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NONLINEAR RESPONSE OF HORIZONTAL SOIL DEPOSITS SUBJECTED TO THREE COMPONENTS OF SEISMIC MOTION AT THE SOIL-BASEROCK INTERFACE

P.E. Capelli[1] and J.D. Riera[2]

[1]Empresa Nuclear Argentina de Centrales Eléctricas S.A., Buenos Aires, Argentina
[2]CPGEC, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brasil

1. INTRODUCTION

Significant progress has been recently achieved in the characterization of the rupture mechanisms and energy liberation at the fault, as well as in the subsequent determination of seismic acceleration at the base rock. Within this context, proposals have been advanced by one of the authors to evaluate the response spectrum on rock surface, taking into consideration basic geometric properties of the seismic source [Riera et al, 1986]. It was also shown that the consideration of source parameters allows the generation, by simulation, of samples of the three components of the seismic motion [Bruna & Riera, 1988].

On the other hand, the influence of soil properties on the seismic excitation at or near the surface of flexible soil deposits is today universally acknowledged. The effect has paramount importance in the analysis of seismic resistance structures and constitutes an essential aspect of risk studies, as well as in microregionalization. In spite of this unquestionable relevance, most available studies and procedures for practical analysis are nevertheless based on very crude descriptions of the soil behavior under cyclic loading, such as unidimensional relationships between shear stress and strain, used in conjunction with similar unidimensional excitation at the soil-rock interface.

In this paper, the assumption concerning the unidimensional character of the base excitation is relaxed. For such purpose, a modified version of the constitutive criterion proposed by Konder [1963] and further developed by Duncan [1970,1981] is adopted. The formulation, which presents excellent correlation with experimental results for a wide class of soils and loadings, adequately accounting for the effects of nonlinearities, stress path and volumetric variations, is employed for determining, by means of numerical integration in the time domain, the response of layered soil deposits to the three components of the seismic base motion.

After qualifying the method by comparison of predictions with results available in the literature, the approach is used to evaluate the error that results from uncoupling the problem, i.e. from a unidimensional analysis.

2. CONSTITUTIVE EQUATIONS FOR THE SOIL

In addition to providing an adequate description of the nonlinear material behavior of the soil under cyclic loading, any model suitable for practical applications in Seismic Engineering should also allow the identification of all needed parameters by means of standard laboratory tests. This is one of the basic features of the proposal, due to Konder [1963], of approximating the stress-strain relations obtained in triaxial tests by means of hyperbolic curves. The model was subjected to an extensive experimental evaluation, after which Duncan [1981] introduced the following modified equations :

$$(\sigma_1 - \sigma_3) = \varepsilon / [1 / E_0 + \varepsilon R_f(\sigma_1 - \sigma_3)_f] \qquad [2.1]$$

in which σ_1 and σ_3 denote the largest and smallest principal stress, respectively, while R_f and $(\sigma_1 - \sigma_3)_f$ are material parameters. Moreover, the moduli for initial loading, unloading/reloading and virgin loading are given by :

$$E_0 = KP_a(\sigma_3/P_a)^n \qquad [2.2]$$

$$E_{ur} = K_{ur}P_a(\sigma_3/P_a)^n \qquad [2.3]$$

$$E_t = \left[1 - \frac{R_f(1-\sin\phi)(\sigma_1-\sigma_3)}{2C\cos\phi + 2\sigma_3\sin\phi}\right]^2 KP_a\left(\frac{\sigma_3}{P_a}\right)^n \qquad [2.4]$$

The modulus of volumetric deformation is defined by :

$$B = K_bP_a(\sigma_3/P_a)^m \qquad [2.5]$$

Finally, rupture is characterized by the Mohr-Coulomb criterion :

$$(\sigma_1 - \sigma_3)_f = \frac{2C\cos\phi + 2\sigma_3\sin\phi}{1-\sin\phi} \qquad [2.6]$$

Further details concerning the formulation, as well as procedures to determine the required parameters, may be found, for instance, in Duncan [1981] or Capelli [1990].

3. PROBLEM DEFINITION AND NUMERICAL SOLUTION

As discussed in Section 1 and schematically represented in Fig. 3.1, the system to be considered consists of an arbitrary number of horizontal, homogeneous soil layers, which lie on the top of a horizontal base rock surface.

With reference to a cartesian coordinate system x, y, z, with its origin at the soil-rock interface and the z-axis oriented in the vertical (upward positive) direction, the motion is specified at z = 0 by the acceleration time histories $\ddot{u}$, $\ddot{v}$ and $\ddot{w}$, where dots indicate time derivates and u, v, w are the displacements in the coordinate directions. The assumption of a horizontal wave front in the underlying rock implies that the resulting motion will not depend on the x, y coordinates.

The first of the three equations of motion for a linearly elastic, isotropic soil layer is :

$$(\lambda + G)\frac{\partial e}{\partial x} + G\nabla^2 u - \rho\frac{\partial^2 u}{\partial t^2} = 0 \qquad [3.1]$$

in which λ and G are Lamé's constants, e the volumetric strain and ρ the specific mass of the soil. Similar equations define the motion in the y and z directions. In view of the hypotheses concerning the geometry of the problem, in linear systems the three equations of motion would be uncoupled. However, when material nonlinearity is considered, coupling occurs through the equivalent elastic constants. Thus, the solution of coupled equations is obtained in an incremental form, in terms of the displacements u(t), v(t) and w(t) by numerical integration in the time domain using the constant acceleration scheme (Newmark's method). A small amount of viscous damping -about 1% of critical damping in the 1st. mode- was added to the system to eliminate spurious high frequency components. The procedure, which is known to be unconditionally stable for linear systems, was implemented in Program TDS and qualified by comparison with linear and nonlinear solutions available in the literature [Idriss & Seed, 1967, 1970; Streeter et al, 1974; Brito, 1979].

4. APPLICATIONS

Since complete experimental data involving the three acceleration components, both at the soil-rock interface and on the surface of soil deposits with known characteristics, were not available to the authors, the ensuing example was based on records obtained during the Friuli sequence of 1976 [Scherer & Schuëller, 1985], registered at San Rocco (rock outcrop) and Forgaria (soil surface) for the same seismic event. Since the two stations are close to each other in comparison with the epicentral distance, the corrected motion measured at San Rocco could be used as input for the prediction of the Forgaria spectra. In view of the large uncertainties concerning various factors, including soil properties, the results can be considered excellent. Fig. 4.1 shows, for example, the predicted and measured response spectra in the EW direction at Forgaria for the 11/09/76 earthquake.

Finally, results from uni- and three-dimensional analyses for the two typical soil profiles indicated in Table 4.1, subjected to the Somplago amplified input (registered at the date above mentioned) at the base rock, were compared. It is verified that negligible differences occur for small amplitudes of the base motion. Above a threshold acceleration value, however, the 3-D solution presents significant departures from the 1-D analysis. The computed acceleration spectra at the surface in both the horizontal and the vertical directions are shown in the Figs. 4.2 through 4.4. It may be seen that, in the soft soil case, base acceleration amplitudes of around 0.1 g can produce surface spectra that would be underestimated in more than 50% by a unidimensional solution. For the rigid soil and the same excitation amplitude, the mean difference in the horizontal spectra is about 13%.

5. CONCLUSIONS

The Konder-Duncan hyperbolic expressions are used to describe the three-dimensional cyclic soil behavior. On that basis, it is shown that common unidimensional solutions may be expected to yield significant errors for large amplitudes. This study allows for perceiving coupling influence for horizontal acceleration amplitudes in the soil-rock interface above 0.10 g. Such limit increases as strata rigidity increases.

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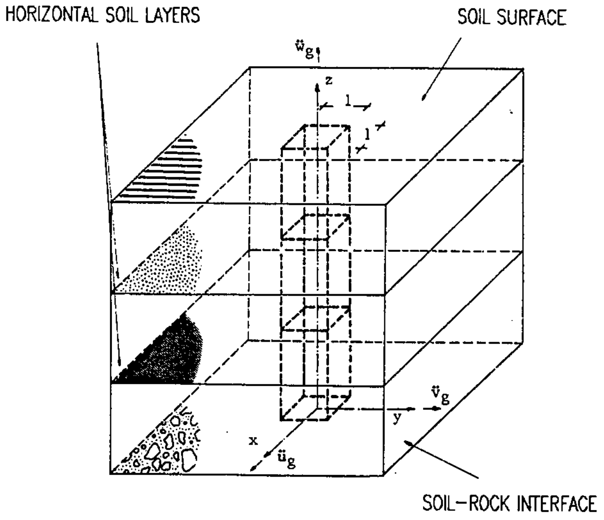

Fig. 3.1 PROBLEM IDEALIZATION

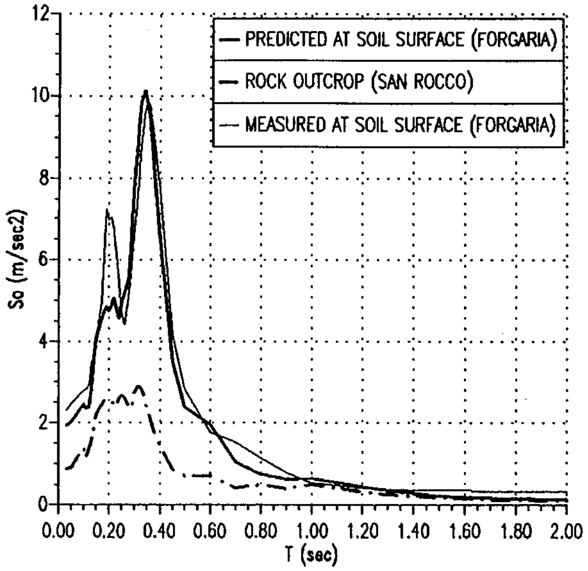

Fig. 4.1 PREDICTED AND MEASURED RESPONSE SPECTRUM IN THE EW DIRECTION AT FORGARIA (11/09/76)

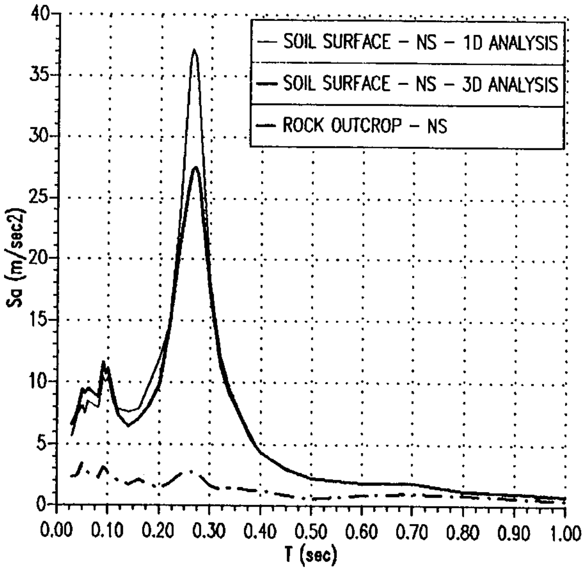

Fig 4.2 COMPUTED ACCELERATIONS SPECTRA FROM UNI- AND THREE-DIMENSIONAL ANALYSES - SOFT SOIL - NS DIRECTION

Table 4.1 : Tipical Soil Profiles

Soil	Depth (m)	1/s (m/seg)	Vp (m/seg)
soft	21	300	500
hard	15	700	950

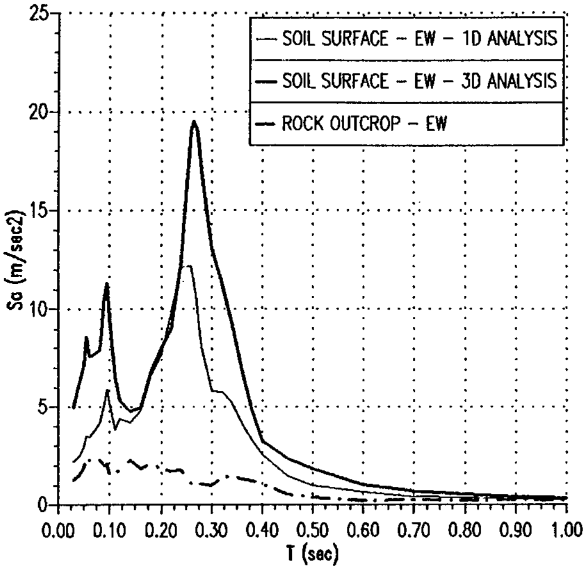

Fig 4.3 COMPUTED ACCELERATIONS SPECTRA FROM UNI- AND THREE-DIMENSIONAL ANALYSES – SOFT SOIL – EW DIRECTION

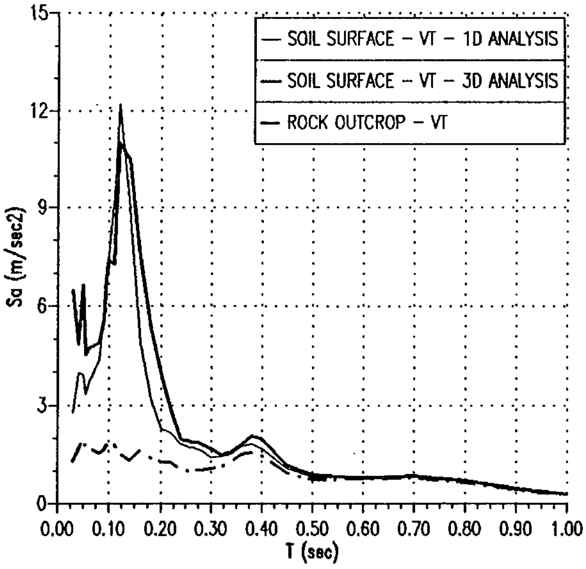

Fig 4.4 COMPUTED ACCELERATIONS SPECTRA FROM UNI- AND THREE-DIMENSIONAL ANALYSES – SOFT SOIL – VT DIRECTION