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SEISMIC RESPONSE AMPLIFICATION DUE TO TOPOGRAPHIC INFLUENCES

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SUMMARY

It is well known that there is a correlation between the map of earthquake damages and the local topography. The two-dimensional analysis in the present paper is devoted to the determination of response amplification due to topographic irregularities. By a time-stepping Boundary Element Method (BEM) procedure focussing effects are studied for the case of surface irregularities (hills and valleys) as well as for irregular, e.g. basin-shaped bedrock profiles.

INTRODUCTION

Observations after earthquakes, for example in Friuli (1976) or Mexico City (1985), as well as studies in earthquake engineering established that earthquake damage can be highly localized. This is attributed in part to the stratification of the soil media, i.e. the geological inhomogeneity or the underground topography (e.g. Refs. 1,2) and in part to the surface topography (e.g. Refs. 3,4).

Up to now, most analysis based on the study of two-dimensional irregularities in the frequency domain, i.e. assumed steady state waves. Due to the fact that close form fundamental solutions, e.g. for the antiplane problem (Ref. 5), or even Green's functions exist, the source method is often used, mainly to study the influence of valley or canyon-like irregularities (Refs. 3,5). Besides these semi-analytical techniques, the frequency domain formulation of the BEM has already been used for a zoned viscoelastic plane (Ref. 1) to analyze the effects of the slope of the deposit near the end zones.

The BEM has the great advantage that it is a very easy matter to change the boundary geometries, i.e. to study the influence of different topographies. Moreover, it automatically takes into account the radiation damping to infinity which is essential in all infinite or semi-infinite domains. The only disadvantage, the restriction to homogeneous media, can be eliminated by using a hybrid technique, i.e. by coupling boundary elements and finite elements (FE). In order to obtain a BE formulation which can be used in combination with FE for treating non-linear behavior, an algorithm which works directly in the time domain has been developed (Ref. 6). This time-stepping BEM procedure has already been applied successfully to several interaction problems, e.g. the interaction between elastic structures (Refs. 7,8,9) or soils and compressible fluids (Refs. 10,11).

It is the aim of this contribution to present studies which are conducted for rigid strip-foundations on elastic layers with various types of underground und surface topographies. Their time-dependent responses to impulse-type excitations were determined in order to find out potential amplification effects.

TIME STEPPING BOUNDARY ELEMENT METHOD

The basic idea of the proposed method is to describe the initial-boundary value problem by boundary integral equations. Assuming zero body forces and zero initial conditions, Graffi's reciprocal theorem (Ref. 12) and a regularization procedure (Ref. 6) yields the following system of integral equations (similar formulations have been given by Mansur (Ref. 13), Spyrakos (Ref. 14) and Fukui (Ref. 15))

$$c_{ik}(\boldsymbol{\xi})u_k(\boldsymbol{\xi},t) = \int_0^t \oint_\Gamma [\overset{*}{u}{}_k^{(i)}(\mathbf{x}-\boldsymbol{\xi};t')T_k(\mathbf{x},\tau) + \overset{*}{P}{}_k^{(i)}(\mathbf{x}-\boldsymbol{\xi},t')u_k(\mathbf{x},\tau) - \overset{*}{Q}{}_k^{(i)}(\mathbf{x}-\boldsymbol{\xi},t')\dot{u}_k(\mathbf{x},\tau)]\, d\Gamma_{\mathbf{x}} d\tau, \qquad (1)$$

where $\overset{*}{u}{}_k^{(i)}(\mathbf{x}-\boldsymbol{\xi},t')$ indicates the displacement at a point $\mathbf{x}$ in an unbounded domain without any imposed initial conditions to a unit impulse at the time τ in the direction x_i and located at point $\boldsymbol{\xi}$ (Ref. 6). The kernels $\overset{*}{P}{}_k^{(i)}$ and $\overset{*}{Q}{}_k^{(i)}$ are obtained from the corresponding singular traction $\overset{*}{T}{}_k^{(i)}$ after carrying out integrations by parts with respect to time. All three kernels in Equ. (1) have a $1/R$ (with $R = \sqrt{c_\alpha^2 t'^2 - r^2}$) singularity. Thus, the only singularity in these integral equations occur when $r = |\mathbf{x}-\boldsymbol{\xi}|$ and $t' = t-\tau$ approach to zero simultaneously.
The factor $c_{ik}(\boldsymbol{\xi})$ is defined as zero, $0.5\delta_{ik}$ and δ_{ik} when $\boldsymbol{\xi}$ lies outside, on a smooth boundary Γ and in the interior of the domain Ω, respectively.

These equations (1) describe the motion in the interior as well as along the boundary Γ of a homogeneous, isotropic elastic medium with density ρ and the propagation velocities c_1 and c_2 of the dilatational and distortional waves, respectively. However, one must first find the values of the unknown boundary reactions $T_i(\mathbf{x},t)$ on Γ_u and $u_i(\mathbf{x},t)$ on Γ_T, when the prescribed values, indicated by super-bars, are $\bar{u}_i(\mathbf{x},t)$ on Γ_u and $\bar{T}_i(\mathbf{x},t)$ on Γ_T, $\Gamma = \Gamma_u+\Gamma_T$. The numerical implementation consists of

(i) a discretization of the boundary in which displacements and tractions are assumed to be constant over each boundary element Γ_l, $l=1,2,\dots,L$.

(ii) a step-by-step integration in time where displacements and tractions are taken to be linear and constant over each time interval Δt, respectively.

In order to arrive at systems of algebraic equations, collocation is used at every node $\boldsymbol{\xi}_\lambda$, $\lambda=1,2,\dots,L$, and at all time steps $t_n=n\Delta t$. Then, integrations over each time interval and over each boundary element have to be carried out, according to (i) and (ii).

The integrations with respect to time have been performed analytically. The results can be found in reference 6. Finally, when the integrals over each boundary segment Γ_l have been evaluated (Gaussian eight-point formula has been used), the discrete analogues of equations (1) are obtained; there, if all time steps Δt have the same duration, all matrices with the same time difference, i.e. the same difference of indices $n-m = \mu$, are equal

$$\mathbf{U}^{nm} = \overset{(\mu+1)}{\mathbf{U}} \quad \text{and} \quad \mathbf{T}^{nm} = \overset{(\mu+1)}{\mathbf{T}} \quad , \text{ for all } n \geq m,\ m=1,2,.. \qquad (2)$$

Thus, for each extra time step t_n, it is necessary to determine only one extra $\mathbf{T}$ and one extra $\mathbf{U}$ blockmatrix. Then, the following algebraic equation system has to be solved in conformity with the actual boundary conditions:

$$(0.5\mathbf{I} + \overset{(1)}{\mathbf{T}})\cdot\mathbf{u}^{(n)} + \sum_{\mu=2}^{n} \overset{(\mu)}{\mathbf{T}}\cdot\mathbf{u}^{(n-\mu+1)} = \sum_{\mu=1}^{n} \overset{(\mu)}{\mathbf{U}}\cdot\mathbf{t}^{(n-\mu+1)} . \qquad (3)$$

PARAMETRIC STUDIES

Wave radiation to infinity, as well as wave reflections, which may occur in case of any inhomogeneities inside the soil medium (i.e. rigid bedrock), influences the response of a foundation substantially. Since the significance of these two phenomena is strongly influenced by the topographical situation, it is appropriate to perform a parametric study in order to show how the behavior of a foundation can be affected.

For the sake of clarity, only one set of soil properties is used throughout these examinations: Young's modulus $E = 2.66 \cdot 10^5$ KN/m^2, material density $\rho = 2000$ kg/m^3 and Poisson's ratio $\nu = 0.33$. Assuming plane strain conditions, the wave speeds are $c_1 = 444$ m/s and $c_2 = 224$ m/s. Moreover, only one type of transient load is considered: the foundation will be subjected to vertical rectangular impulse of time duration $\Delta t = 0.00135$ secs and of intensity $P_v = 741$ KN/m.

Stratum with basin- and hill-shaped bedrock Figure 1 shows a surface foundation (2B = 2.0 m) resting on the top of an elastic soil medium. In order to demonstrate the influence of a rigid bedrock and especially the importance of its shape, several soil-rock interfaces (marked by different lines) have been introduced (L = 5 m) and compared: a horizontal base (H = 2 m), a circular rock (radius R = 3.63 m) and an angular bedrock (h = d = 1 m).

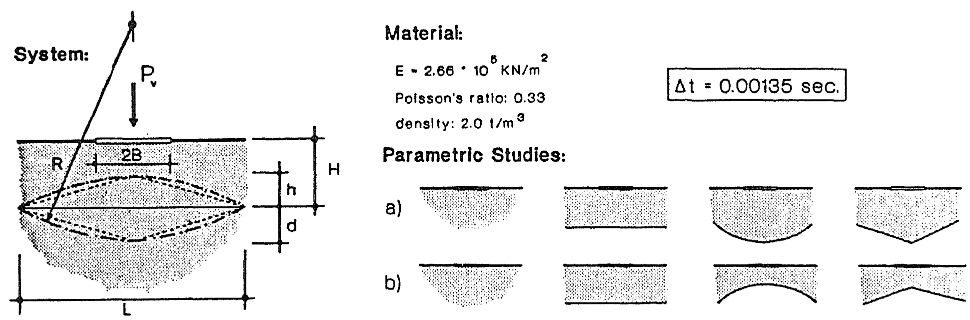

Fig. 1: Geometry and Discretization of a Stratum with Basin- and Hill-Shaped Bedrock

The soil-foundation interface is discretized by four equal boundary elements (0.5 m) while the free surface on each side of the foundation is modeled using three elements of the same length. The soil-rock interface is subdivided into 10 straight elements, even modeling the circular shapes.

For the first couple of time steps, the response of halfspace and stratum with basin-shaped bedrock (Fig. 2) are identical, because in the beginning the foundation at the surface can not yet be influenced by a rigid rock inside the soil. Later, however, significant differences between both types of soil profiles can be observed: waves were reflected at the soil-bedrock interface and returned back to the surface. Thus, while the responses at the halfspace surface nearly vanish for $t > 0.07$ secs., the amplitudes of motion of the foundation on a stratum increase remarkably by the reflections. Moreover, comparison of the response in case of a horizontal bedrock to that of a basin-shaped bedrock shows that the later will be damped only very slowly with increasing time, although energy can radiate to infinity out of equal 'openings' (H = 2 m). This difference indicates that in the case of basin-shaped bedrocks, wave focusing effects lead to a significant response amplification during later time steps. The exact shape of the basin, circular or angular, seems to be of minor importance.

Considering the results for a bedrock like a hill, as presented in Figure 3, one can observe the following contrary behavior: during later time steps both hill shapes lead to a reduction of the foundation response in comparison to the horizontal bedrock. Moreover, the response strongly depends on the actual shape of the hill (circular or angular).

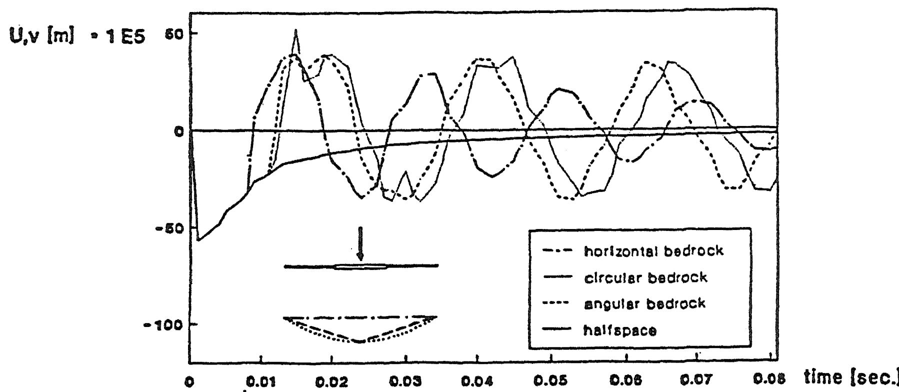

Fig. 2: Time History of Verticale Response to Rectangular Impulse
Influence of Basin-Shaped Bedrock of a Stratum

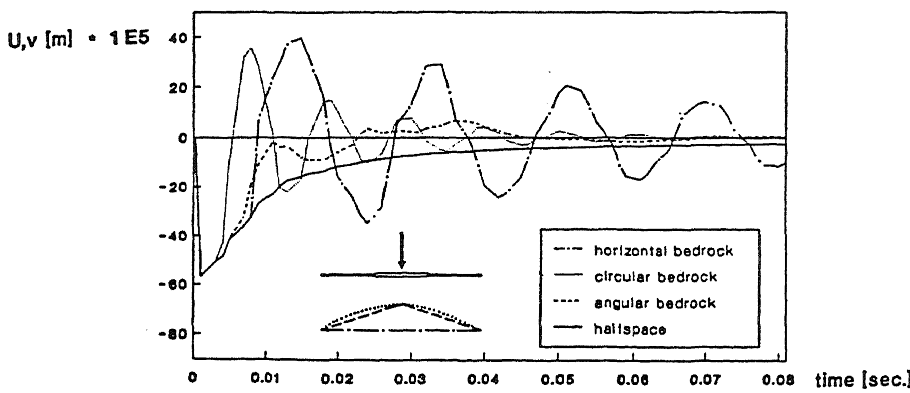

Fig. 3: Time History of Vertical Response to Rectangular Impulse
Influence of Hill-Shaped Bedrocks of a Stratum

The reason for the remarkable differences in the responses obtained for the circular and the angular hill-shaped bedrock can be in the fact that the vertically generated wave front, when hitting the angular rock, is separated and reflected towards the 'openings' on both sides of the system. If the base is circular, on the other hand, most of the waves are at first reflected in such a way that most of the energy hits the foundation again, before radiating to infinity.

Stratum with Dam- and Hollow-Shaped Surface In order to get an impression as to how different surface shapes affect the vibration behavior of a system, the foundation has been placed on a dam and in a hollow, respectively. Figure 4 displays the system under consideration. The dimensions indicated in the sketch of the system are as follows: a = 2 m (4 elements), b = 1 m (2 elements), c = 1 m (2 elements).

Two parametric studies were performed: a variation of different heights of the dam (h = 0 m / 0.5 m / 1 m, Fig. 5), and an investigation of different depths of the hollow (d = 0 m / 0.5 m / 1 m, Fig. 6).

Considering the results for the foundation placed on the crest of the dam, one can observe that the amplitudes of the responses seem to be hardly affected by the height h of the dam, only the 'frequencies' of the foundation motions differ because of the different time duration the waves need to return back to the foundation. On the other hand, since the amplitudes stay almost constant, i.e. the radiation damping is rather slow, a small focussing effect exists, the higher the dam, the more.

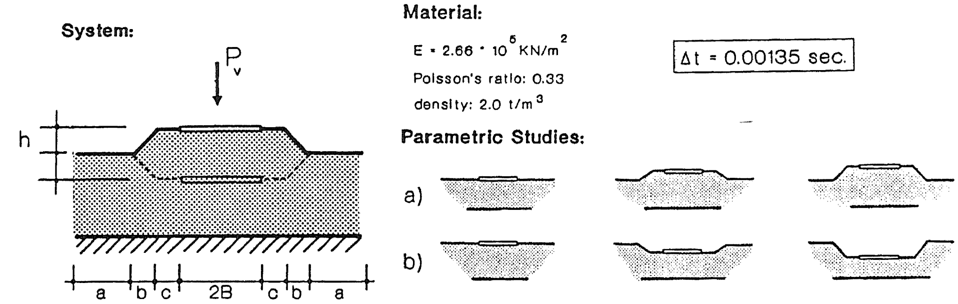

Fig. 4: Geometry and Discretization of a Stratum with Dam- and Hollow-Shaped Surface

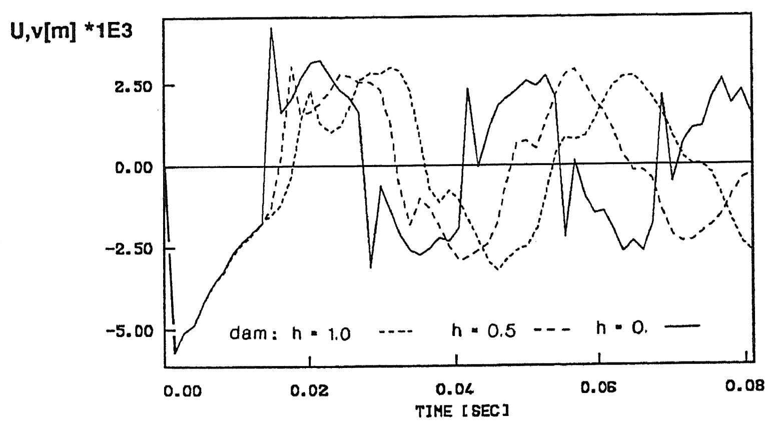

Fig. 5: Time History of Vertical Response to Rectangular Impulse Influence of Dam-Shaped Surface of a Stratum

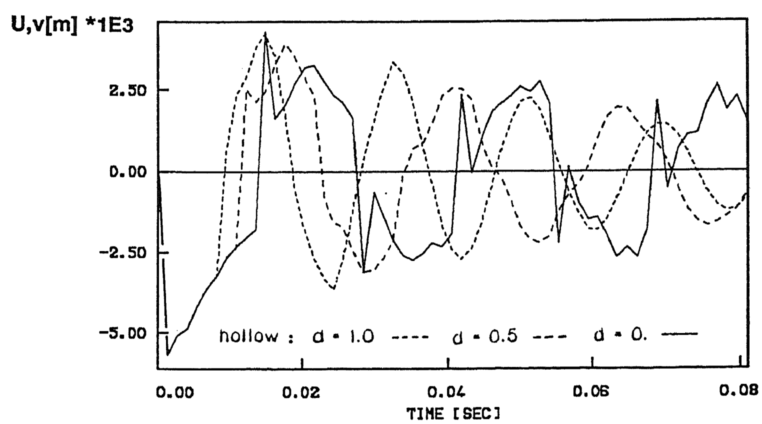

Fig. 6: Time History of Vertical Response to Rectangular Vertical Impulse Influence of Hollow-Shaped Surface of a Stratum

The second parametric study shows a reverse behavior: the embedment of the foundations reduces significantly the amplitudes, i.e. increases the radiation damping. At the same time, the change of the foundation motion 'frequencies' is opposite: the deeper the hollow, the higher the frequency, whereas the higher the dam, the lower the frequency.

On the whole, one can state that the bedrock profile is the more important topographic irregularity (at least, if the foundation itself is the excitation source) because it can cause really significant response amplifications.

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