SOIL-STRUCTURE INTERACTION OF MASSIVE EMBEDDED STRUCTURES DURING EARTHQUAKES

by

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SYNOPSIS

Methods of analyzing soil-structure interaction effects for massive embedded structures during earthquakes are reviewed and possible differences in results are illustrated. The finite element method of analysis is used to show the possible effects of soil characteristics, depth of embedment and proximity of rock surface to the base of a structure on the response of a deeply embedded structure.

SOIL-STRUCTURE ANALYSIS METHODS

A situation encountered with increasing frequency in recent years is the seismic design of a massive structure embedded at a considerable depth in a soil deposit; this is often the case, for example, in the design of nuclear power plants and pumping plants. A typical example is shown in Figs. 1 and 2, where a massive structure, with a base pressure of about 9000 psf, a height of 120 ft, and a natural period of vibration of about 0.25 second is embedded at a depth of about 75 ft below the ground surface.

An important aspect of the seismic design of such a structure is the evaluation of the dynamic interaction between the structure and the surrounding soil. This is usually accomplished in one of two ways--either by representing the effects of the soil on the structural response by a series of springs and dashpots as illustrated schematically in Fig. 1 or by modelling the soil-structure system by a finite element model as shown in Fig. 2. Each method has its advantages and limitations, and they will sometimes lead to significantly different evaluations of the seismic response of the structure.

For the structure shown in Fig. 1 for example, the earthquake motions were specified at the ground surface in the free field, where the maximum acceleration was 0.25g. The soil conditions at the site were about 200 ft of sand and gravel with a shear wave velocity of about 1800 fps. If it is assumed that the ground surface motions for such a relatively thin deposit are the result of vertically-propagating shear waves, it is a simple problem to determine the maximum accelerations and corresponding time histories of motions at other depths in the deposit (Schnabel et al., 1972). For the particular case shown, the maximum acceleration at a depth of 75 ft was 0.18g and the maximum acceleration in the underlying rock formation was 0.145g.

For the spring-dashpot model shown in Fig. 1 it is customary to assume that the motions in the soil around and below the structure are everywhere

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the same; for the conditions shown it was considered that a reasonable average motion would be about 0.2g. Representative values of the spring constants, determined by conventional methods (Whitman and Richart, 1967) and by static finite element studies, were selected to be:

$$k_h = 10\text{x}10^6 \text{ kip/ft}$$
$$k_v = 12.5\text{x}10^6 \text{ kip/ft}$$
$$k_\phi = 7.5\text{x}10^{10} \text{ kip ft/rad}$$

and an analysis of the structural response was made for system damping ratios of 7 and 15 percent. These computations led to values of maximum acceleration at the base of the structure of 0.38g and 0.32g respectively.

An analysis of the response of the same structure was then made using a finite element model similar to that shown in Fig. 2. In this case, the system was subjected to the previously-computed base rock motions having a maximum acceleration of 0.145g with free field motions giving a maximum acceleration of 0.18g at a depth of 75 ft and 0.25g at the ground surface. Damping was 5% in the structure, but representative damping and modulus values, compatible with the strains developed in the different elements of the deposit, were used for the soil; in general these values ranged from about 5 to 15 percent. For these conditions, the computed motions at the base of the structure had a maximum acceleration of only 0.16g, or less than half of that determined by the spring-dashpot model of soil effects.

Since the finite element model provides a reasonable representation of the soil-structure system and the associated acceleration distributions it seems reasonable to conclude that the spring-dashpot model used in this case considerably over-estimated the magnitude of the motion likely to develop in the structure.

FINITE ELEMENT ANALYSES OF SOIL-STRUCTURE SYSTEMS

The finite element method of analysis provides a convenient means for investigating the effects of changes in the soil-structure system including the soil type and stiffness, the depth of embedment of the structure, and the proximity of the rock surface to the base of the structure. To illustrate these effects, analyses are presented in Figs. 4 to 9 for a massive structure, weighing about 100,000 kips, located in different soil deposits.

The structure has a height of 120 ft with weights and stiffnesses in various zones as follows:

Dist. Below Top of Structure -feet	Average Unit Weight -lb per cu ft	Average Elastic Modulus ksf	Poisson's Ratio
0 to 44	2	500	0.2
44 to 70	93	53,000	0.2
70 to 93	62	149,000	0.2
93 to 120	67	78,000	0.2

Soil properties were selected in accordance with the representative properties for cohesionless soils shown in Fig. 3 (Seed and Idriss, 1971). In the finite element analyses, the non-linear characteristics of the soils were taken into account by selecting values of shear modulus and damping ratios for all elements which were compatible with the strains developed in the elements. This involved an iterative process with repeated analyses being made until strains and soil characteristics were compatible with the relationships shown in Fig. 3. The analysis procedure is described in detail in Reference 1.

In all cases, the motions developed in the underlying rock formation were assumed to be the same as those recorded at the Taft station in the Kern County, California earthquake of 1952, with a maximum acceleration of 0.16g.

EFFECT OF SOIL CHARACTERISTICS

Fig. 4 shows the results of an analysis with the structure embedded to a depth of 76 ft in dense sand and Fig. 5, the results when the soil deposit is a dense sand and gravel having twice the stiffness of the sand. It may be seen that the acceleration distributions are essentially the same in both cases and that in this case a marked change in soil properties has almost no effect on the maximum accelerations developed in the structure.

Fig. 6 shows the results of an analysis of the same soil-structure system shown in Fig. 4 except that in this case, the lateral pressures on the structure were eliminated by placing zones of very soft clay along the sides. Again the maximum accelerations within the structure are very little affected by this change in conditions, although there is a slight change in the amplitudes of motions in the adjacent sand. However it appears that in some cases the lateral pressure effects on an embedded structure can be eliminated without significantly affecting the response amplitudes.

EFFECT OF DEPTH OF EMBEDMENT

The effect of depth of embedment on the response of the structure is illustrated in Fig. 7 which shows the maximum accelerations developed in the soil-structure system when the structure is embedded to a depth of only 25 ft. In this case reducing the depth of embedment reduces the accelerations developed at the base of the structure.

EFFECT OF PROXIMITY OF ROCK SURFACE TO BASE OF STRUCTURE

Figs. 8 and 9 show the effect of changing the proximity of the rock surface to the base of the structure. In Fig. 8, the structure has the same depth of embedment (76 ft) as shown in Fig. 4, but the depth of soil is only 100 ft so that the base rock is only 24 ft below the base of the structure. However the maximum acceleration at the base of the structure is essentially the same in both cases.

In Fig. 9, the structure has the same depth of embedment (25 ft) as shown in Fig. 7, but the depth of soil is reduced to 40 ft so that the rock surface is only 15 ft below the base of the structure. In this case, the change in proximity of the rock surface causes a significant increase in the maximum acceleration at the base of the structure.

CONCLUSIONS

The results presented in the preceding pages lead to the following conclusions concerning the seismic response of deeply embedded, massive structures:

1. The use of a lumped mass model of the structure in conjunction with a spring and dashpot representation of the adjacent soil may under some conditions lead to a severe over-estimate of the acceleration levels developed in the structure.

2. A marked change in stiffness of the soil underlying and surrounding a buried structure will sometimes have no significant effect on the accelerations developed in the structure (see Figs. 4 and 5).

3. Isolating the sides of a buried structure so that it is no longer in contact with the surrounding soil may have no significant influence on the response of the structure; thus in some cases it is unnecessary to use horizontal springs in modelling the effects of the soils adjacent to a structure (see Figs. 4 and 6).

4. Decreasing the depth of embedment may in some cases reduce the response of a structure even though the free field accelerations at the level of the base of the structure are increased (see Figs. 4 and 7).

5. A marked change in the proximity of the underlying rock to the base of an embedded structure will in some cases cause no significant change in the response of the structure (see Figs. 4 and 8).

6. A marked change in the proximity of the underlying rock to the base of an embedded structure may in some cases increase the response of the structure significantly (see Figs. 7 and 9).

7. The effects of changes in stiffness of the soil underlying an embedded structure, changes the depth of embedment or changes in the proximity of the underlying rock formation cannot readily be investigated by spring-dashpot models of soil-structure interaction effects. The finite element method offers considerable advantages for investigating the effects of changes of this type but in many cases it is necessary to use a non-linear analysis program which will accommodate different moduli and damping ratios in each element if satisfactory results are to be obtained.

ACKNOWLEDGEMENTS

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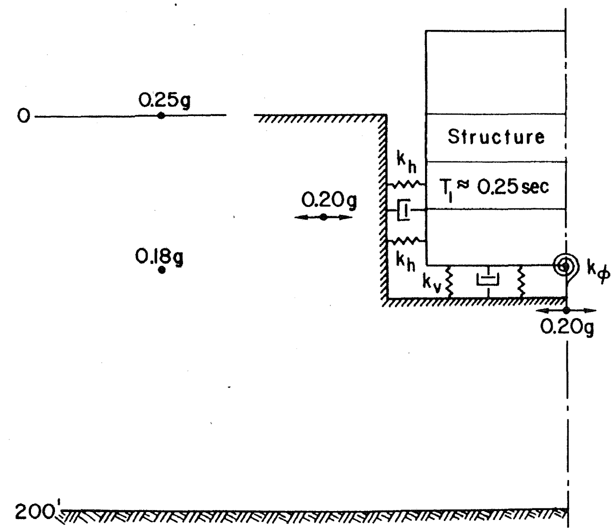

Fig. 1 SOIL-STRUCTURE INTERACTION MODEL

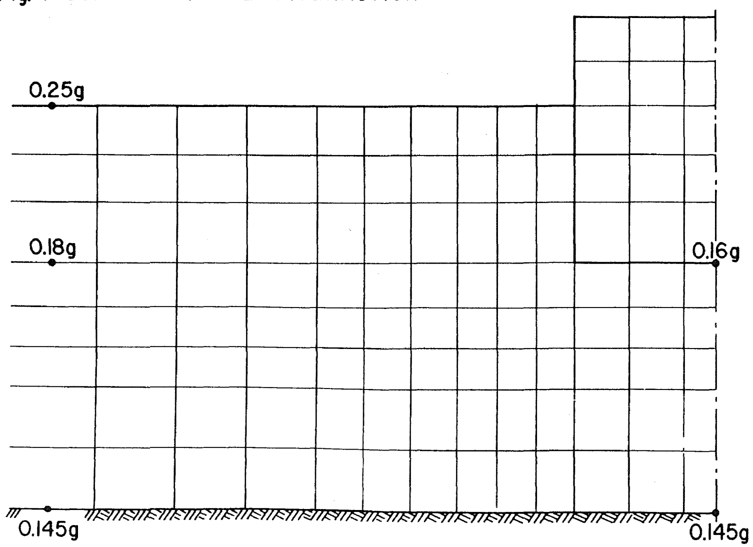

Fig. 2 FINITE ELEMENT MODEL OF SOIL-STRUCTURE SYSTEM

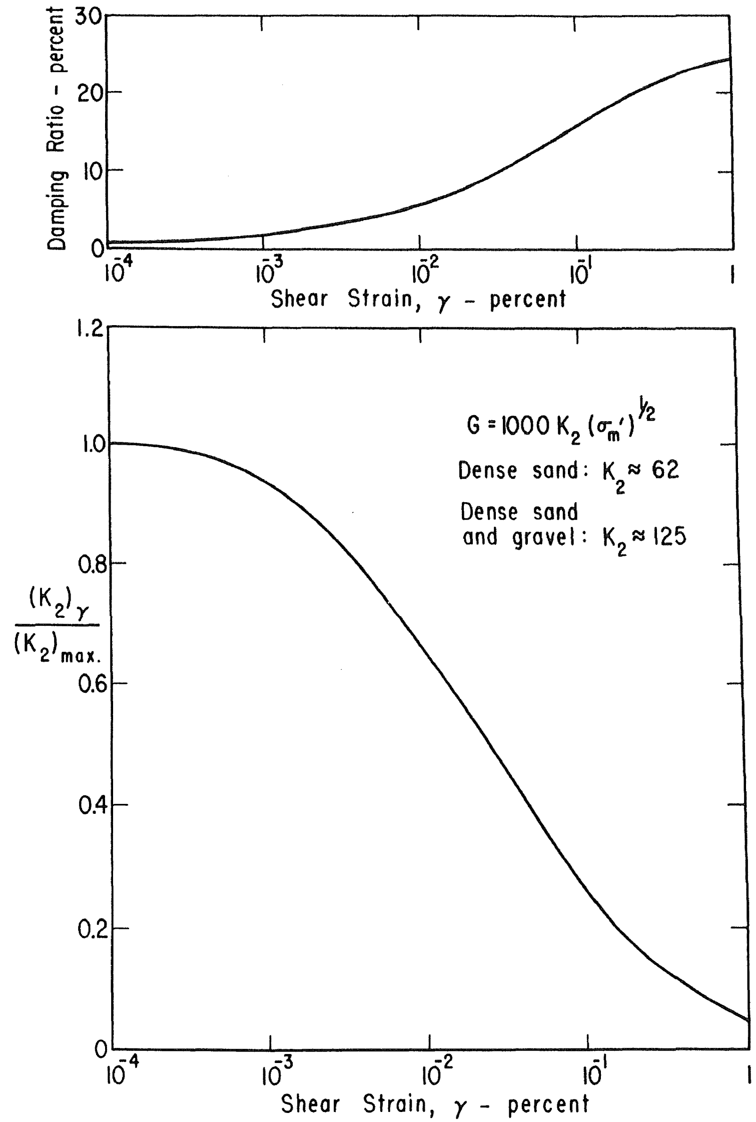

Fig. 3 AVERAGE SHEAR MODULI AND DAMPING CHARACTERISTICS FOR COHESIONLESS SOILS

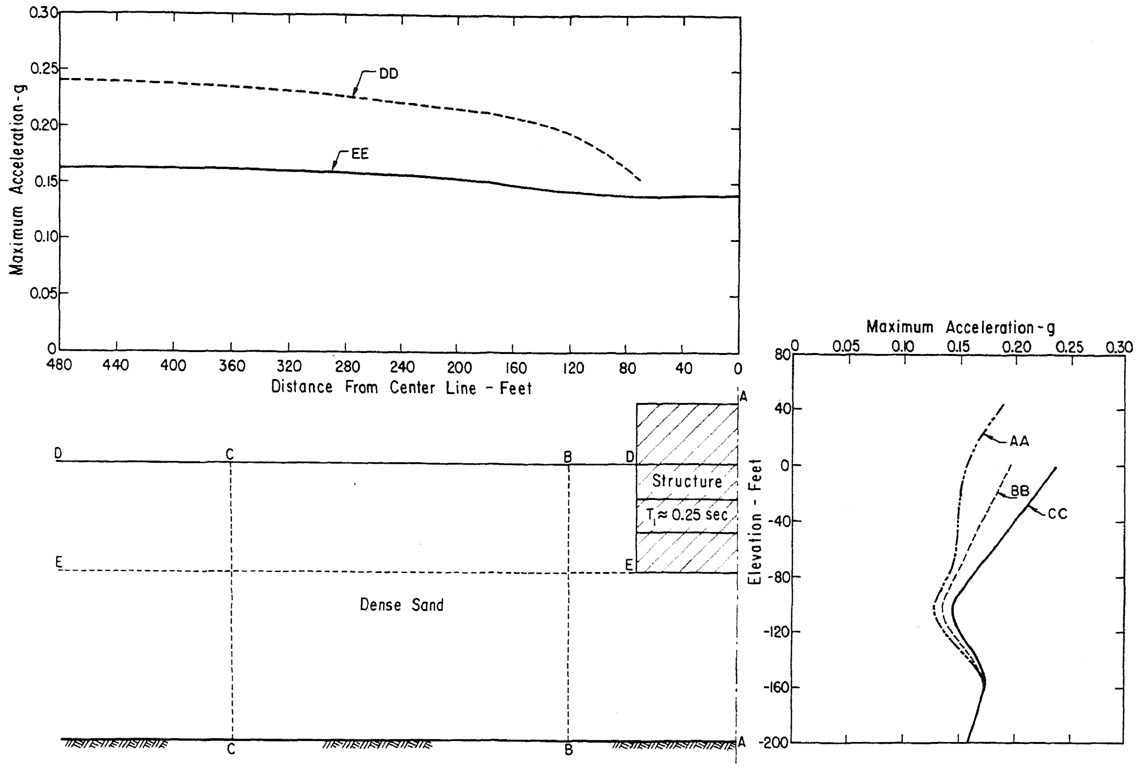

Fig. 4 RESPONSE VALUES FOR CASE A-1

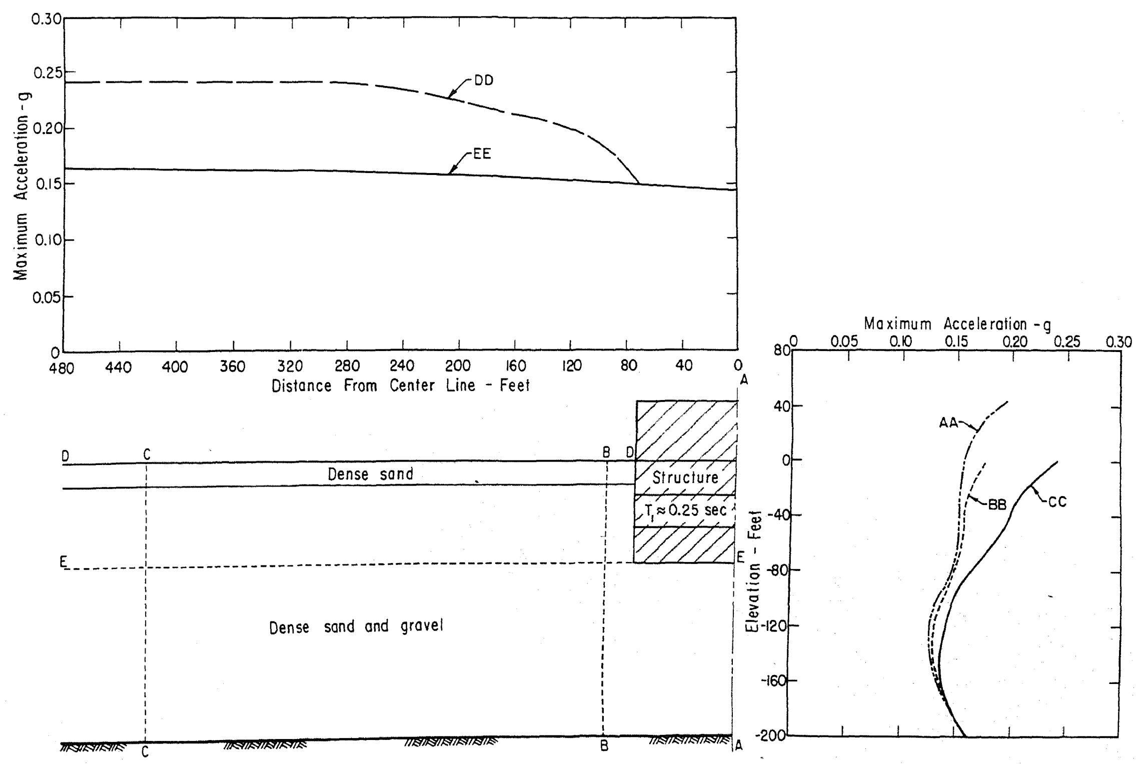

Fig. 5 RESPONSE VALUES FOR CASE A-2

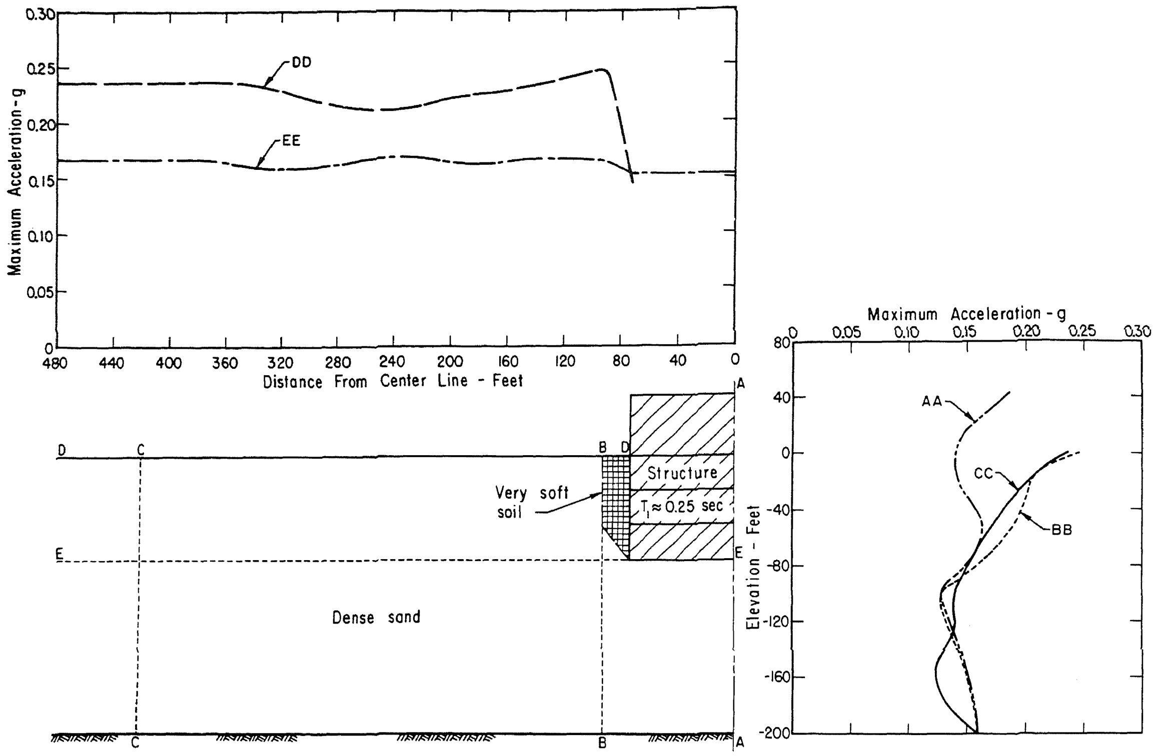

Fig. 6 RESPONSE VALUES FOR CASE A-3

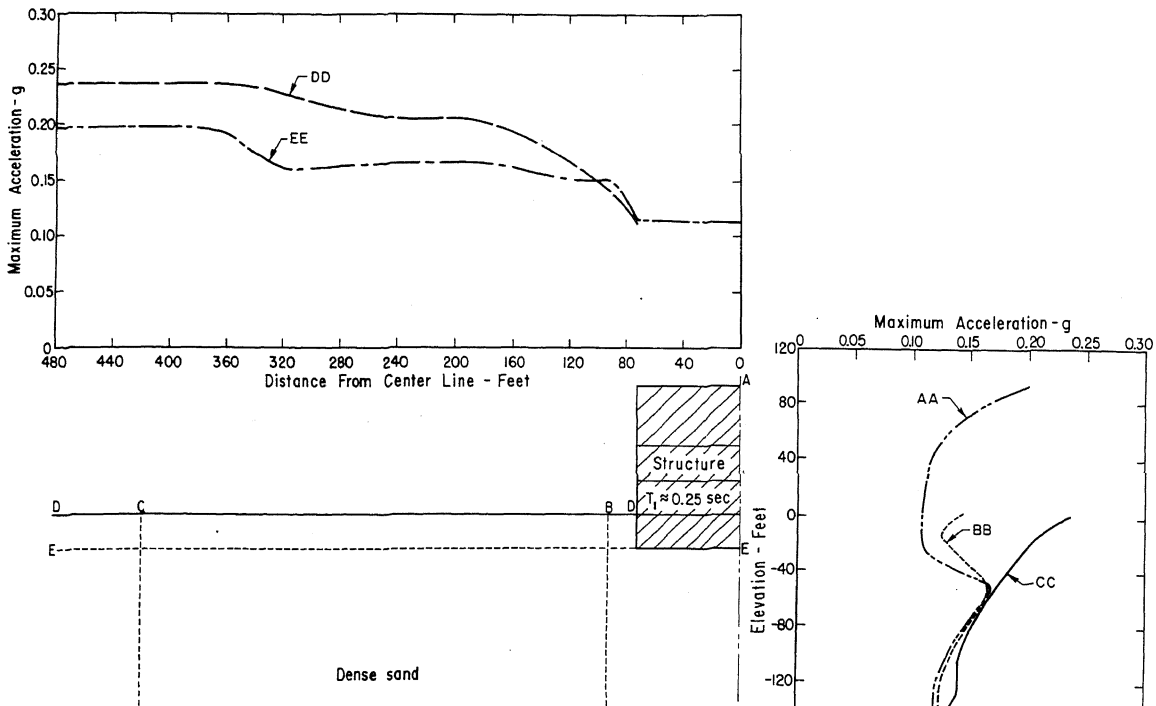

Fig. 7 RESPONSE VALUES FOR CASE A-4

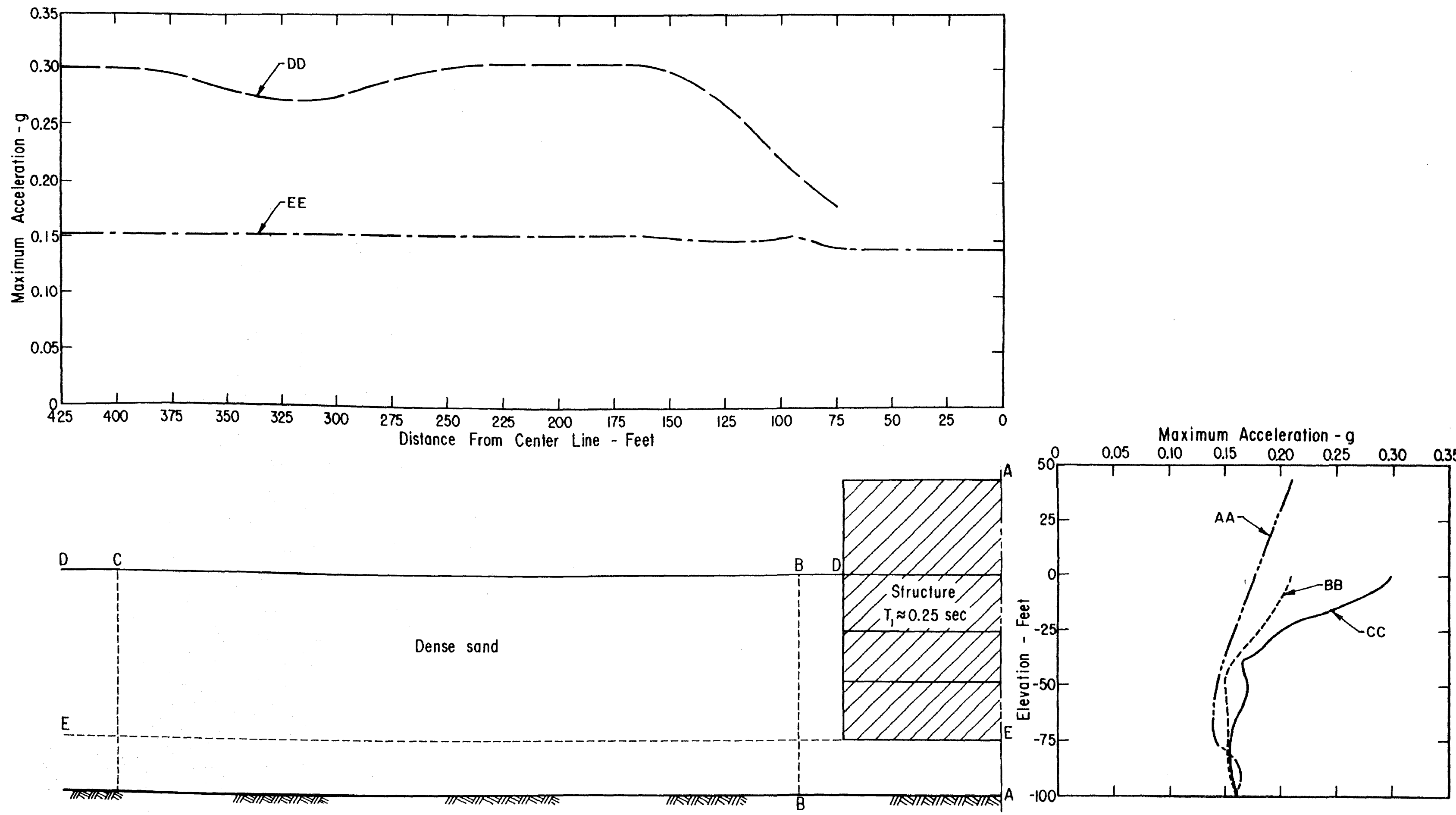

Fig. 8 RESPONSE VALUES FOR CASE B-1

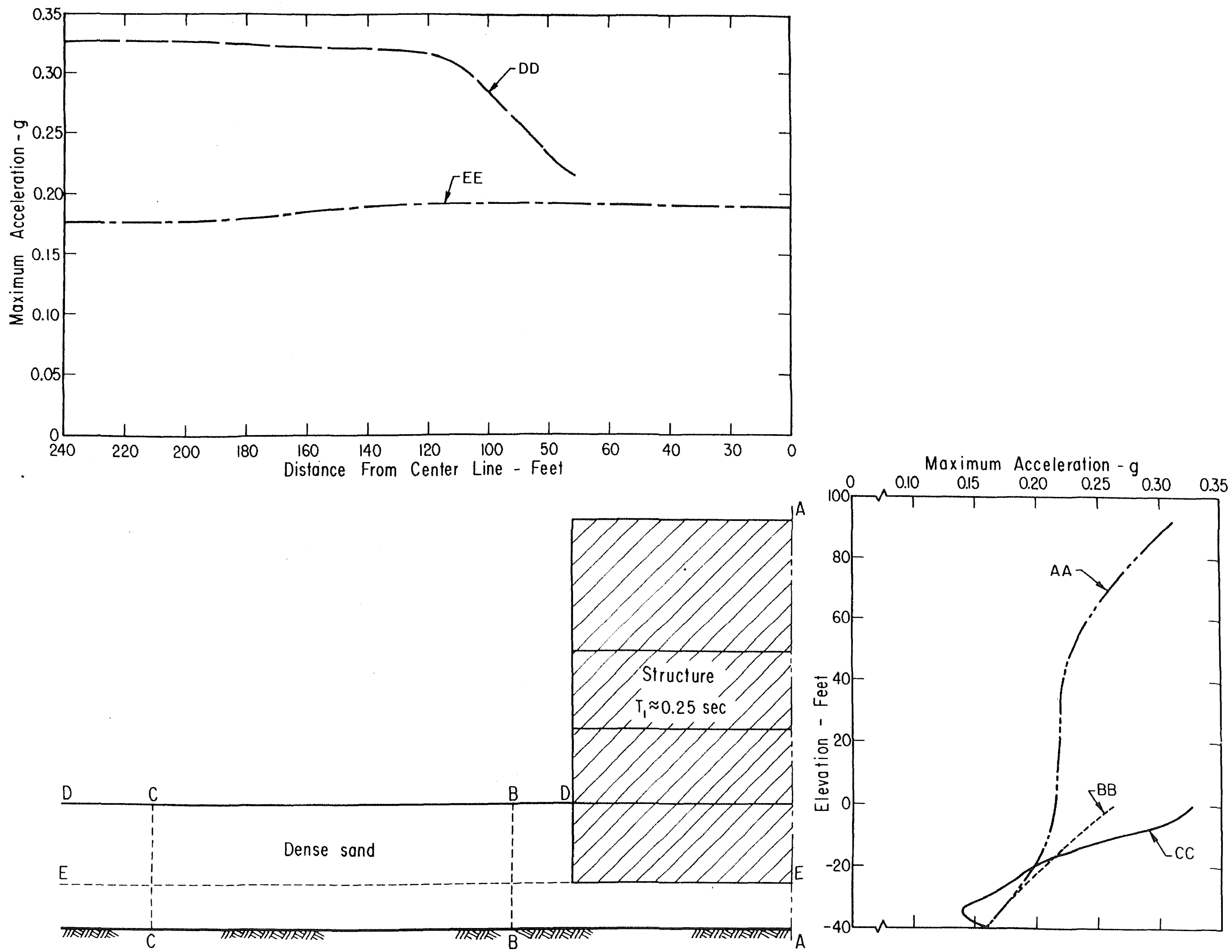

Fig. 9 RESPONSE VALUES FOR CASE C-1