INFLUENCE OF GEOMETRY AND MATERIAL PROPERTIES ON THE SEISMIC RESPONSE OF SOIL DEPOSITS

by

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Synopsis

The influences of geometry and material properties on the seismic response of soil deposits are examined using finite element representations and semi-infinite layer solutions. Several deposits with varying geometrical configurations and material property distributions are studied by these methods. The influences on seismic response are assessed in terms of maximum accelerations, maximum stresses and response spectral values. Finally, the role of the fundamental period of the deposit in response evaluation is examined.

Nomenclature

D = depth of foundation material beneath an earth bank as shown in Fig. 2b;

E = modulus of elasticity;

H = thickness of semi-infinite layer (Fig. 2a) or height of earth bank (Fig. 2b);

[K] = stiffness matrix;

L_t, L_b = lengths as shown in Fig. 2b;

[M] = mass matrix;

P_n = modal participation factor;

T_1 = fundamental period of vibration;

$\ddot{u}_g$ = base acceleration;

X_n = normal coordinate for nth mode of vibration;

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α = slope angle of earth bank;

γ = unit weight;

λ_n = fraction of critical damping for nth mode of vibration;

μ = Poisson's ratio;

$\{\phi^n\}$ = vector of mode shape for nth mode of vibration;

ω_n = circular frequency of nth mode of vibration

Introduction

Soil deposits in nature exist in a variety of geometrical configurations and have various distributions of material properties. The study of the response of such deposits during earthquakes forms a major part of aseismic design. Accordingly, it is of interest to ascertain the influences of both the geometrical configurations and the distribution of material properties of soil deposits on their seismic response.

These influences are studied in this report by analyzing the response of the 8 deposits shown in Fig. 1. Deposits (a) and (b) are soil deposits with both a horizontal level ground surface and a horizontal level rock boundary extending a great distance in the horizontal direction; thus they constitute horizontal semi-infinite layers. Deposit (c) has horizontal level surface and a sloping rock boundary connecting two semi-infinite layers having thicknesses equal to those of deposits (a) and (b). Deposits (d) to (h) are earth banks, i.e., a sloping surface having an extensive horizontal surface behind the crest of the slope and an extensive horizontal surface beyond the toe. Deposits (a), (b), (c) and (d) are analyzed to assess the influence of the shape of the deposit on seismic response. Deposits (d), (e) and (f) are analyzed to study the influence of the slope angle on the response of earth banks. Deposit (h) is analyzed to evaluate the influence of the distribution of material properties.

From a soil behavior point of view, the two most important response values in the seismic analysis of a deposit are the time histories of the horizontal surface accelerations and the shear stresses developed within the deposit. The influence of a soil deposit on the response of structures built in the vicinity of the deposit are most conveniently studied using response spectra. Therefore, the influences of geometry and material properties on the seismic response of soil deposits are examined in this report in terms of maximum horizontal surface accelerations, maximum shear stresses and acceleration response spectra.

Analytical Procedures

The evaluation of the seismic response of a horizontal semi-infinite layer subject at its base to a horizontal seismic motion is most conveniently accomplished using a one-dimensional shear-beam analogy. If the material properties of the layer are uniform or can be expressed by a prescribed mathematical function, closed-form solutions can be readily derived for evaluating this response. However, when these properties vary in an irregular manner, numerical procedures, such as a lumped-mass idealization, must be used. In a lumped-mass solution, the deposit is idealized as shown in Fig. 2a by a series of discrete (lumped) masses interconnected by springs that resist lateral deformations. The springs represent the stiffness properties of the material between any two discrete masses. Damping is considered linearly viscous. When the appropriate number of masses is used in this idealization, the lumped-mass solution has a very high degree of accuracy. Details of the closed-form solutions and the lumped-mass solution and criteria for the accuracy and use of the lumped-mass solution are available elsewhere (1,2).

The evaluation of the response of deposits, such as the earth banks shown in Fig. 1, requires the use of a two-dimensional model. The finite element method of analysis has been shown (3) to provide suitable means for this evaluation. The basic concepts of the finite element method have been fully described in several recent publications (4,5) and its use for dynamic response analyses has been covered elsewhere (3,6,7).

The use of this method in response evaluation involves choosing a finite region of the deposit and idealizing it as an assemblage of triangular elements interconnected at a finite number of nodal points as illustrated in Fig. 2b. The equations needed for the evaluation of the response can then be derived with the aid of this idealization. The materials comprising the deposit are considered to be linearly elastic and damping is assumed linearly viscous. The equations of motion can then be readily solved by the method of mode-superposition.

The choice of the finite region of the deposit and the number of elements used in the idealization affect the accuracy of the evaluation of the response. The influence of these factors on response values have been studied in detail and criteria for the appropriate extent and division for an earth bank have been proposed (7).

The lumped-mass solution has been used to evaluate the response of deposits (a) and (b) shown in Fig. 1. The finite element method was used to evaluate the responses of deposits (c) to (h). The results of these studies are utilized in assessing the influence of geometry and material properties on the seismic response of soil deposits as described in the following pages.

Influence of Geometry

The influence of geometry on the seismic response of soil deposits was assessed by analyzing deposits (a) to (g) shown in Fig. 1. Deposits (a) to (d) were studied to evaluate the influence of the shape of the deposit. Deposits (e) to (g), which constitute earth banks on flexible foundations, were studied to evaluate the influence of the slope angle. All these deposits were considered to have uniform material properties and each deposit was subjected to the motion shown in Fig. 3 which was applied as a horizontal base motion. Only the horizontal component of the base motion was included in the present analyses because comparisons to the results of semi-infinite solutions are to be made; the semi-infinite solution can be used only for horizontal base motion. In addition, it has been shown (3) that the vertical component of the base motion has little or no effect on horizontal accelerations or shear stresses developed in the deposits. The soils comprising each deposit were considered to have a unit weight, γ = 120 pcf, an elastic modulus, $E = 2 \times 10^6$ psf and a Poisson's ratio, μ = 0.45. A damping ratio of 20 percent was assigned to all modes of all deposits.

It should be noted that the use of uniform moduli and damping factors is not representative of field conditions since these material properties are in fact strain dependent and thus vary with depth in a deposit and with the response to the base excitation. Evaluations of field behavior should take these variations into account. However uniform characteristics have been used in the present study in order to assess the influence of geometry on response values while all other parameters are kept constant.

For the lumped mass analysis of deposits (a) and (b), each deposit was idealized by using 20 lumped masses; this number was chosen to ensure a high degree of accuracy in the response evaluation (1). The solution of the resulting lumped-mass system provided time histories and maximum values of horizontal accelerations, velocities, displacements and shear stresses throughout the depth of the deposit.

Deposits (c) to (g) were analyzed by the finite element method. Since only a finite region of the deposit could be included in the analysis, the choice of this region was made in accordance with criteria previously established for such deposits (7). Thus, the lengths L_t and L_b were taken equal to 1500 ft and 750 ft, respectively. Each deposit was then divided into 204 triangular elements with 128 total nodal points. Twenty-eight of these nodal points were considered fixed relative to each other in both the horizontal and vertical directions. Thus, each bank had 200 degrees of freedom, i.e., 200 natural frequencies and mode shapes. All the frequencies were determined in the computer program, but only the first 60 mode shapes were obtained and used in the response evaluation. The solution of the resulting system when subjected to the horizontal base rock motion shown in Fig. 3 provides values of accelerations, velocities, displacements of all nodal points in the system and element and nodal stresses for the duration of the motion. The maxima of these response values everywhere in the system were also computed. The time histories of horizontal accelerations at selected points along the surface of the deposit were used to evaluate appropriate response spectra.

The influences of the shape of the deposit on response values are illustrated in Figs. 4, 5 and 6. Figure 4 shows the variations of maximum surface accelerations. The accelerations of deposits (a), (b) and (c) are shown in the upper part of this figure. The accelerations of deposit (d) together with those of deposits (a) and (b) are shown in the lower part of the figure. As may be noted, deposits (c) and (d) develop essentially equal values of maximum surface accelerations for all points along the surface of the deposit. Thus, the fact that deposit (c) has a sloping base rock boundary and a level surface while deposit (d) has the inverse geometry but an equal slope angle do not seem to affect the acceleration values. In addition, the acceleration values of both deposit (c) and (d) coincide with those of corresponding semi-infinite layers at points well behind the crest of the slope or well beyond the toe.

Figure 5 shows the variations of maximum shear stresses along selected planes in these deposits. Equal values of maximum shear stresses develop in all the deposits at locations well behind the crest of the slope or well beyond the toe. However significant differences occur in the vicinity of the slope as illustrated in the figure. Thus, the shape of the deposit does influence the maximum shear stresses developed in the vicinity of a sloping boundary.

Figure 6 shows the variations of acceleration response spectra (for a spectral damping ratio of 5 percent) evaluated using the computed time histories of horizontal accelerations at selected points along the surface of the deposits. The data presented in this figure indicate that essentially identical spectra are obtained for both deposits (c) and (d) although these deposits have dissimilar shapes. In addition, the spectra obtained for the surface accelerations at a distance of 300 ft beyond the toe of the slope of deposits (d) and the corresponding location for deposit (c) are identical to the spectrum computed for the surface accelerations of deposit (a). Similarly, the spectra obtained for the surface accelerations at a distance of 500 ft behind the crest of the slope of deposit (d) and the corresponding location for deposit (c) are identical to the spectrum computed for the surface accelerations of deposit (b).

It is of interest to note the variations of the response spectral values shown in Fig. 6 along the surface of either deposit (c) or (d). The maximum spectral value occurs at points well beyond the toe of the slope; it develops in this region for structures having a fundamental period of about 0.45 seconds. The peak spectral values decrease as the toe is approached. However, near the toe the spectrum begins to show a second peak at a period of about 0.9 seconds. The spectrum for the motions near the crest of the slope shows this second peak developed more strongly and as the distance increases behind the crest the peak at a period of 0.45 seconds becomes less and less prominent compared to the peak at a period of 0.9 seconds. Finally, well behind the crest of the slope, the spectrum has only one major peak at a period of about 0.9 seconds. It may be noted that deposit (a) [i.e., the 50-ft thick semi-infinite layer] has a fundamental period equal to 0.46 seconds, while deposit (b) [i.e., the 100-ft thick semi-infinite layer] has a fundamental period equal to 0.93 seconds. Thus, the peaks on the response spectral curves, at points well beyond toe and at points well behind the crest, occur at periods approximately equal to those of corresponding semi-infinite layers.

The influences of the slope angle on response values were studied by analyzing deposits (e), (f) and (g) shown in Fig. 1. These deposits have identical material properties and except for the slope angles, they have identical geometry. The slope angles of deposits (e), (f) and (g) are 1:1, 2:1 and 4:1 respectively. It may be noted that deposit (g) is identical to deposit (d).

The influences of the slope angle on response values are illustrated in Figs. 7 and 8. The maximum horizontal surface accelerations and the maximum shear stresses developed along two horizontal planes within each bank are shown in Fig. 7. The variations of the response values shown in this figure indicate:

1. The response values behind the crest of the bank are almost unaffected due to a change in the slope angle.

2. The major influence of the slope angle is exhibited within the slope and to some distance beyond the toe.

3. A decrease in the value of the slope angle (i.e., flatter slope) seems to lessen the abrupt changes in the maximum horizontal accelerations along the surface of the slope.

4. The maximum horizontal accelerations along the surface of the slope are least when cot $\alpha = 1$ and greatest when cot $\alpha = 4$ (i.e. these accelerations increase as the slope angle becomes flatter). The maximum horizontal surface accelerations beyond the toe, however, decrease as the slope angle becomes flatter.

5. The effect of the slope angle on the magnitude of maximum shear stresses along a horizontal plane within the bank depends on the depth of this plane below the surface of the bank. Along a plane close to the surface [plane AA in Fig. 7], these stresses increase as the slope becomes steeper. Along a deep-seated plane [plane BB in Fig. 7], the stresses increase as the slope angle becomes flatter.

Acceleration response spectra, for a spectral damping ratio of 5 percent, at points in the vicinity of the crest and toe of the 1:1 and 4:1 slopes are presented in Fig. 8 (the spectra at these points for the 2:1 slope are not shown because they represent intermediate values). As may be noted, identical spectra are obtained in the vicinity of the crest of the slope. In the vicinity of the toe, however, the spectra are identical in shape, but differ considerably in amplitude. The spectrum for a slope of 4:1 shows the highest peak and the magnitude of the peak decreases as the slope angle becomes steeper. Spectra for points beyond the toe and for points behind the crest are not shown in this figure because essentially identical spectra were obtained at these locations for all slopes; the spectra at these locations for a 4:1 slope are shown in Fig. 6.

Thus, it appears that the slope angle does not influence the response values behind the crest nor beyond the toe. It may, however, have a considerable influence within the slope, especially in the vicinity of the toe.

Influence of Material Properties

It is a common occurence in practice to find that the material properties of an earth bank differ considerably from those of the foundation material. In order to assess the influence of this difference on the response values, deposit (h) was analyzed. This deposit is identical to deposit (f) in geometrical configuration. Deposit (f), however, has uniform material properties while the soils within the height of the bank of deposit (h) are considered to have a modulus value different from that for the soils comprising the foundation material. The response of deposit (h) was computed for several values of E_H and E_D, where E_H is the elastic modulus of the soil comprising the bank and E_D is the elastic modulus of the foundation material. The same values of unit weight and Poisson's ratio were used for the soils of deposit (f) and deposit (h). Using the finite element representation discussed earlier, the responses of earth banks having the configuration of deposit (f) were determined for the following conditions:

$E_H = 2 \times 10^6$ psf ; $E_D = \infty$

$E_H = 2 \times 10^6$ psf ; $E_D = 2 \times 10^6$ psf

$E_H = 2 \times 10^6$ psf ; $E_D = 0.5 \times 10^6$ psf

$E_H = 0.5 \times 10^6$ psf ; $E_D = 2 \times 10^6$ psf

$E_H = 0.5 \times 10^6$ psf ; $E_D = 0.5 \times 10^6$ psf

Again, the motion shown in Fig. 3 was utilized as a horizontal input base motion and a damping ratio of 20 percent was used for each mode for all these banks.

The results of these analyses are presented in Figs. 9 and 10. The maximum horizontal surface accelerations for each bank are shown in Fig. 9. The maximum shear stresses developed along a horizontal plane passing through the toe of the slope are shown in Fig. 10.

The upper part of Fig. 9 shows the variation of the maximum horizontal surface accelerations for the banks with $E_H = 2 \times 10^6$ psf as the values of E_D increase from 0.5×10^6 psf to ∞. This figure indicates that these accelerations increase as the value of E_D increases. The lower part of Fig. 9 is a plot of the maximum horizontal surface accelerations for 2 pairs of banks, each pair having the same value of E_D but different values of E_H. This plot indicates that the response values for banks having the same value of E_D are essentially the same although the values of E_H for these banks are quite different. Similar conclusions regarding the variations of maximum shear stresses are evident from the data shown in Fig. 10.

Thus, the material property distribution can have a considerable influence on the response of a deposit. In particular, however, the material properties of the foundation material seem to have a dominant influence on the response values of an earth bank.

Role of the Fundamental Period of Vibration

The fundamental period of vibration of a soil deposit may be evaluated from the solution of the characteristic value problem of the system which is used for the idealization of the deposit. The equation expressing this relationship for both a lumped-mass solution (1) and a finite element representation (6,7) may be written as follows:

$$[K]\{\phi^n\} - \omega_n^2 [M]\{\phi^n\} = 0 \qquad (1)$$

where [K] and [M] are the stiffness and mass matrices of the system, ω_n is the natural frequency and $\{\phi^n\}$ is the mode shape of the nth mode of vibration. Hence, the fundamental period, $T_1 = 2\pi/\omega_1$. The contribution of each mode of vibration to the response is evaluated by obtaining the normal

Table 1 Maximum Horizontal Accelerations at the Crest of Earth Banks Having Identical Geometric Configuration and Material Property Distribution*

Height of Bank (ft)	Depth of Foundation Material (ft)	Elastic Modulus (ksf)	Fundamental Period (sec.)	Max. Horz. Acc. at Crest (g)
20	20	1000	0.51	0.350
24	24	1000	0.61	0.334
50	50	500	1.79	0.105
50	50	1000	1.26	0.162
50	50	2000	0.89	0.250
50	50	4350	0.61	0.334
50	50	6260	0.51	0.350

*Each bank had a slope angle, cot $\alpha = 2$, a unit weight, $\gamma = 120$ pcf, and Poisson's ratio, $\mu = 0.45$.

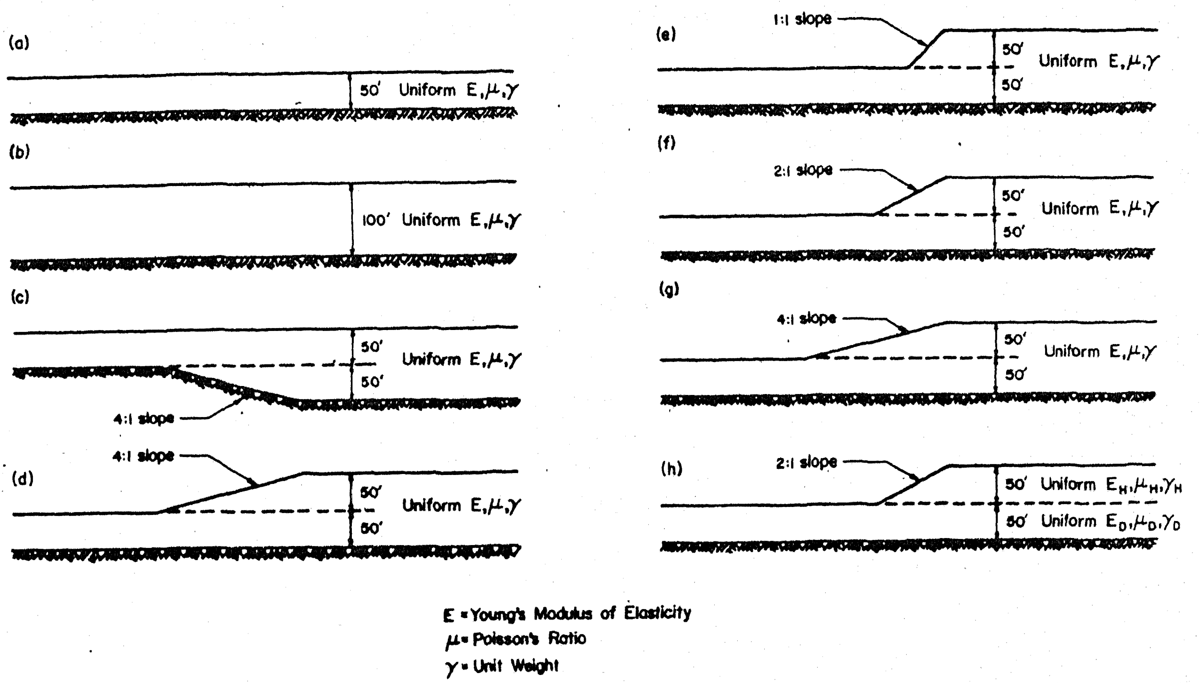

FIG. I SOIL DEPOSITS USED IN ANALYSES.

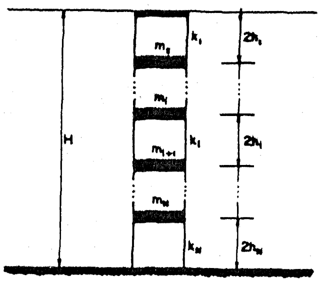

FIG.2a LUMPED-MASS IDEALIZATION OF A SEMI-INFINITE LAYER.

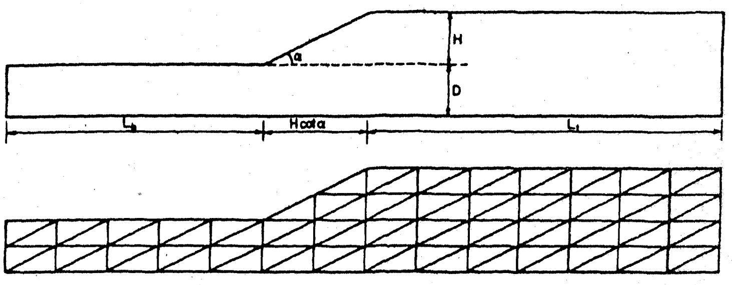

FIG.2b CROSS SECTION AND FINITE ELEMENT IDEALIZATION OF AN EARTH BANK.

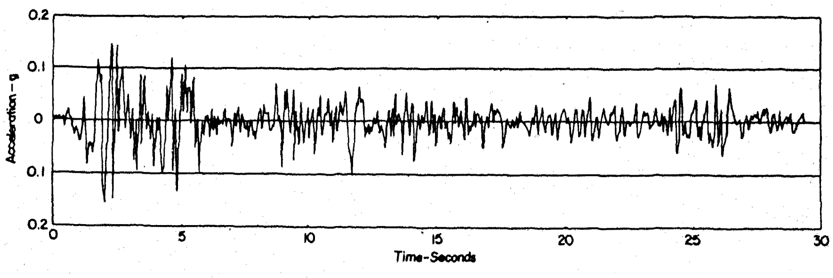

FIG. 3 RECORD OF BASE ROCK ACCELERATION USED IN ANALYSES.

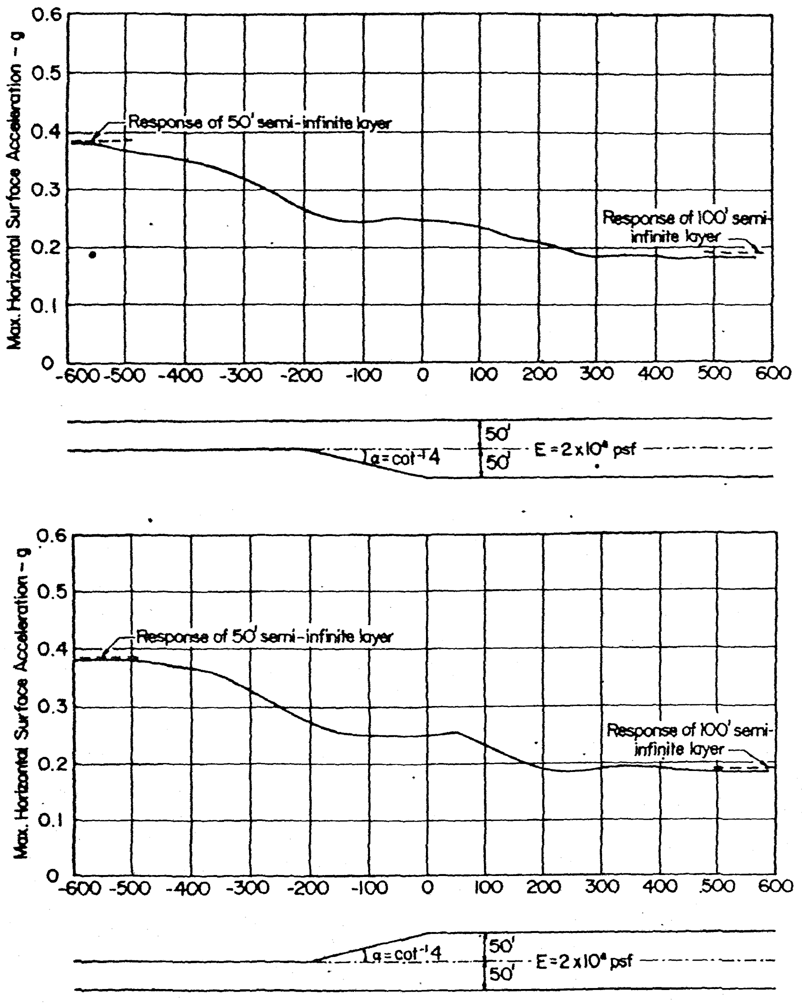

FIG. 4 INFLUENCE OF SHAPE OF DEPOSIT ON MAXIMUM HORIZONTAL SURFACE ACCELERATIONS.

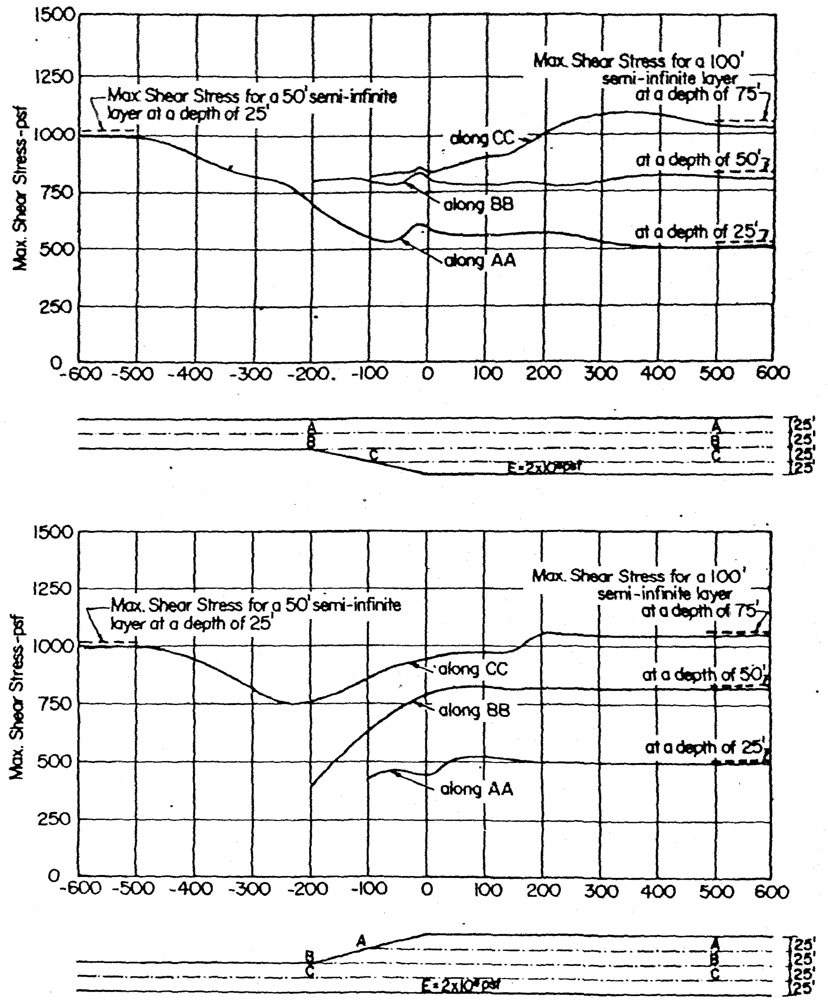

FIG. 5 INFLUENCE OF SHAPE OF DEPOSIT ON MAXIMUM SHEAR STRESSES.

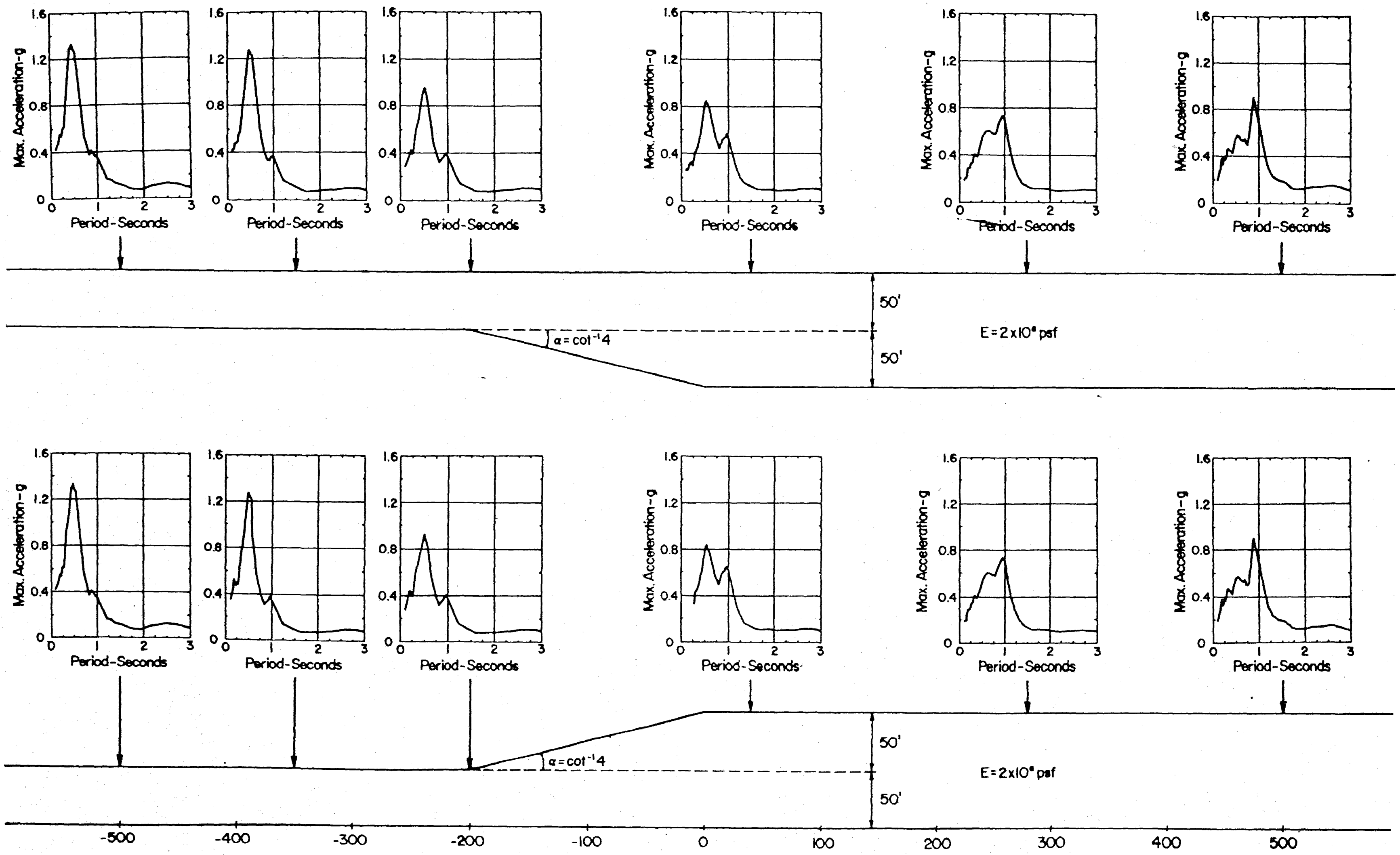

FIG. 6 INFLUENCE OF SHAPE OF DEPOSIT ON ACCELERATION RESPONSE SPECTRA FOR GROUND SURFACE MOTIONS DEVELOPED AT VARIOUS POINTS IN VICINITY OF DEPOSIT

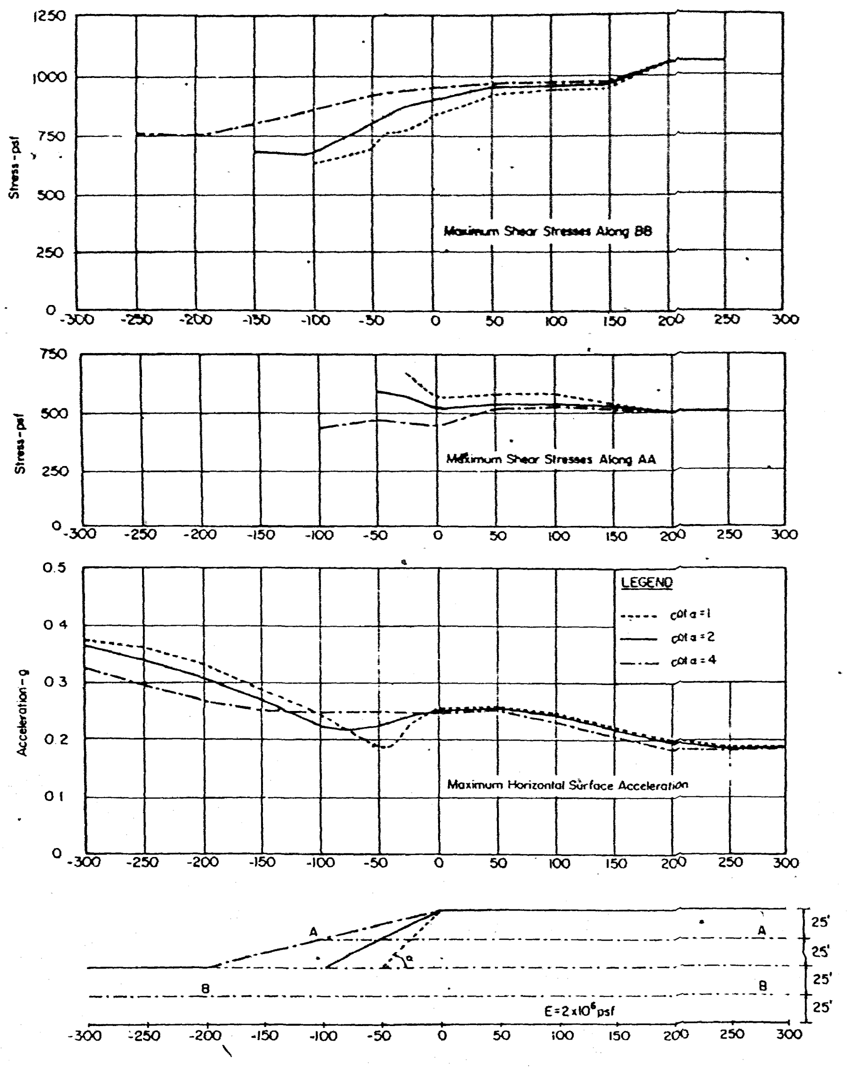

FIG. 7 INFLUENCE OF SLOPE OF EARTH.BANK ON MAXIMUM HORIZONTAL SURFACE ACCELERATIONS AND MAXIMUM SHEAR STRESSES

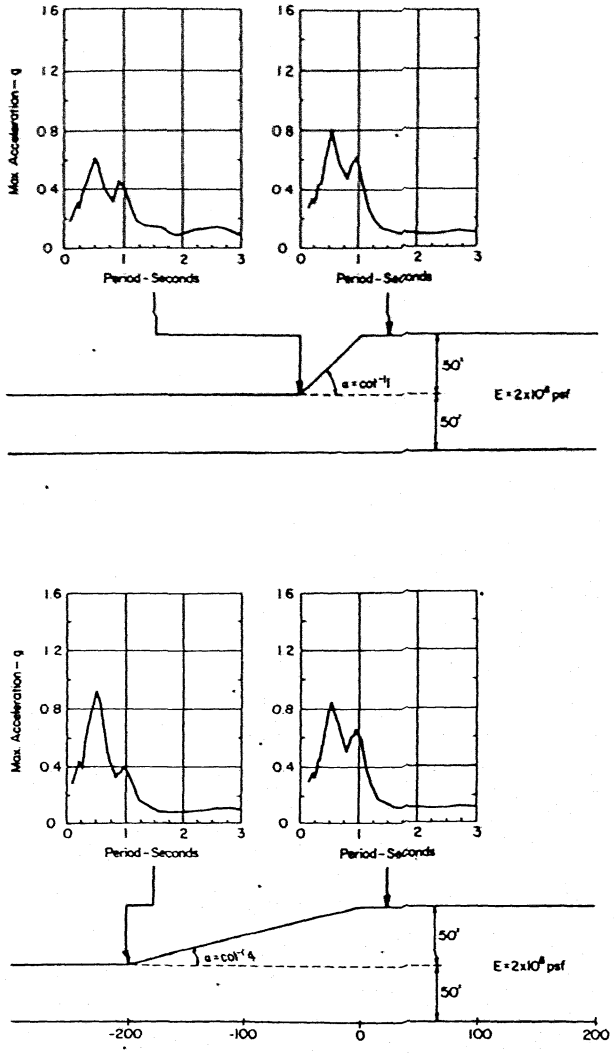

FIG. 8 INFLUENCE OF SLOPE OF EARTH BANK ON ACCELERATION RESPONSE SPECTRA FOR GROUND SURFACE MOTIONS DEVELOPED IN VICINITY OF EARTH BANK.

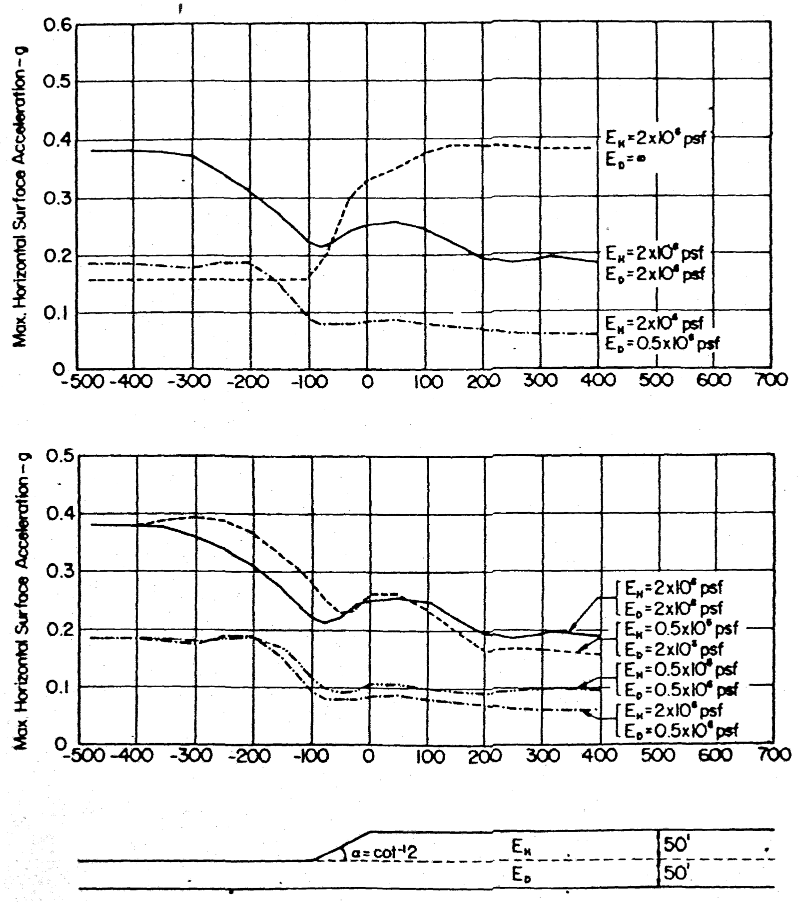

FIG. 9 INFLUENCE OF DISTRIBUTION OF MATERIAL PROPERTIES ON MAXIMUM HORIZONTAL SURFACE ACCELERATIONS.

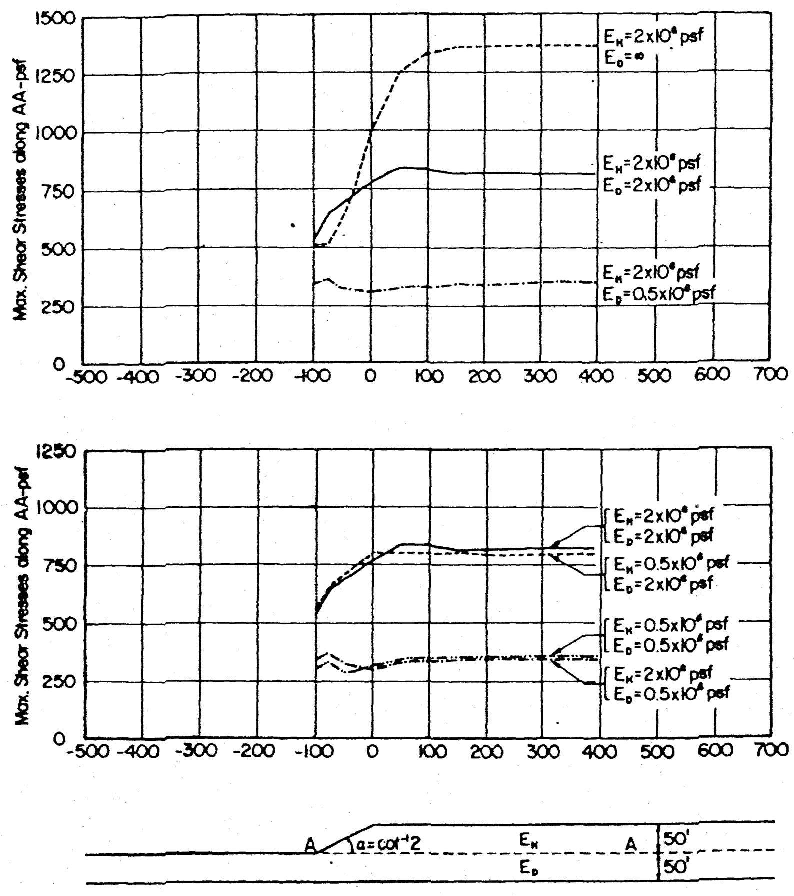

FIG. 10 INFLUENCE OF DISTRIBUTION OF MATERIAL PROPERTIES ON MAXIMUM SHEAR STRESSES.