Surface effects of seismic waves at mountain sites

SURFACE EFFECTS ON SEISMIC WAVES AT MOUNTAIN SITES

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Summary

An impulse motion, propagating orthogonally towards a free surface, within a continuum homogeneous material, doubles its amplitude in the proximity of the surface. An earthquake excitation propagating upwards, vertically, in the same continuum, is affected by an amplification near the surface, up to the same order, if the surface is horizontal.

In presence of valleys or mountains, a variety of reflections and refractions occurs, and in general the intensity of the shaking at the surface is further more amplified.

To evidence such geometric effects from those due to material discontinuities, an investigation is carried out on two sites of Friuli - Northern Italy earthquake of '76'. Comparison with the vertical profile of maximum acceleration in monodimensional propagation put in evidence the amplification likely to be ascribed to the geometric effect.

The relevancy of a deep embedment as a measure to reduce the seismic shaking is suggested.

Resumé

Une impulsion qui se propage orthogonalement vers une superficie libre, à l' intérieur d' un continu homogène, redouble son amplitude dans les environs de la superficie.

Un tremblement de terre qui se propage verticalement en haut, dans le même continu, ressent une amplification du même ordre dans le environs de la superficie si celle-ci est horizontale.

En présence de vallées ou montagnes, l' intensité de la secouse à la superficie est ultérieurement amplifiée parce qu' il y a un certain nombre de réflexions et de réfractions des ondes incidentes sur la superficie.

Pour mettre en évidence ces effets géometriques entre ceux dûs à la discontinuité du Friuli, la région la plus frappée par le tremblement de terre du Nord - Italie du 1976.

Des comparaisons avec le profil des accélérations maximales pour le cas monodimensional mettent en évidence l' amplification due aux effets géometriques.

En outre, on suggère l' importance de profondes fondations comme mesure pour réduire les effets du sisme.

1. INTRODUCTION

In wave propagation theory a surface effect exists, according to which, in the general case , an impulse motion, propagating orthogonally towards a free surface, doubles its amplitude in the proximity of the surface itself. Here, in fact a complete reflection occurs, and the impinging and the reflected waves sum up. Such "surface effect" can be felt up to some depth, near the surface, depending on the shape and the duration of the impulse.

As to a seismic harmonic wave vertically propagating in a horizontally stratified soil, the amplification may be greater than two, and develops in the upper L/4 stratum, where L is the wavelength of the wave type under examination. For instance, in a sand with a void index 0.8 , a confining pressure of 0.5 Kg/cm^2, and under a shear wave motion of predominant frequency 2 cps, this amplification applies in the last 20 m. In a homogeneous rock with shear wave velocity 2000 m/sec, with a predominant frequency 5cps, this applies in the upper 100 m.

Effects of this nature are further complicated, and even hidden by the soil's peculiar stratigraphy and by the presence of inclined surfaces, hills or valleys.[8,10,15,19] In the latter case, assuming again vertically propagating seismic waves, reflection and refraction occur along the sides of the surface discontinuity, and the resulting combination gives rise, in general, to an amplification relative to the bedrock motion and even to the free field motion at the nearby flat country. This was in theory observed for valleys by [3,16,22]. But as to authors' knowledge, no precise experimental evidence has been collected and analysed so far, in particular for hilly sites, where the amplification is likely to be greater than for valleys.

During the northern Italy earthquake of '76', a mountain region - Friuli- was affected, and the damage distribution could confirm the above rule. See for instance the large damage concentration at Buia and Gemona, two hilly sites, relative to the less intense shaking in the nearby plane. But this could also be ascribed to the different soil characteristics under the two sites and the plane. [4, 21]

The same problem of filtering the material effects from the geometric effects arose for a proper understanding of the earthquake records, after that a network of strong motion recorders was installed in the region.
In this research, by applying a suitable input motion at the base of the hill through a numerical model - see fig. 1 - , the authors tried to derive a map of amplification factors for all the surface points of the hill - see figs. 2,3,4 . The vertical profile of acceleration at a single point, compared with the profile obtained for horizontally layered soils of the same vertical stratigraphy - i.e. obtained in a monodimensional propagation problem - has allowed for separating geometric from material effects.

The main conclusions so far collected are as follows :

1. Along the hill surface the maximum ground acceleration may be considerably greater than ground acceleration in a monodimensional propagation problem. It is, besides, always greater than the acceleration at the surface of the nearby plane.
2. The acceleration map seems subject to great dispersion, while the velocity map may be more appropriate for zoning purposes.

3. As to the input motion for construction design purposes, the need of a proper choice of foundation level is exasperated in regard to flat surface constructions. For instance, if L is the wavelength of top soil deposit, an embedment of L/10 may reduce in several cases the earthquake effects by a factor of two.

2. REVIEW OF THE NUMERICAL MODELS FOR SOIL AMPLIFICATION ANALYSIS IN BI - TRI DIMENSIONAL PROBLEMS

2.1 Numerical Models

A complete analysis of a soil deposit subjected to earthquake effects should take into account ground motions which vary from point to point and propagate in any direction in the soil deposit.[12] In the great majority of cases the information about the excitation is provided in the form of accelerograms recorded at one or several locations and this is not sufficient to define completely the characteristics of the incoming seismic waves. For instance, it is not possible to determine the propagation direction of the waves. In practice, analytical techniques are confined to the hypothesis of vertical propagation of shear waves from a given horizontal layer at some depth in the soil deposit.

The past years have seen a considerable development of finite element techniques to solve dynamic problems both for soil deposit and for soil-structure interaction analysis, taking advantage of the flexibility and ease with which the finite element method can be adapted to different geometries, which are usually met in soil mechanic problems [13]. But, the use of finite elements to simulate an infinite space calls for suitable boundary conditions to avoid spurious reflections from the model contour [7]. Three techniques, of increasing sophistication, have been proposed up to now - see Fig. 5.

Models shown in figure 5a and 5b have both rigid base and respectively rigid or free lateral boundaries. With these models the motion is applied simultaneously on the entire rigid boundary but the absorption of the waves impinging on the boundary is not allowed. To have satisfactory results, avoiding spurious reflections, it is necessary to resort to very large meshes that often reach the limits of computer storage availability and execution time. It is possible to overcome in part this drawback with models as in figure 5c, having lateral transmitting boundaries and rigid bedrock, [14].

Some standard tests have been developed by the writers, considering a horizontally stratified soils, i.e., a rigorously monodimensional wave propagation problem. The theoretical solution of the problem was also available [20]. Figure 6 shows the comparison between the latter solution and that of a model as in figure 5c.

The agreement can be considered satisfactory; in fact even the lateral acceleration profiles are in good agreement with the theoretical solution, confirming the correct absorption of energy due to the transmitting boundaries. Little differences are visible close to the ground surface where the propagation mechanism is of the Rayleigh type and relevant lateral absorption is not properly simulated by the model.

The limit of assuming a horizontal rigid bedrock, inherent in this tech nique, implies the assumption that the seismic excitation at some depth consists of vertically propagating shear waves.

A more sophisticated model, which avoids this assumption, has been presented by Ayala et al. [1] - see figure 5d.

In this model "active" boundaries allow free transmission of waves - both for outgoing and incoming waves - as would occur if the discrete domain were continuous, thus providing a consistent representation of an infinite space. Besides, an earthquake source simulation has been included, to generate the seismic waves at the boundary of the mesh. [18]

A few results up to now confirm the relevance of such "active" boundaries in the absolute motion of a surface point. Limited influence, on the other hand, is shown as to the amplification between the motions of two different layers.

The drawback of this model for soil amplification analysis is that ..... it is too advanced; as a matter of fact the input data, in general, are not available on an experimental basis.

2.2 Checks of numerical models

In recent times checks of these analyses were possible when records have been collected simultaneously in nearby sites where layering and material properties of the entire zone were known. Checks of this kind have been presented since 1971, [11] , based on San Fernando earthquake records. Two indipendent methods were presented as giving self-consistent spectral estimates at three sites in agreement with records.

As proof of this agreement a figure was exhibited where the results were reported in a logarithmic scale. It is interesting to note now that the same comparison, reported in a linear scale - see figure 7 - instead of a logarithmic one, should be ascribed as unsatisfactory, on the base of a qualitative judgement.

Only recently, using Shake [20] or Flush [14] techniques, i.e., models of the kind of fig.5c more satisfactory results have been presented [17] [23] .

3. THE SURFACE EFFECT

The propagation of elastic disturbances in layered media is considered, each layer being continuous, isotropic, homogeneous and linear-elastic. In a single layer, the equilibrium for small strain is expressed by the classical Navier equations :

$$\rho \frac{\partial^2 u_i}{\partial t^2} = (\lambda+\mu)\frac{\partial \theta}{\partial x_i} + \mu \Delta^2 u_i + \rho F_i \qquad i = 1,2,3 \tag{1}$$

where :

$u_1\ u_2\ u_3$ are the displacements in a space-fixed rectangular coordinate system x_1, x_2, x_3,

t is time

$\theta = \operatorname{div} \bar{u} = \varepsilon_1+\varepsilon_2+\varepsilon_3$ cubical dilatation;

F_1, F_2, F_3. are the unit volume forces in the directions of the coordinates, which will be considered zero in our problems ;

λ and μ are the Lamè constants ;

ρ is density.

In the numerical models considered in the present research, the effect of internal friction is introduced into the equations of motion by replacing an elastic constant, such as μ by $\mu+\mu'\frac{\partial}{\partial t}$ in the same equations.This is equiv alent to stating that stress is a linear function of both the strain and the time rate of change of strain. For simple harmonic motion such effect leads to replacing μ by the complex rigidity $\mu e^{2i\beta}$ where β is the so called fraction of the critical damping for the element.

Notice that this representation of internal friction is not backed by adequa te experiences, in particular in the range of high frequencies where the dissi pation is greater. In fact, if a modal analysis is applied to the entire sys tem, the normal modes of vibration result are damped by a damping fac tor proportional to the frequency of the mode, precisely:

$$v_i = \frac{\beta}{2}\omega_i$$

where v_i is the damping relative to the critical one for the i^{th} mode of vibration and ω_i is the ith frequency. So the high frequency content of the response might be underestimated in such a model.

In the same subject notice that if the Poisson ratio is a real number, the above assumption implies that the P and S waves have the same attenu ation factor.

Under these limits the picture of the maximum acceleration during one Friuli ground shaking, at two different sites have been derived numerically. The input motion was applied at the base of the hill, i.e., at the free sur face of the flat country. It was based on two records respectively, collect ed in the neighbourhood.

The computer code applies this motion simultaneously to all points at free surface which are far enough from the hill to be undisturbed by the hill's presence, [14]. Therefore monodimensional propagation of seismic waves is assumed for such points.

In order to understand the "surface effect" in the shown analyses let us first consider a homogeneous non dissipative, elastic soil. The following simple theorem will be proved in the Appendix.

"If the amplitude of a harmonic displacement component, at some depth , is A, then the amplitude of the same component at the surface is

$$\frac{2\cos\varphi}{1+\cos 2\varphi} A ,$$

where :

V is the wave velocity for the wave type under examination;

A is an arbitrary fixed amplitude ;

ω is the harmonic motion frequency

H is the depth .

$$\varphi = \frac{H\omega}{V}$$

The above results apply both to compressional and to shear waves.

Figure 8 shows the amplitude transfer function under examination. As evident, this is always greater than one, being one in practice only for :

$$\varphi = \frac{H\omega}{V} \leq \frac{\pi}{20} \qquad \text{or} \qquad H \leq \frac{L}{20}$$

where L is the wavelength for the wave under examination. Therefore, the presence of the surface effect is not a mere question of rigidity of the upper layer, but mainly a matter of the ratio between the depth of the soil deposit and the wavelength.

The above-mentioned result can be worked out further on in terms of earthquake intensity

Let $S_0(\omega)$ be the power spectral density for acceleration at the depth and $S_H(\omega)$ be the analogous quantity at free surface.

Let moreover the earthquake intensity be evaluated as

$$I_0 = \left[\int_0^\infty S_0(\omega)\, d\omega \right]^{\frac{1}{2}}$$

and analogously at the free surface.

To derive the ratio between I_0 and I_H, a hypothesis need be assumed as to the frequency distribution of the energy of the earthquake, i.e., on the function $S_0(\omega)$. If for instance, as in figure 9, S_0 is of a parabolic type, then :

$$I_H \simeq 2\, I_0$$

The importance of this solution is related to the experiences so far collected on the simultaneous registration of the earthquake motion at surface and underground, see for instance [2]. In particular in the paper [6], where all the available experiences have been reviewed, no singular case is reported at variance with the above rules. On the average, the above-mentioned ratio appears to be two.

As it was previously mentioned such effect can be further on amplified by the presence of non horizontal deposit : see figure 10, which confirms the observations already presented in Fig. 2, for the Buia hill.

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APPENDIX

Vertical propagation of harmonic shear waves through th system shown in fig. 11 will cause only horizontal displacements

$u = u(x,t)$

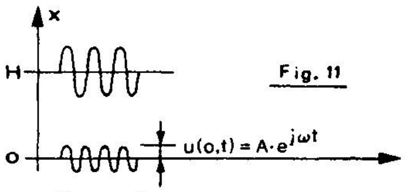

Fig. 11

which must satisfy the wave equation [5, 9] :

$$\rho \frac{\partial^2 u}{\partial t^2} = G \frac{\partial^2 u}{\partial x^2} \qquad (1)$$

Let assume an harmonic motion at the layer $x = o$, $u(o,t) = A \cdot e^{j\omega t}$
General solution of Eq. 1 is :

$$u = B_1\, e^{j\omega(t-\frac{x}{v})} + B_2\, e^{j\omega(t+\frac{x}{v})} \qquad (2)$$

The coefficients B_1 and B_2 can be related by imposing the boundary condition for $x = H$:

$$\gamma = \left[\left(\frac{\partial u}{\partial x}\right)\right]_{x=H} = 0 \quad (3) \quad \text{where } \gamma \text{ is shear strain}$$

Defining $\varphi = \frac{\omega H}{V}$ where V is the wave velocity it is immediate to obtain as a consequence of equation (3) :

$$B_2 = B_1\, e^{-2j\varphi}$$

At $x = 0$ the displacement function $u(o,t)$ is according to Eq. 2

$$u(o,t) = (B_1 + B_2)\, e^{j\omega t}$$

and, by the definition :

$$A = B_1 + B_2 = B_1(1 + e^{-2j\varphi})$$

Relating the coefficient B_2 with A the transfer frequency function takes the expression :

$$\frac{u(H,t)}{u(o,t)} = \frac{2\, e^{-j\varphi}}{1 + e^{-2j\varphi}}$$

and finally with algebrical operations results :

$$\left| \frac{u(H,t)}{u(o,t)} \right| = \frac{2 \cos\varphi}{1 + \cos 2\varphi}$$

which represents the frequency transfer function versus φ, in the case of homogeneous non dissipative linear elastic half space.

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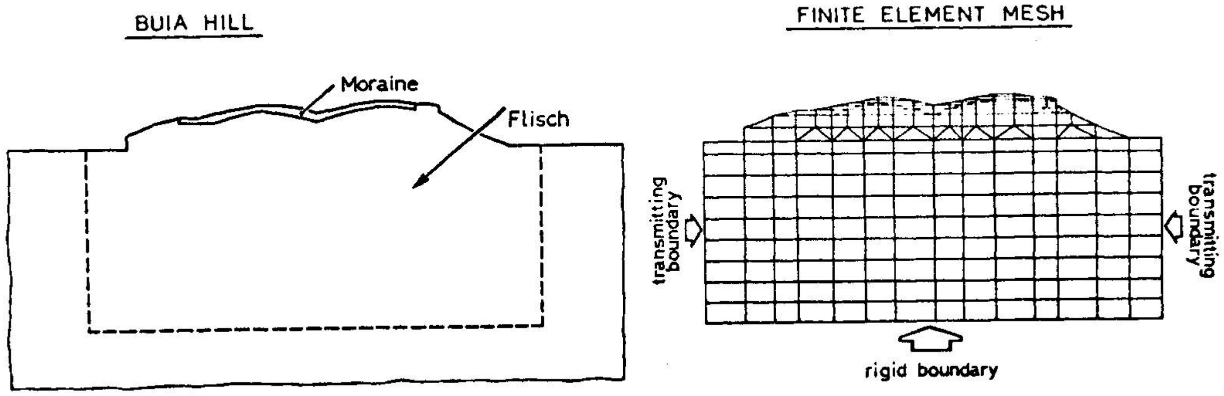


FIG. 1 - Buia hill. Geometry and finite element mesh

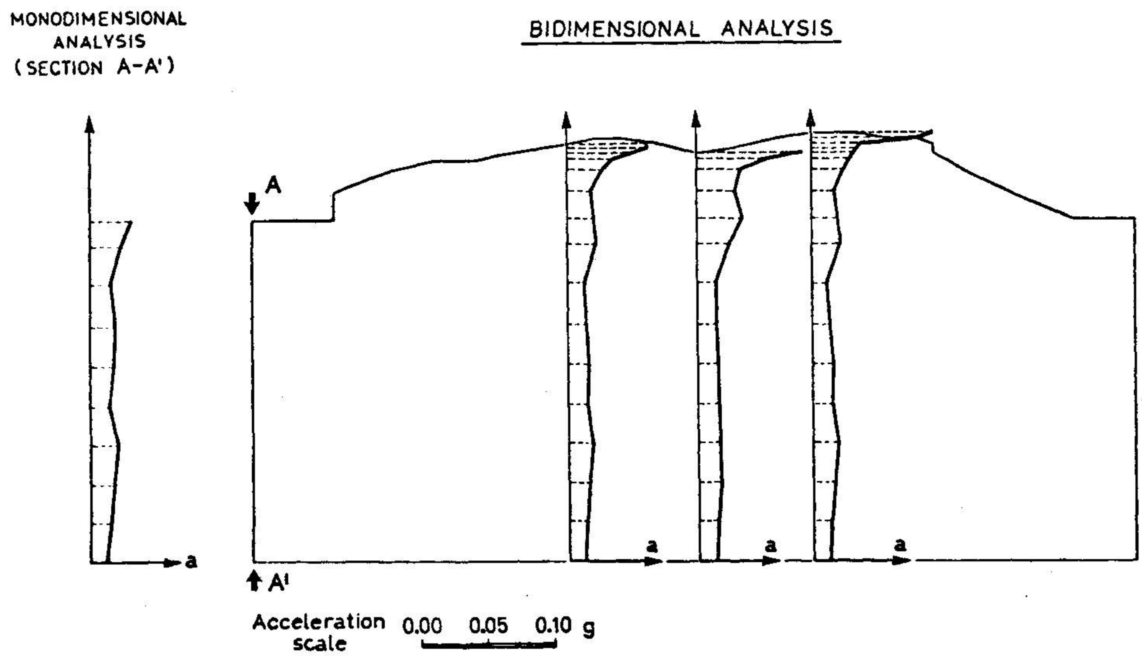


Fig. 2 - Buia hill. Comparison of accelerations obtained with monodimensional and bidimensional analysis

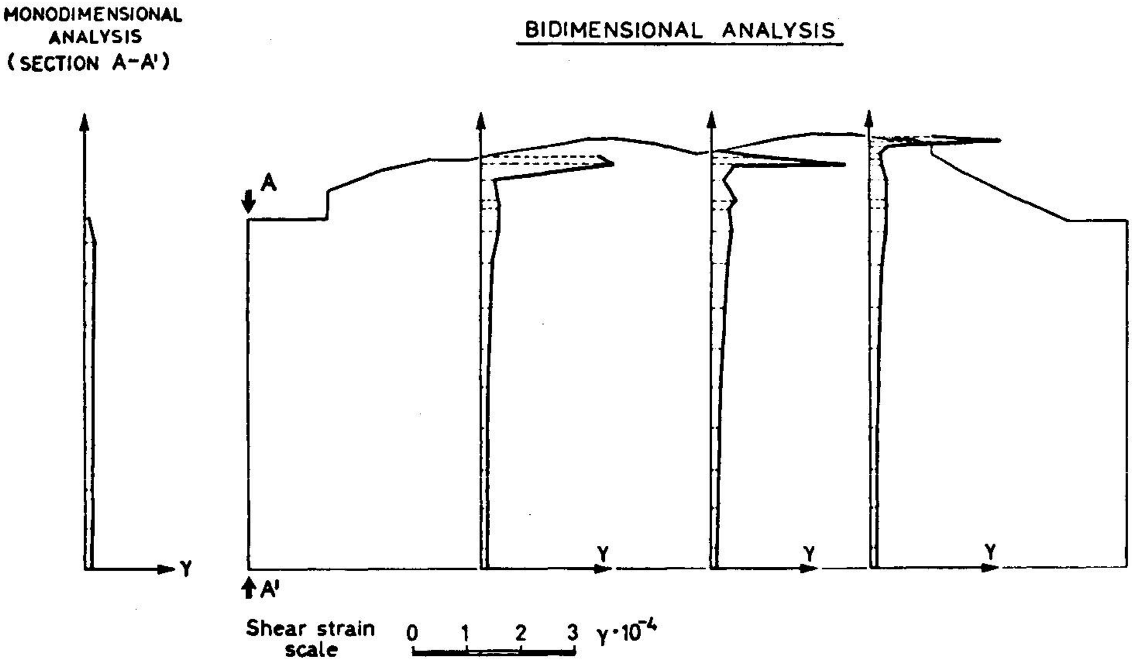


Fig. 3 - Buia hill. Comparison of shear strains obtained with monodimensional and bidimensional analysis

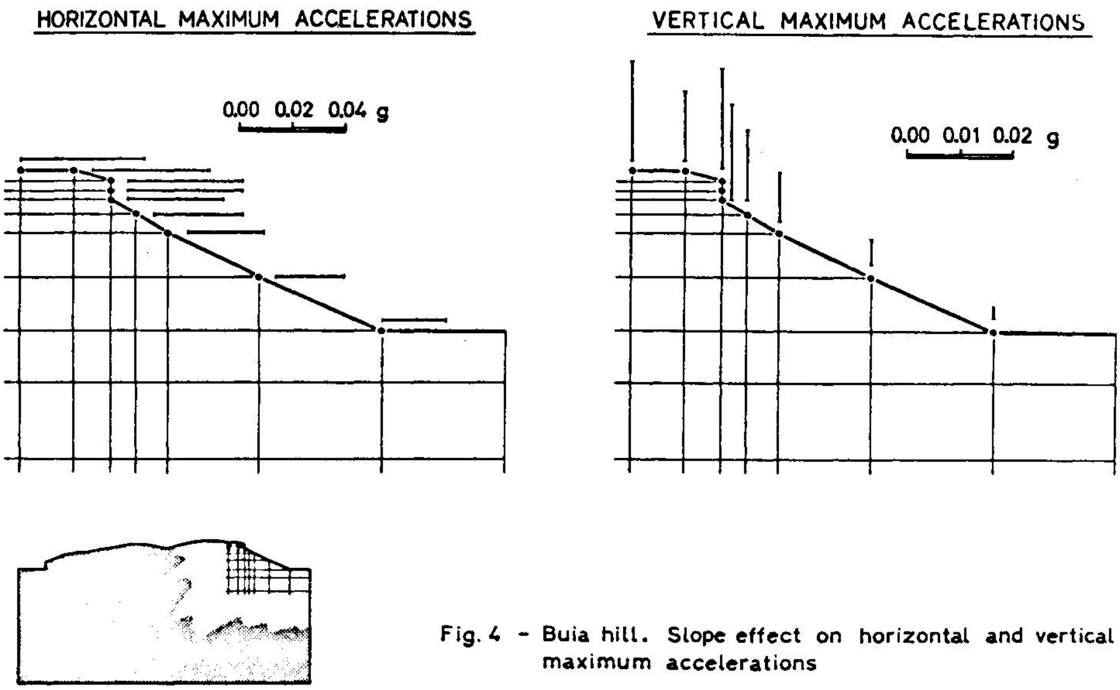


Fig. 4 - Buia hill. Slope effect on horizontal and vertical maximum accelerations

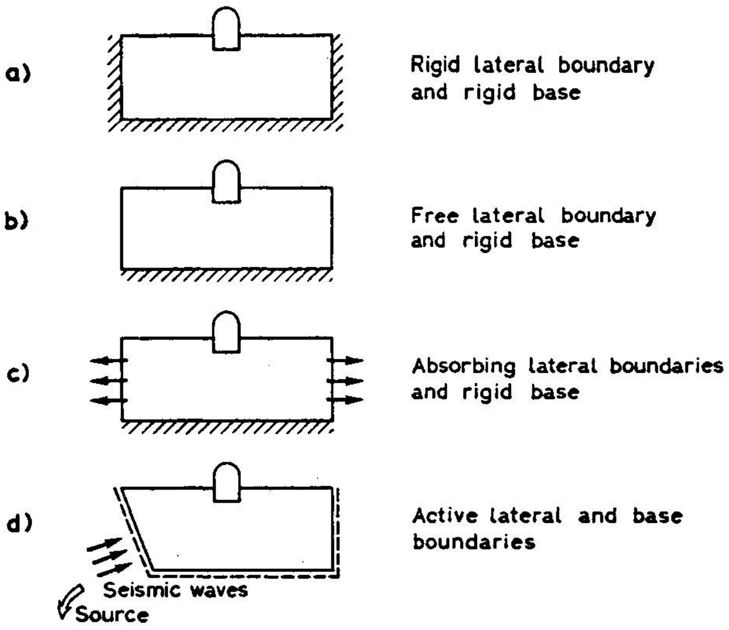


Fig. 5 - Different analytical model for earthquake response of soil deposits

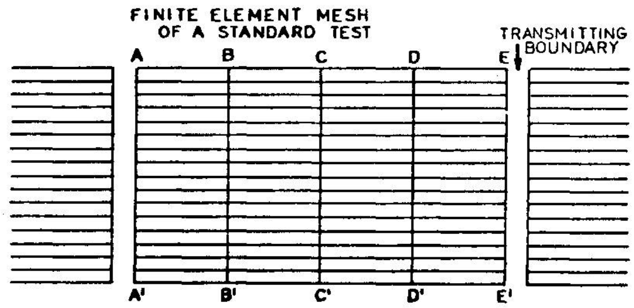
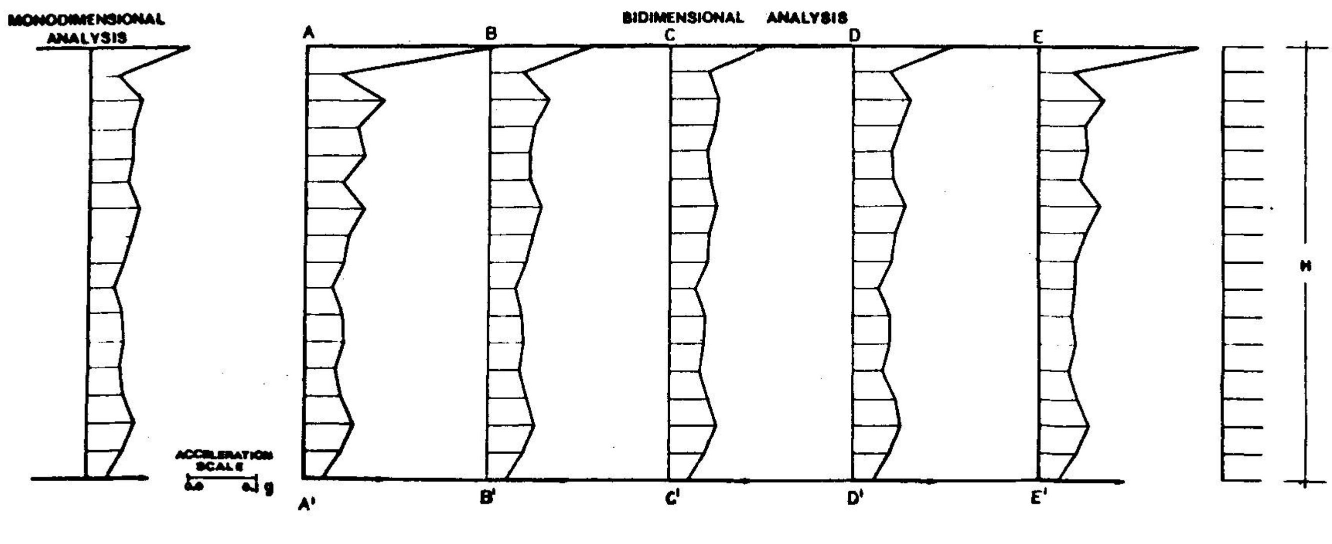


Fig. 6 - Flush technique. Comparison between monodimensional and bidimensional analysis



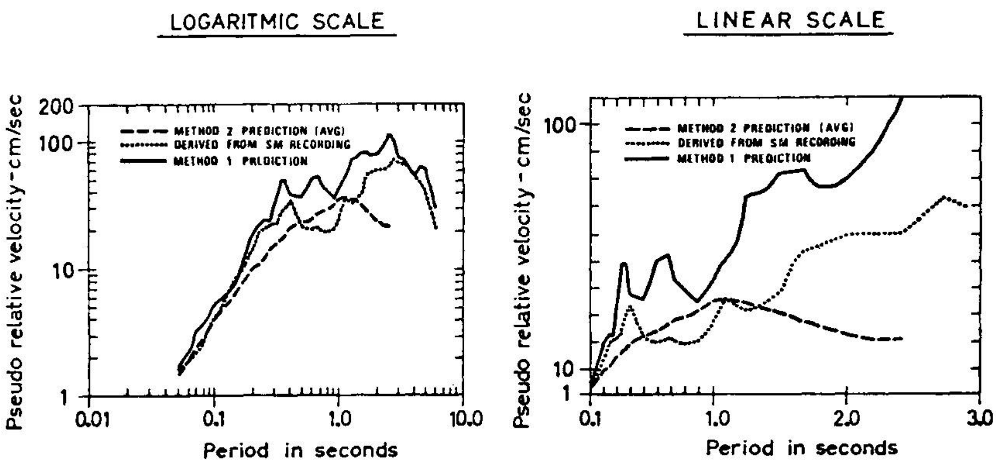


Fig.7 - Calculated relative site transfer function and comparison of spectral prediction methods - Hays et al. results [11]

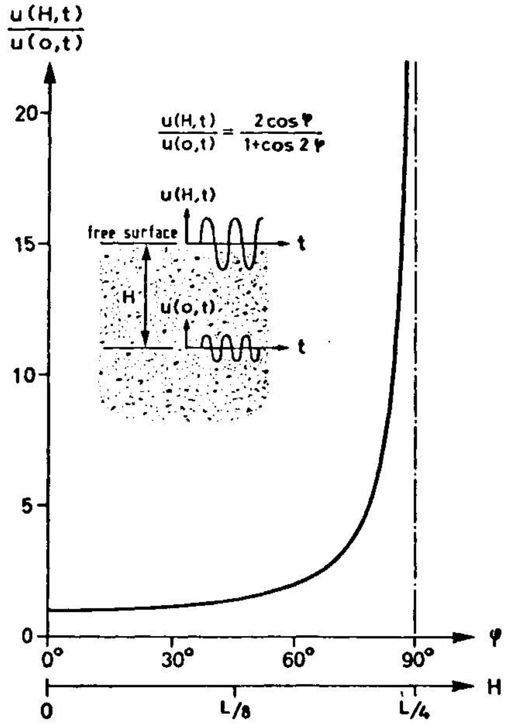


Fig. 8 - Frequency transfer function

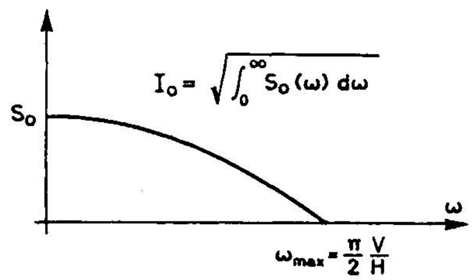


Fig. 9 - Assumption for power spectral density of seismic acceleration at some depth

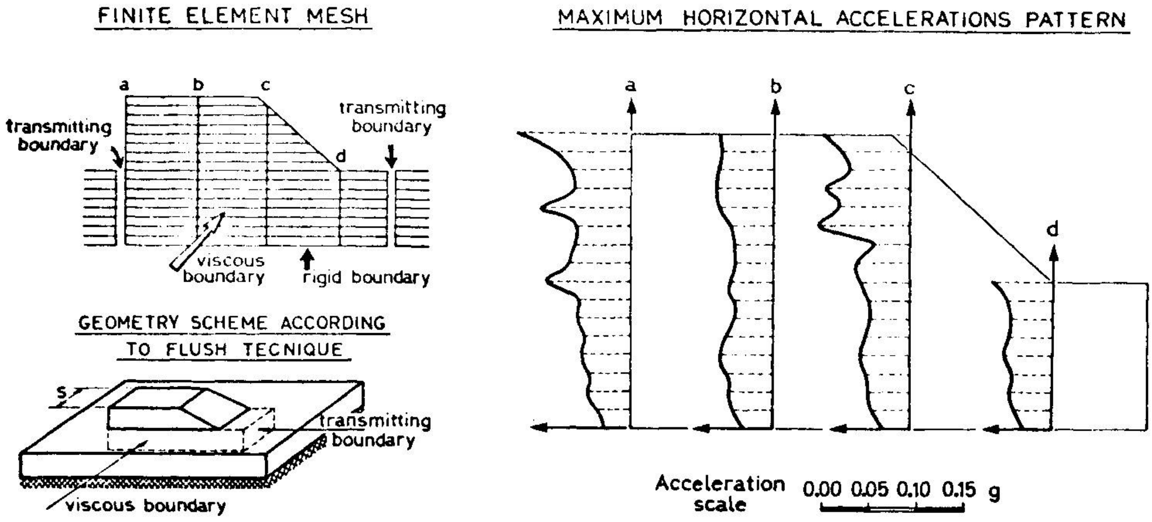


Fig. 10 - Hilly site. Geometric effect on accelerations