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ABSTRACT

A modelling technique of the cross-sections of underground structures based on the combination of modal shapes by response spectra is developed and calibrated according to the vertically propagating shear-wave model. Using the developed technique, the influence of several parameters in the flexibility index (ground-structure relative stiffness) were studied. To point out a few practical implications and simplifications introduced in the model, essentially related to the material behaviour adopted, four cases were studied in detail. To cover the lack of compatibility between the damping of the response spectrum, the ground stiffness and the strain level, more analyses with compatible properties were conducted.

1 - INTRODUCTION

Nowadays, most underground structures are designed and built without regard to seismic effects, even in highly seismic regions.

Since the static design of underground structures still is deeply related to empirical and simplified methods, based on accumulated experience, it is difficult to develop a consistent seismic and static design methodology.

An expedite technique based on the finite element method (F.E.M.) is presented herein to compute seismic forces induced to shallow underground structures, using response spectra analysis (Gomes, 1999). Although this numerical technique is usually adopted for the seismic design of above-ground structures, it can be applied to shallow underground structures. The technique is very attractive from the computational point of view, due to its consistency with the static design and also because it gives the envelops of the seismic forces induced (simple results analysis).

The main goal is to identify under which critical condition the seismic loads are significant, when compared with the static loads, justifying the need of more accurate and detailed analyses.

In spite of the non-linear ground behaviour, the analyses in the linear elastic domain allows the clear identification of most relevant structural parameters, producing valuable data for designers concerning to key parameters and their sensitivity for design practice. With better understanding of the structural performance, designers can (i) realise which characteristics should be explored with more detail, (ii) assess the need of monitoring the performance of the structure, (iii) redefine partially or totally the project to better conform performance and failure criteria.

Therefore, a significant amount of freedom to conceive structures that match the seismic criteria is given to the designer engineer, since, to keep the safety control simple, engineering judgement is essential in the practice of geotechnical earthquake engineering.

This work reports to a circular cavity response of a subway or road tunnel with radius R, a support thickness t and elastic properties E_c *and* ν_c, surrounded by ground characterised by E and ν.

The behaviour of a tunnel support is a typical ground-structure interaction problem. The dimensionless parameter F, flexibility index, which is a measure of the relative stiffness of the ground-support system under anti-symmetric loading condition, reflects the flexural stiffness of the system (Einstein and Schwartz, 1979):

$$F = \frac{ER^3\left(1-\nu_c^2\right)}{E_c I_c\left(1-\nu^2\right)} \tag{1}$$

in which I_c = the moment of inertia of the tunnel support per unit length of tunnel.

2- METHODOLOGY

Before the occurrence of a seismic event, the support under influence of the in-situ ground stresses contracts and changes its initial shape. During the seismic event, the vibratory ground motion induces support deformations and, consequently, additional effects. Therefore, the support should be designed to withstand both seismic and static loads. It should be mentioned that, exception made to liquefaction or soil deposit compaction phenomenum due to seismic shaking, the geostatic stress field is assumed to be maintained unaffected by seismic waves passage. In addition, since the linear elastic behaviour is assumed, the analysis can be divided in two independent steps: (i) geostatic elastic solution

(Hartmann, 1970), (ii) seismic stress-strain analysis (Gomes, 1999).

3 - NUMERICAL MODEL DEFINITION

Assuming that support seismic deformation is mainly due to the horizontal deformation imposed by the ground motion, ground response should be accurately characterised without including site effects.

As it was previously referred, a spectral response analysis is conduced throughout the combination of the modal shapes, adopting a 5% damping ratio. Therefore, to assure the solution validity, the mode shapes and associated frequencies were controlled.

To assess the numerical solution validity, the vertically propagating shear-wave model was adopted as reference.

The F.E. mesh is composed by a central region (Fig. 1), to simulate the ground-support interaction, and two lateral regions, simulating the free-field ground motion.

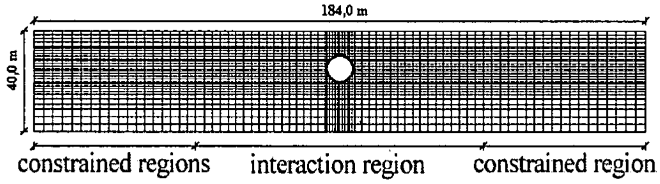

Fig. 1 - F.E. mesh with a 10 m diameter cavity

The horizontal displacement is constrained in the lateral regions, in order to adjust their motion to the free-field ground motion. In other words, only horizontal degrees of freedom are considered in each horizontal node alignment. The benefits from this option are related with the minimisation of computational effects to extract modes compatible with the reference 1D model. The participation factors of the compatible modes, shown in Fig. 2, were studied, and it was concluded that 1^{st} and 2^{nd} mode contribution prevail over the upper modes contribution, since the error is less than 0.1% when the analysis considers 6 compatible modes instead of only two firsts compatible modes.

Therefore, the following analysis include only the 1^{st} and the 2^{nd} modes.

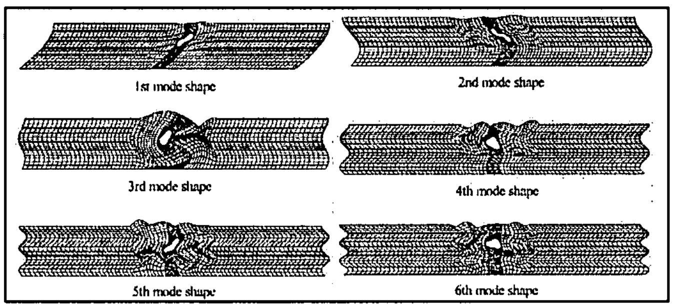

Fig. 2 - First 6 compatible modes shape

The visual analysis of the mode shapes agrees with the prior remark, since only the 1^{st} and 2^{nd} modes shape present credible configurations. The upper modes present local deformations in the interaction region, disagreeing with the lateral regions motion.

4 - SENSITIVITY ANALYSIS

A circular cavity representative of a transportation tunnel was studied. It has a diameter D=10.0m, the centre is located at 15.0m beneath ground surface, and the support properties are E_c=29GPa; v_c=0.25.

The Poisson ratio has an important role since the shear deformation is dominant, four distinct cases were analysed: v = 0.25; 0.33; 0.40; e 0.50. A wide range of the ground Young modulus, E, was studied, varying from 1 MPa, representing soft clays, to 10 000 MPa, representing hard rock.

The geostatic stress computation considers a weight density γ =19 kN/m^3, a lateral earth pressure coefficient K_o = 0.5 and a 30% decompression level of the ground prior to the placement of the support.

In order to simplify the results analysis, a constant response spectra was adopted with a spectral acceleration = 0.5g.

In those studies, dimensionless action-effects, m and n, express the relative amount of the additional effects induced by seismic ground deformation in the cavity support:

$$m = \frac{M_{total}^{\max}}{M_{geostatic}^{\max}} \quad ; \quad n = \frac{N_{total}^{\max}}{N_{geostatic}^{\max}} \tag{2}$$

where M = bending moment and N = axial force.

For the same t/R ratio, the dimensionless effects are fairly independent of both cavity diameter, D, and support Young modulus, E, although this conclusion is drawn because the cavity depth and layer thickness were the same in all analyses performed, in other words, the relative displacement between the cavity crown and floor was keep approximately constant.

Poisson ratio influence in the dimensionless effects is shown in Fig. 3 and 4. As expected, the action-effects increase for higher v, although for v = 0.25; 0.33 e 0.40 the deviation is less than 15% for m curves and practically coincident for n curves, while a notable difference is registered for v = 0.5.

It should be also noticed that for F > 500 m-curves significantly decrease and the n-curves slightly increase.

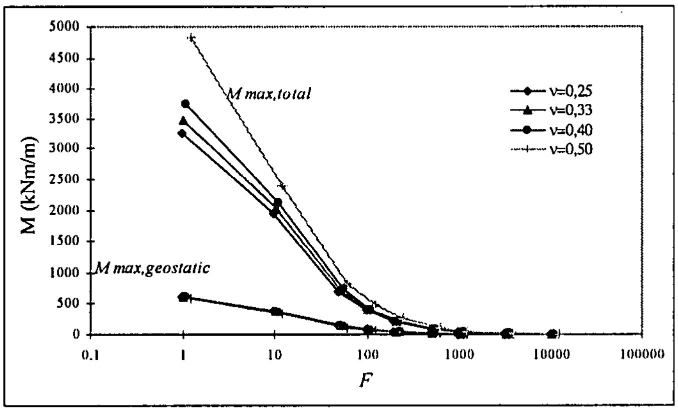

Fig. 3 - Poisson ratio influence on bending moment (t/R = 0.075; E_b = 29GPa)

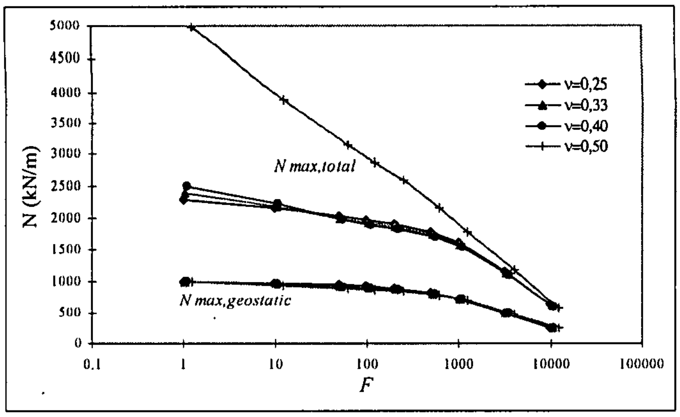

Fig. 4 - Poisson ratio influence on axial force (t/R = 0.075; E_b = 29GPa)

The t/R ratio influence on dimensionless effects is shown in Fig. 5; as expected, the m-values grow for higher t/R ratio, while the n-curves are practically coincident.

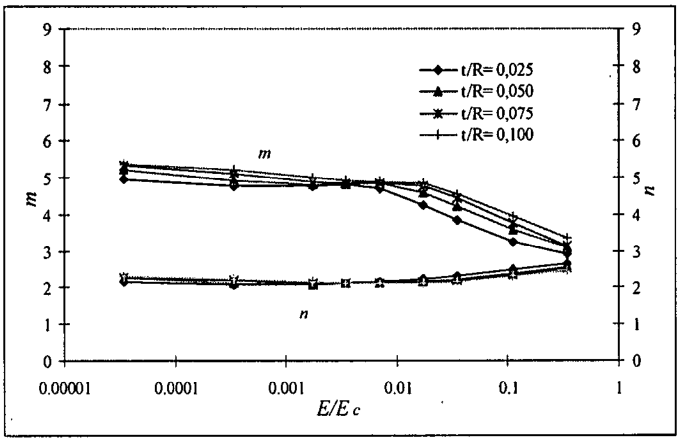

Fig. 5 - t/R ratio influence on additional seismic effects (E_c = 29GPa; ν = 0.25)

It should be remembered that the previous analyses considered the same geostatic stress field, represented by lateral earth pressure coefficient K_o=0.5. However, a wide range of variability of this parameter is observed in geotechnical material, essentially in soil deposits where K_o strongly depends both on the intrinsic material properties and on the stress path. K_o values can vary from 0.5, in loose sand deposits, to 4.0, in overconsolidated clay deposits.
According to the previous assumptions, K_o value only affects the geostatic stress analysis. Special attention should be given to the significant dependency of m- and n-value related to the geostatic effects. Fig. 6 presents, as an example, maximum geostatic bending moment dependency over K_o.

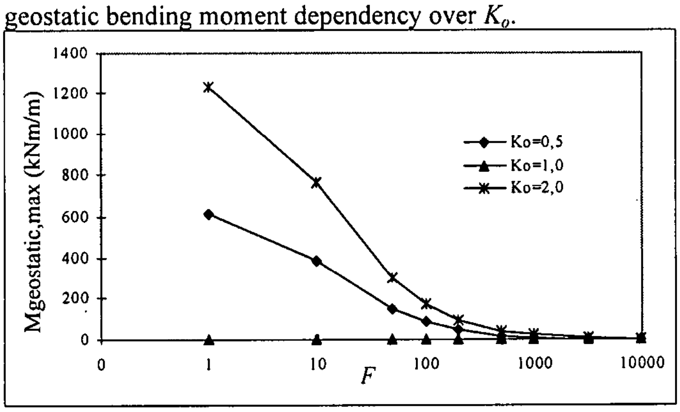

Fig. 6 - K_o influence on maximum geostatic bending moment

The previous figure clearly shows the disparity among the results computed for K_o = 0.5; 1.0; 2.0. For K_o = 1.0 the cavity is roughly submitted to an hydrostatic stress state, and consequently no meaningful bending moments are developed. For K_o=0.5; 2.0 the distortional load component is important, and a high bending moment level is achieved.

5 - SEISMIC ACTION-EFFECTS

In the following analysis, the EC8 (1994) response spectra, defined with the boxed values and with a 0.20g design ground acceleration, was considered. The cavity and support characteristics were the same as in the previous analysis.

It should be pointed out that is no long valid to express the seismic effects curves by F, because spectral acceleration depends on the system frequency that, in turn, is directly associated to the ground elastic properties. In addition, it should be remembered that F correlates the ground elastic properties with the ones from the support. So two cases with the same F value can be defined (maintain E/E_c ratio and change the E and E_c values) but with different seismic effects, because in its computation distinct spectral accelerations were used.
In presenting the seismic effects as function of E, as shown in the subsequent figures, it permits the assessment, in coarse terms, about the type of ground that transmits higher seismic effects to the support.

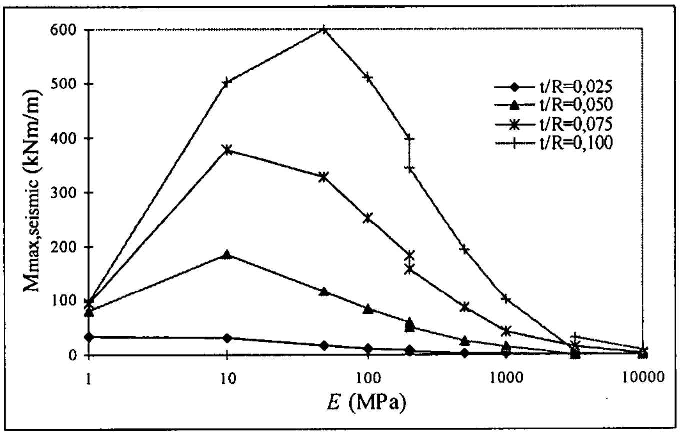

Fig. 7 - Support maximum seismic bending moment (D=10.0m)

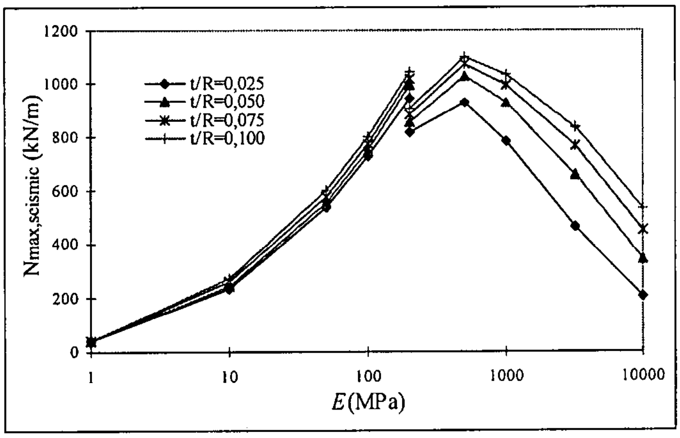

Fig. 8 - Support maximum seismic axial force (D=10.0m)

To clearly understand the results, it should be taken into account the EC8 elastic response spectrum and the seismic effects curves shapes computed for a flat response spectra. Since a minor spectral acceleration is induced to soft/loose soils, because of its high fundamental period values, a modest level of seismic effects is registered. Also modest seismic effects are computed for hard rock ground, whereas low deformation levels are obtained even for strong motions. Conversely, significant seismic effects are computed for intermediate cases, which are subjected to severe spectral accelerations.

Particularly, it should be noticed that when $E > 3200$MPa, the bending moment values tend to zero, agreeing with the observation drawn by Einstein and Schwartz (1979) stating that for $E/E_b > 0.1$ the support can be considered flexible.

Moreover, for t/R=0.025 the maximum seismic bending moment is fairly independent from E, thus the support can be considered flexible from a seismic point of view. As the support thickness increases, higher action-effects develops in the support.

6 - REPRESENTATIVE CASES

Four representative cases defined with a coherent group of characteristics (see Table 1), ranging from a soft soil to an hard rock, were investigated with the purpose of highlight over some of the simplifications introduced in the prior analyses.

Table 1: Characteristics of 4 representative case studies

Designation		E (MPa)	ν	ϕ'	C' (kPa)	K_o	t/R	OCR	Subsoil class
Soil	Soft	10	0.45	16°	0	0.70	0.100	1	C
	Hard	100	0.30	30°	100	1.50	0.075	9	C
Rock	Soft	1000	0.20	33°	250	0.25	0.050	-	B
	Hard	10000	0.20	50°	600	0.25	0.050	-	A

Fig. 9 illustrate typical action-effects variation along the support and summarises the maximum total (seismic + geostatic) action-effects computed for each case.

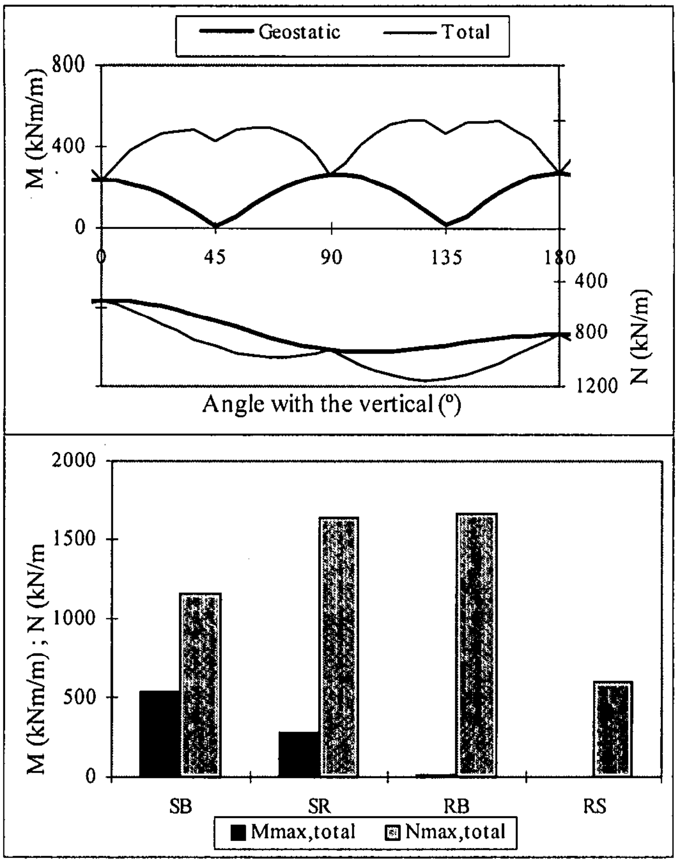

Fig. 9 - Typical action-effects variation along the support in the soft/loose soil case and total maximum actions-effects computed for each case (0° - crown; 90° - sidewall; 180° - floor)

It is known that maximum geostatic effects occurs in the middle part of the crown and floor and at sidewall mid-height. However, adding the seismic effects, the maximum values are shifted to approximately 45° in relation to vertical (see Fig. 9).

Bending moments are meaningful in less competent ground, while higher axial force values arises in the Hard Soil and Soft Rock cases. Just in Soft Rock case axial force seems to be excessively high in relation to the support thickness considered. The remaining cases were considered to fall in the acceptable range (Gomes, 1999).

Regarding to ground deformation level, by adopting Mohr-Coulomb criteria and analysing the deformation levels, only for Hard Rock case the surrounding ground remain elastic. However, general trends remain valid.

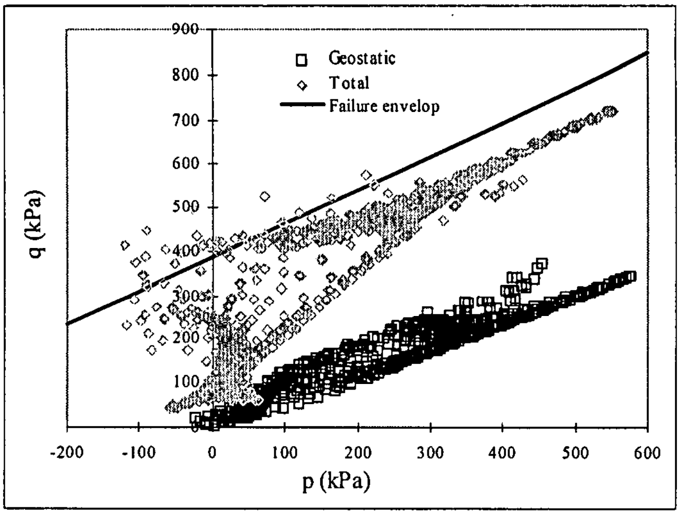

Fig. 10 - Stress state installed in the surrounding ground - Hard Rock

where p = mean stress and q = deviatoric stress.

7 - DAMPING AND STIFFNESS COMPATIBIZATION

As it is widely known, the ground stiffness decreases and damping increases for higher deformations. The previous analysis main focus was the ground-support interaction, since no compatibility was established between the strain level and the ground stiffness and damping. This was the motive to conduce two sets of analyses with compatible ground stiffness and damping for several strain level (see Table 2), namely 10^{-6}, 10^{-5}, 10^{-4}, and 10^{-3}, adopted from Vucetic e Dobry (1991) and Schnabel *et al.* (1972).

Table 2. Ground properties compatible with the strain level

E (MPa)	IP	Strain level	10^{-6}	10^{-5}	10^{-4}	10^{-3}
100	15	G/G_0	1.00	1.00	0.83	0.39
		ξ (%)	3.0	3.0	5.0	12.0
3000	-	G/G_0	1.00	0.99	0.90	0.73
		ξ (%)	0.4	0.8	1.5	3.0

With this procedure, a coarse estimation of the effects developed in the support by interpolating results can be achieved, quantifying the influence of the stiffness reduction (inducing higher effects) counterbalance by damping growth (motion attenuation, followed by reduction of effects) for increasing shear strain. The range of applicability is not so wide as desired, essentially because the response spectra are not calibrated for damping ratios above 12%, according to the new European Standard codes (EC8, 1994). Moreover, for shear strains over 1%, the linear equivalent procedure clearly looses its accuracy, only full plastic behaviour is appropriated for modelling purposes.
The following figures present the main results extracted from two computations: E = 100 MPa; 3000 MPa.

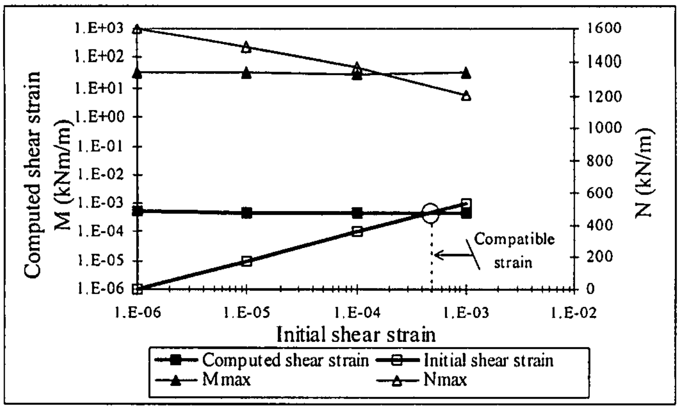

Fig. 11. Strain level and maximum seismic effects developed for several compatible ground stiffness and damping (E= 3000 MPa)

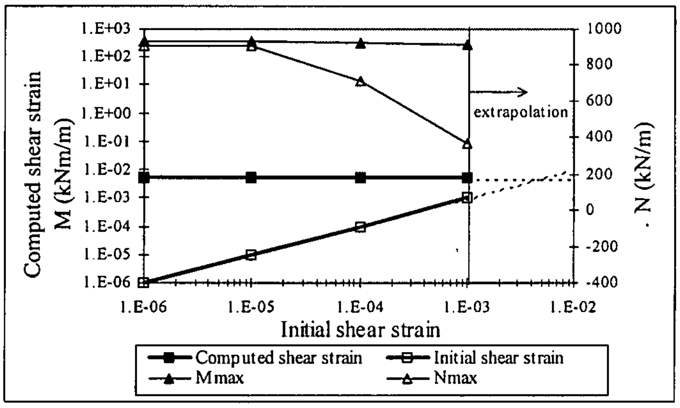

Fig. 12. Strain level and maximum seismic effects developed for several compatible ground stiffness and damping (E= 100 MPa)

First comment is addressed to the limitation of this procedure, since for typical values of soils elastic properties, around E < 250 MPa, the compatibility between the initial strain level and the strain level computed are over the applicability range, allied to the fact that no response spectra are available for large damping ratios (>12%).
The prior figures show, on one hand, that M_{max} is practically independent of the shear strain. On other hand, the maximum seismic axial force trend to decrease for higher shear strains, permitting to conclude that N_{max} is well correlated with the ground stiffness. Therefore, when the stiffness reduction is not taken into account in the analysis, N can be overestimated.

8 - CONCLUSIONS

The analysis clearly demonstrate that the first two mode shapes can accurately describe the ground-structure seismic response.
The additional seismic effects strongly increase for Poisson ratios values near 0.5. As expected, the additional seismic effects grow for higher support thickness. Special attention should be given to the significant dependency of additional seismic effects over the related geostatic effects, reducing the relative importance of the seismic load.
A general trend observed, shows the higher aptitude for structures surrounded by ground with *E* between 10 and 1000

MPa to be subjected with higher seismic effects. For seismic loads, supports with $t/R = 0.25$ can be considered flexible and no significant bending moments are developed.

From the representative cases studied, it can be noticed that no significant total bending moments occur in structures surrounded by rock. Also an important aspect to take into account during the detailing procedure is related to the fact that total and geostatic maximum effects do not occur in the same sections.

Finally, the compatibility between strain dependent properties are specially relevant to estimate seismic axial force.

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