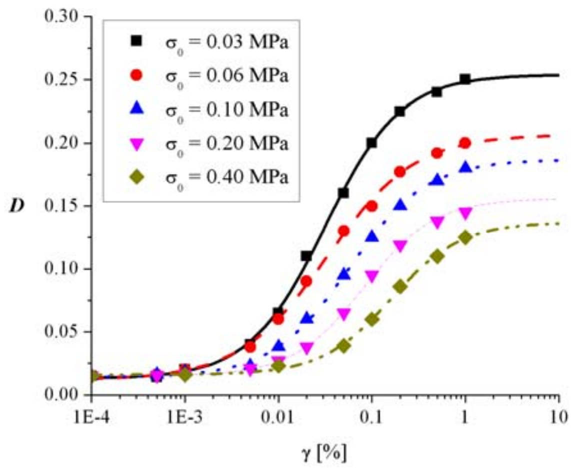

Fig. 4.2

The nonlinear analytical form, obtained by experimental data fitting, is given in eqs. (4.1) for dynamic modulus-function $G = G_0 \cdot G(\gamma)$ and in eqs. (4.2) for damping function $D = D(\gamma)$. As can see, the analytical form is the same and the different confining stress affects only the function parameters.

$$
\begin{aligned}
G &= 72 \cdot \left[0.162 + 0.838/(1+74.024\,\gamma^{1.105})\right] && \text{for } \sigma_0 = 0.03 \text{ MPa} \\
G &= 94 \cdot \left[0.263 + 0.737/(1+79.258\gamma^{1.163})\right] && \text{for } \sigma_0 = 0.06 \text{ MPa} \\
G &= 120 \cdot \left[0.371 + 0.629/(1+83.671\gamma^{1.196})\right] && \text{for } \sigma_0 = 0.10 \text{ MPa} \qquad (4.1) \\
G &= 193 \cdot \left[0.475 + 0.521/(1+89.355\gamma^{1.268})\right] && \text{for } \sigma_0 = 0.20 \text{ MPa} \\
G &= 265 \cdot \left[0.667 + 0.333/(1+96.83\gamma^{1.350})\right] && \text{for } \sigma_0 = 0.40 \text{ MPa}
\end{aligned}
$$

$$
\begin{aligned}
&D = 0.254\text{-}0.241/(1+40.977\gamma^{1.073}) \quad \text{for } \sigma_0 = 0.03 \text{ MPa}\\
&D = 0.207\text{-}0.195/(1+23.356\gamma^{0.923}) \quad \text{for } \sigma_0 = 0.06 \text{ MPa}\\
&D = 0.187\text{-}0.173/(1+19.929\gamma^{1.044}) \quad \text{for } \sigma_0 = 0.10 \text{ MPa}\\
&D = 0.156\text{-}0.141/(1+17.643\gamma^{1.148}) \quad \text{for } \sigma_0 = 0.20 \text{ MPa}\\
&D = 0.137\text{-}0.121/(1+8.47\gamma^{1.169}) \quad \text{for } \sigma_0 = 0.40 \text{ MPa}
\end{aligned}
\tag{4.2}
$$

4.1 Effects on initial modulus values G_0 and on maximum damping values $D_{\max}$

By processing the experimental results from eqs. (4.1) and (4.2) one can obtain the dependence of the initial modulus values $G_0 = G(\gamma)\big|_{\gamma=0}$ (fig. 4.3) and the maximum damping values $D_{\max} = D(\gamma)\big|_{\gamma=10\%}$ (fig. 4.4) in terms of confining stress σ_0.

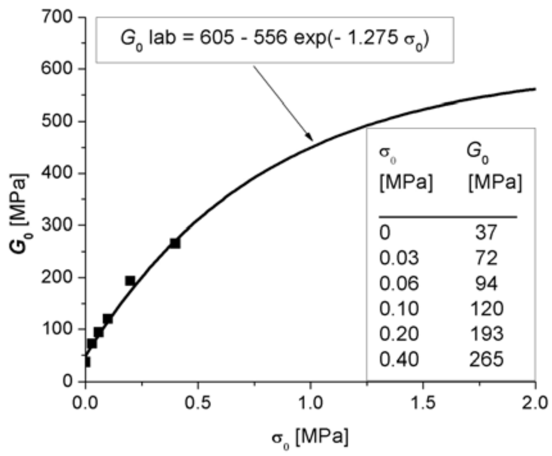

Fig. 4.3

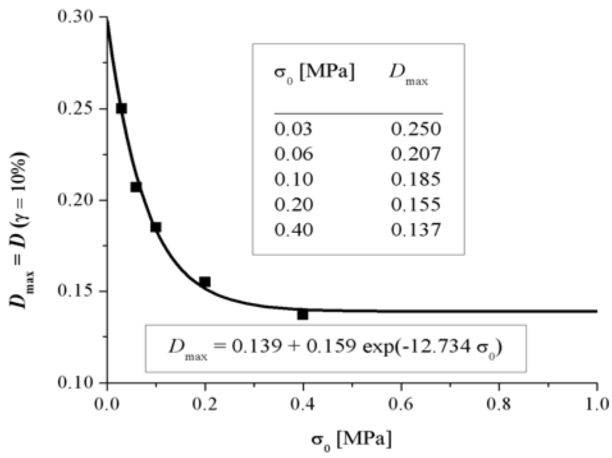

Fig. 4.4

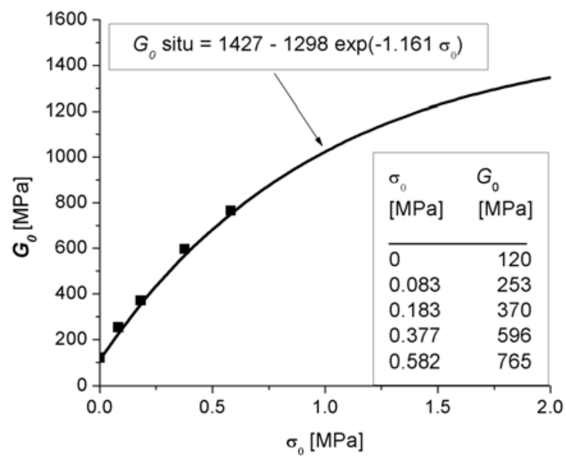

Fig. 4.5

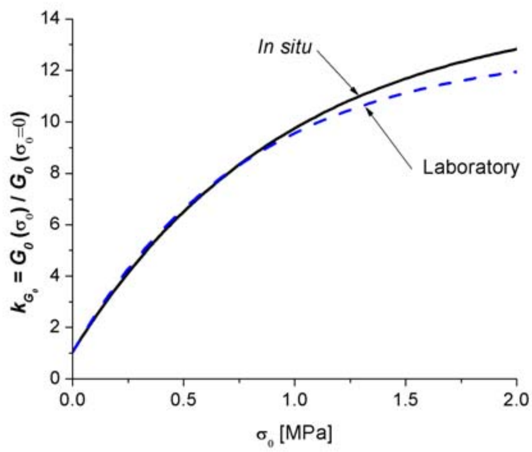

Fig. 4.6

It is well recognized that between the in situ and laboratory G_0 values estimates can arise estimable differences due to not only the sample disturbance but to different loading conditions. As an example, in figs. 4.3 and 4.5 are shown the σ_0 dependences obtained in situ and in laboratory. One can remark the differences between absolute values G_0 but by normalization as in fig. 4.6 one can observe that the shape of the curves $G_0 = G_0(\sigma_0)$ obtained in situ and in laboratory are enough close. This implies that the depth correction for initial G_0 values can be evaluated starting to G_0 *in situ* values and then applying the normalized σ_0 dependence obtained from laboratory tests.

4.2 Shape correction

As can see from eqs.(4.1) and (4.2) as well as from figs.(4.1) and (4.2) the confining stress affect not only the absolute values of the material functions $G = G(\gamma)$ and $D = D(\gamma)$ but the analytical forms of the strain dependence. The confining stress growing leads to changes of the material function curvature but one can observe a stabilization tendency that suggest the existence of a unique nonlinear form for large deepness.

The confining stress effects on nonlinearity form can be numerical evaluated with the aid of the same experimentally results obtained from resonant column test as such are given in eqs. (4.1) and (4.2).

As result from eq. (4.1), for all confining stress the modulus function normalized in terms of his initial values $G_n(\gamma) = G(\gamma)/G_0$ can be written in the same analytical form:

$$G_n(\gamma) = a_g + b_g / \left[1 + c_g \cdot \gamma^{e_g}\right] \tag{4.3}$$

and different cell pressure modify only the material parameters a_g, b_g, c_g and e_g which becomes the functions in terms of cell pressure σ_0 and then the normalized modulus function G_n becomes function in terms of strain level γ and confining pressure σ_0:

$$G_n(\gamma,\sigma_0) = a_g(\sigma_0) + b_g(\sigma_0) / \left[1 + c_g(\sigma_0) \cdot \gamma^{e_g(\sigma_0)}\right] \tag{4.4}$$

where the new σ_0 functions are:

$$\begin{aligned} a_g(\sigma_0) &= 0.768\text{-}0.655 \cdot \exp(\text{-}4.059\sigma_0) \\ b_g(\sigma_0) &= 0.238\text{+}0.651 \cdot \exp(\text{-}4.186\sigma_0) \\ c_g(\sigma_0) &= 99.66\text{-}28.353 \cdot \exp(\text{-}4.984\sigma_0) \\ e_g(\sigma_0) &= 1.398\text{-}0.317 \cdot \exp(\text{-}4.192\sigma_0) \end{aligned} \tag{4.5}$$

Also, damping functions form eq. (4.2) leads to the double variable function:

$$D(\gamma,\sigma_0) = a_d(\sigma_0) - b_d(\sigma_0) / \left[1 + c_d(\sigma_0) \cdot \gamma^{e_d(\sigma_0)}\right] \tag{4.6}$$

where:

$$\begin{aligned} a_d(\sigma_0) &= 0.139\text{+}0.164 \cdot \exp(\text{-}12.987\sigma_0) \\ b_d(\sigma_0) &= 0.123\text{+}0.167 \cdot \exp(\text{-}12.500\sigma_0) \\ c_d(\sigma_0) &= 5.040\text{+}59.165 \cdot \exp(\text{-}8.658\sigma_0) \\ e_d(\sigma_0) &= 1.164\text{-}0.317 \cdot \exp(\text{-}10.419\sigma_0) \end{aligned} \tag{4.7}$$

With the limit values of the functions (4.5) and (4.7), one can build the stabilized curves for modulus and damping functions (figs. 4.7 and 4.8). Therefore, these limit material functions remain in these forms irrespective of depth.

As an example in fig. 4.9 are given an extension by depth correction. The soil material was supported in the provider layer a 0.2 Mpa confining stress. Thus, the sample extracted from this layer was 24 hours consolidated in the resonant column device under the same 0.2 Mpa cell pressure and then tested. By fitting of experimental data was obtained the material functions $G_n = G_n(\gamma)$ and $D = D(\gamma)$ appropriate for this material and this depth:

$$G_n(\gamma) = 0.475+0.521/(1+89.355\gamma^{1.268}) \quad ; \quad D(\gamma) = 0.156\text{-}0.141/(1+17.643\gamma^{1.148}) \tag{4.8}$$

For using these material functions for the same material but situated in another layer (target layer) and in another depth must to perform a depth correction using the relationships (4.5) and (4.7) which can give the new parameters of the material functions in terms of the new confining stress σ_0. Thus, for example, one can obtain for $\sigma_0 = 0.807$ MPa:

$$G_n(\gamma) = 0.743+0.257/(1+99.137\gamma^{1.387}) \quad ; \quad D(\gamma) = 0.139\text{-}0.123/(1+14.393\gamma^{1.164}) \tag{4.9}$$

and for $\sigma_0 = 1.015$ MPa:

$$G_n(\gamma) = 0.768+0.232/(1+100\gamma^{1.500}) \quad ; \quad D(\gamma) = 0.13\text{-}0.113/(1+5.034\gamma^{1.163}) \tag{4.10}$$

As can see from fig. 4.9 the σ_0 increase lead to the stiffness growth but to the damping deterioration.

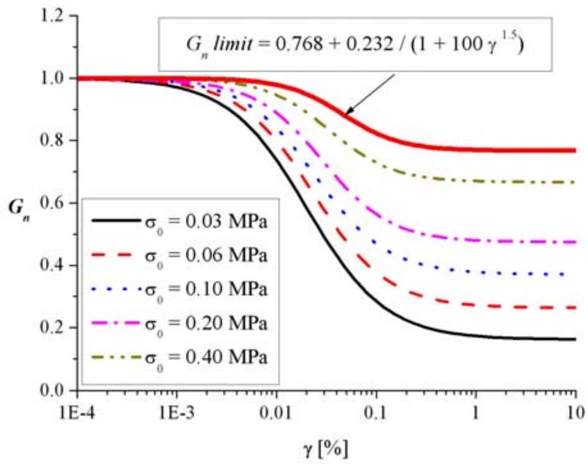

Fig. 4.7

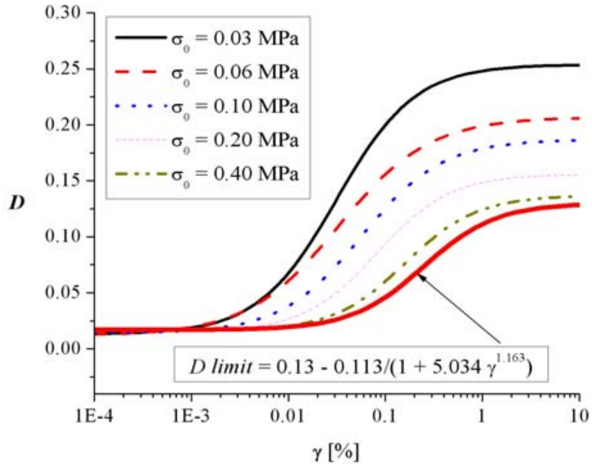

Fig. 4.8

Decreasing of the initial values G_0 and maximum values D_{max}, decreasing of the modulus and damping curvature and the stabilization tendencies of all material characteristics suggest that linear relationships (2.5) of the lithological pressure p_v and of the *in situ* confining stress (2.7) may call in question.

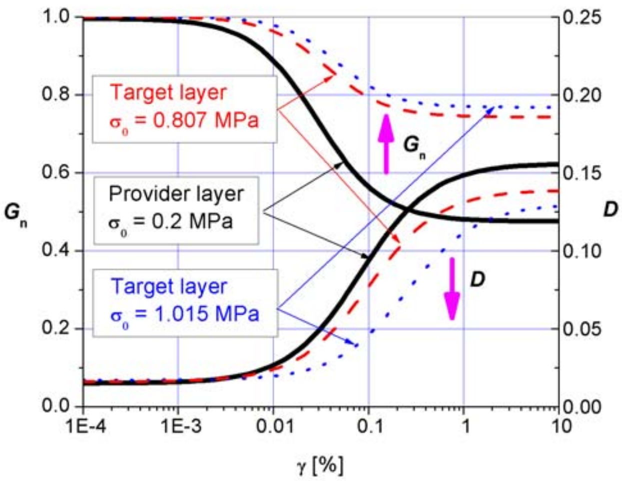

Fig. 4.9

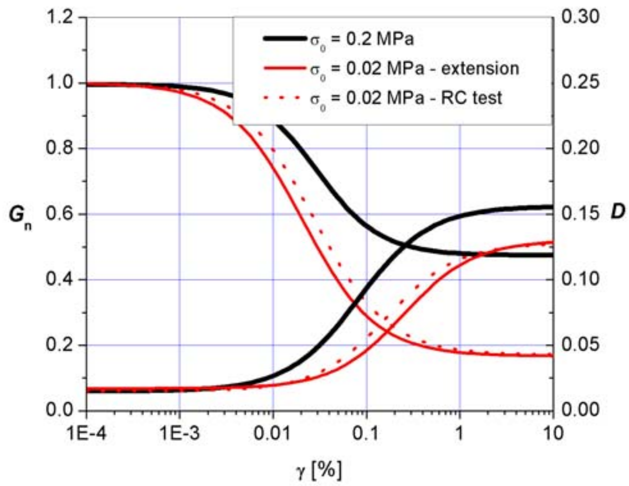

Fig. 4.10

4.3 Laboratory validation of the extesion procedure

The extending technology control can be perform by comparison between $G_n = G_n(\gamma)$ and $D = D(\gamma)$ functions obtained by extension for certain confining stress σ_0 and the same material functions but directly obtained from resonant column test under the same cell pressure σ_0.

As example, in fig. 4.10 a such control are given. Using the material functions from eq. (4.8) experimentally obtained under 0.2 MPa cell pressures as provider functions was build by extension the $G_n = G_n(\gamma)$ and $D = D(\gamma)$ functions for another confining stress $\sigma_0 = 0.02$ MPa using the empirical relationships (4.5) and (4.7). These extended functions was then compared with the same functions but directly obtained by resonant column test using a same material sample and the same cell pressure $\sigma_0 = 0.02$ MPa . As can see from fig. 4.10 the differences are not too big.

The above check was performed using a rebound confining stress σ_0, from 0.2 Mpa to 0.02 Mpa, the both values being into attainable domain of the resonant column device (cell pressure until roughly 0.4 MPa) while habitually the extended technology must cover the confining stresses over resonant column possibilities.

Finally, we mention that because the extended functions are obtained by fitting of the resonant column data for a certain σ_0 values and these function will be used outside the experimental data domain the extension procedure impose an uppermost attention and permanently correlation with *in situ* data.

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