An investigation of dynamic soil-structure interaction as it relates to the design of foundation systems for microelectronics fabrication facilities

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ABSTRACT

In recent years, vibration has become increasingly important as a factor to consider in the design of microelectronics fabrication facilities. As the demand for higher precision tools increases, the importance of vibration control also increases. In fact, at the present time, many aspects of structure/foundation design are controlled by vibration considerations rather than the traditional needs for load-carrying capacity. Vibration design involves geotechnical considerations such as site soils characteristics, soil type, depth of soil medium to bedrock; foundation considerations such as native soil preparation, fill material selection and preparation, types of foundation; and structural considerations such as the type of floor/column system, location of isolation breaks, etc.

This paper examines soil characteristics and foundation design considerations as they apply to vibration transmission and performance in a typical fabrication facility. Dynamic soil-structure interaction analysis is employed to perform a parametric study of the important geotechnical factors affecting vibration performance of such a facility. Different foundation types are investigated in an attempt to arrive at optimum foundation design systems for various areas of the facility. Guidelines are provided in the areas of site selection, soil preparation, and foundation design.

Keywords: foundation design, microelectronics facility, vibration, site selection, dynamic soil-structure interaction

1. INTRODUCTION

Site geotechnical characteristics and a foundation design can play an important role in the final vibration performance of a typical vibration-sensitive building such as microelectronics facility. Several authors[1,2] have investigated some aspects of this issue in past years. However, questions still remain as to the dynamic response of structures (i.e. different foundations), and the interaction between site soil parameters and these foundations.

In the analysis of dynamic soil-structure interaction, two general approaches have been developed during the past three decades as discussed in depth by Gazetas[3]. One approach, known as the "continuum" method, has led to the development of analytical and semi-analytical closed-form formulations. The second method, called the "discrete" approach, has resulted in the development of finite-difference and, primarily, finite-element models. Both these approaches have inherent limitations in their application to dynamic soil-structure interaction problems. The continuum approach creates complexity with respect to inclusion of different boundary conditions; on the other hand, the finite element method requires extensive computer time and capabilities which are beyond the means of conventional desk top computers.

A third approach, which had been widely used in static applications[4], has been developed and applied to dynamic soil-structure interaction problems. This approach utilizes an idealized soil model to represent the soil medium. Using this approach, a dynamic two-parameter model has been developed by Bayat[5] which evaluates the dynamic response of a strip beam foundation resting on a soil medium underlain by rigid bedrock. In the formulation, the beam is represented by its flexural rigidity and mass density to allows dynamic interaction between the beam and the soil medium. In this paper, a modified version of this beam-soil model has been developed. The modification of the model allows for the inclusion of pile foundations or spread footings, as shown in figure 1.

2. DYNAMIC SOIL MODEL

Dynamic soil-structure interaction for an elastic beam resting on a finite soil medium has been investigated by Bayat in Ref. 5. In this reference, a dynamic two-parameter model was developed to represent the soil medium. Additionally, the soil model assumes the following to apply:

1. The soil stratum is a visco-elastic medium underlain by rigid bedrock.
2. The soil medium is comprised of homogeneous and isotropic layers with material damping of the frequency-independent hysteretic type. The program developed based on this approach is capable of handling non-homogeneous conditions. This capability can be useful since, in general, the soil shear modulus tends to increase with soil depth due to increase in overburden pressure.
3. The plane-strain condition applies to the model. Based on this assumption, the soil stratum and all the foundation types (i.e. mat, pile, and spread footings) are infinitely long or stiff in the out-of-plane direction. This assumption generally produces conservative results.

The governing equation for this model in the region of soil overlapping a mat foundation can be written as

$$[EI]\{d^4W/dX^4\} - [N]\{d^2W/dX^2\} + [K_I]\{W\} = \{P\} \tag{1}$$

Where,

$[K_I] = [[K] - \omega^2[M] - \omega^2[M_b]]$
$[EI]$ = Beam flexural rigidity matrix (diagonal)
$[N]$, $[K]$, & $[M]$ = Dynamic two-parameter model representing soil medium
$[M_b]$ = Beam mass matrix (diagonal)
ω = Frequency of vibration
$\{W\}$ = Vector containing vertical displacement responses
$\{P\}$ = Vector containing the dynamic external forces

Matrices [N], [K], and [M] are assembled based on soil parameters of modulus of elasticity, poisson's ratio, soil depth to bedrock, material damping, and mass density. These parameters are readily available from geotechnical reports for a prospective site.

Equation (1), without the [EI] term, applies to soil regions with no beam:

$$- [N]\{d^2W/dX^2\} + [K_s]\{W\} = \{0\} \tag{2}$$

Where,

$[K_s] = [[K] - \omega^2[M]]$

Similar formulations can also be developed for horizontal excitation. However, since the vertical component of the surface waves (i.e. Rayleigh waves) is more dominating, we limit our study to this direction of excitation.

The above model has been modified to allow for the inclusion of pile foundations or spread footings. Pile or spread footing is formulated by assuming that they behave as axial members in the vertical direction. Thus, piles or spread footings interact with surrounding soils through shear force interactions (i.e. skin friction) and end bearing.

3. SOIL PARAMETRIC STUDY

The soil geotechnical characteristics undoubtedly play an important role in the transmission of micro vibration within the soil medium. Questions such as "what is the ideal soil type for micro vibration" have often been confronted in selection of a site, and later on, in determining the vibration levels in a typical microelectronics facility. For instance, a vibration engineer often needs to decide on the location of many mechanical sources, such as chillers and pumps, relative to the vibration-sensitive areas (commonly called "Fab" areas) in such a facility. Allowing for adequate distance between the source and the Fab area is of critical importance. Of course, all these questions require a better understanding of the soil vibration performance.

Figure 2 includes the configuration of soil and foundation systems which have been used for the parametric study. Two types of soils representing a "weak" and a "strong" soil have been studied. For each of these two soil types, the study includes variations in soil depth (H) from a "shallow" to a "deep" condition. In the study, the vibration excitation is applied to a pile foundation. The vibration response is computed at the nearest edge of the mat foundation (point A) as indicated in Figure 2. This represents a common case where the Fab floor is supported on a mat foundation, and the vibration sources such as chillers, pumps, etc. are supported on piles at a distance from the Fab floor. The soil and foundation parameters are defined as follows:

γ = Weight density of soil or foundation
ν = Poissons's ratio of soil
G = shear modulus of soil
$V_S = \sqrt{Gg/\gamma}$ = Shear wave velocity
η = Soil or foundation damping
E = Young modulus of foundations (beam, pile or spread footing)
I = Moment of inertia of beam (mat foundation)
P = The amplitude of the excitation force

In Figure 3, we show the non-dimensionalized displacement response (GW/P) at the edge of the mat foundation (i.e. the horizontal beam) as a function of the soil depth to wavelength ratio (H/λ). For this figure, we provide the following comments:

- The soil response at the edge of the mat (i.e. point A) due to excitation on the pile is more pronounced for the stronger soil with greater depth (case 4). In other words, the weaker soil provides less of a coupling with the pile through skin friction and end bearing. In addition, in the deep soil cases, the ratio of the pile length to soil depth is small (i.e. 3/16). As this ratio decreases, the soil surface response increases.
- For shallow soil depth, the soil response at point A is almost the same for both weak and strong soils. This could be due to the fact that the ratio of pile length to soil depth is very high (3/4). As it is seen later on in section 5 of this paper, when the ratio of the pile length to soil depth is high, most vibration energy is transmitted to the deeper soil and the bedrock. As a result, the maximum soil response on the soil surface (i.e. point A) is greatly improved and stabilized. By stabilized response, we mean that the soil characteristics do not affect the response to any significant degree.
- In comparing deep vs. shallow soil conditions, the response at point A due to excitation on the pile is significantly increased for the deeper soil. This is due to the fact that the ratio of pile length to soil depth is decreased in the case of deep soils (cases 2 and 4).

4. DYNAMIC SOIL-FOUNDATION INTERACTION (HORIZONTAL SEPARATION)

In this section, we examine the horizontal separation between the source and the receiver foundations. Additionally, we vary the configuration for the source foundation at each separation distance. As in the previous section, we take the mat foundation to be the receiver foundation. Again, this is the more common practice where soils conditions permit the use of mat foundations. Figure 4 shows the cases studied. The excitation has been applied at three locations as shown. The displacement response is again calculated at the edge of the mat foundation at point A. Figures 5 and 6 compare the non-dimensional displacement response as a function of soil depth to wavelength ratio. In Figures 5 and 6, the excitation is applied at 20 and 50 feet from the edge of the mat foundation, respectively. At each excitation location, three different source foundations (i.e. short pile, long pile, and spread footing) have been studied, as shown in Figure 4. From these figures, we can make the following comments:

- Response at point A due to excitation at locations 2 and 3 is considerably less than for the case where the force is applied at location 1 (i.e. at the edge of the mat foundation). This response due to source at locations 2 or 3 is not very sensitive to the foundation configuration at these locations. The maximum response at the first soil resonance frequency is decreased by about 10 percent from the spread footing case to the 30 foot long pile. As discussed in section 3, greater improvements are achieved when the pile length to soil depth ratio is high. In the cases studied in Figure 4, this ratio varies from 13% (for embedded spread footing) to 30% (for 30 foot long pile).

- Comparing Figures 5 and 6, the maximum response at point A is only decreased by about 10 percent by increasing the separation distance from 20 feet to 50 feet. This is reasonable for a plane strain condition, since the excitation is infinitely long in the out-of-plane direction (i.e. the geometric attenuation of Rayleigh waves does not exist for line sources). In non plane strain condition, significantly higher attenuation will be achieved by increasing the horizontal separation.
- The soil resonance is slightly shifted to the left for the cases with excitation at locations 2 and 3 as compared to location 1. This means that the wavelength at which the soil resonance occurs is slightly longer for cases with excitation at locations 2 and 3 as compared to location 1.

5. DYNAMIC SOIL-FOUNDATION INTERACTION (VERTICAL SEPARATION)

Another issue that we often encounter in a design is whether or not to provide vertical separation between the source and the receiver foundations. For instance, a typical microelectronics facility might have Structural Isolation Breaks (SIBs) between the process Fab floor and the shell structure (i.e. the roof of the facility where most recirculation and make-up air handling units are located). A question often raised is whether the columns for the shell structure, which are potential sources of vibration, should share the same foundation as the Fab floor structure. Even if we decide on separate foundations, is there any benefit to gain by creating vertical separation between these foundations? It should be noted that in this practical problem, the horizontal separation between the Fab floor outer columns and the shell structure columns often is only a few inches. In Figure 7, we depict a case study that resembles this problem. The horizontal distance between the edge of the mat foundation and the source foundation is assigned to be one foot. Three different pile lengths extending from 30 feet to the full depth of the soil medium have been selected. The top of the pile is located at 0, 5, and 10 feet from the top of the soil; thus providing vertical separation. The excitation is applied at the top of the pile. The results from these cases are compared to the case where the vibration force is applied at the edge of the mat (i.e. representing the case where both the receiver and the source share the same foundation).

Figure 8 compares the response at point A due to a load applied at the edge of the mat and on top of a 30-foot long pile. Figure 9 is the same as Figure 8 except that the pile length is 60 feet. Both these figures indicate that substantial improvements are gained by providing separate foundations for the receiver and the source structures. Minor improvements may also be gained by embedding the source foundation. In this case, the decrease in the maximum response is about 5 to 10 percent.

Figure 10 shows the response at point A due to excitation applied to the edge of the mat and on different foundation configurations. All the source foundations here are flush with the surface of the soil (i.e. the top of these foundations are not embedded in the soil). In this figure, in addition to pile lengths of 30, 60, and 100 feet, we have included two cases with the source foundation being spread footings (cases 9 and 10 in Figure 7). Again this figure shows that substantial decrease in the response of the soil at point A is achieved by using pile foundations with longer length. It is clear that the increase in pile length (i.e. increase in pile length to soil depth ratio) results in significant improvements in the soil response at point A. Another way to interpret this is that the spread footing (cases 9 and 10) apply the excitation to the soil surface, where as the piles (cases 2, 5, and 8) transmit the vibration energy to the deeper soil and the bedrock. As case 8 curve indicates, in the extreme case of pile bearing against the rigid bedrock, the vibration energy is directly transferred to rigid bedrock with little interaction between the soil medium and the pile. On the other hand, in the other extreme cases (9 and 10), the excitation is applied to the soil surface resulting in soil response at point A approaching case 1 condition.

6. CONCLUSIONS

A dynamic two-parameter soil model has been employed to study the effects of soil parameters and the interaction between different foundation types in a vibration-sensitive facility. The model is capable of including foundations such as mat, pile, and spread footings at different locations along the soil surface or embedded within the soil medium. This allows us to study the dynamic interaction between different foundation systems at varying horizontal and vertical separations. Based on the studies performed in this paper, we conclude the following:

- The cases analyzed indicate that improvement is achieved by providing separate foundations for the source and the receiver structures. This improvement is significantly increased when the source foundation is pile having greater length (i.e. high pile length to soil depth ratio, perhaps > 50%). In general, vertical separation produces significant improvement either through embedment of foundation or increase in pile length. Of course, there are practical limitations in increasing embedment to a level that would be as effective as a pile with higher length.
- The model indicates that minor improvements are gained by increasing the horizontal separation. In light of the fact that the model is based on the plane-strain condition where the vibration sources resemble a line excitation rather than a point source, we may state that, in actuality, more significant improvements would be recognized for point sources by increasing the horizontal separation between the sources and the vibration-sensitive foundation. This option should be exercised where possible to attenuate the vibration due to point sources such as pumps, chillers, etc.
- A weaker soil provides less of a coupling between the source and the receiver foundations. Hence, the response at the vibration-sensitive (or receiver) foundation is less for the weaker soil. Of course, the case analyzed here is for ideal case. In actual cases, the weaker soil is normally associated with a shallow water table level, and settlement problems which makes it unsuitable for mat foundations, etc.
- In addition to above conclusion, we should emphasize the importance of site soil preparation to accept these foundations once they have been selected. Adequate native soil recompaction, selection and compaction (to high level of compaction effort) of proper fill material will undoubtedly eliminate potential amplification of the ground vibration through the foundation structural resonances.

7. REFERENCES

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Figure 1. Soil-Foundation Model

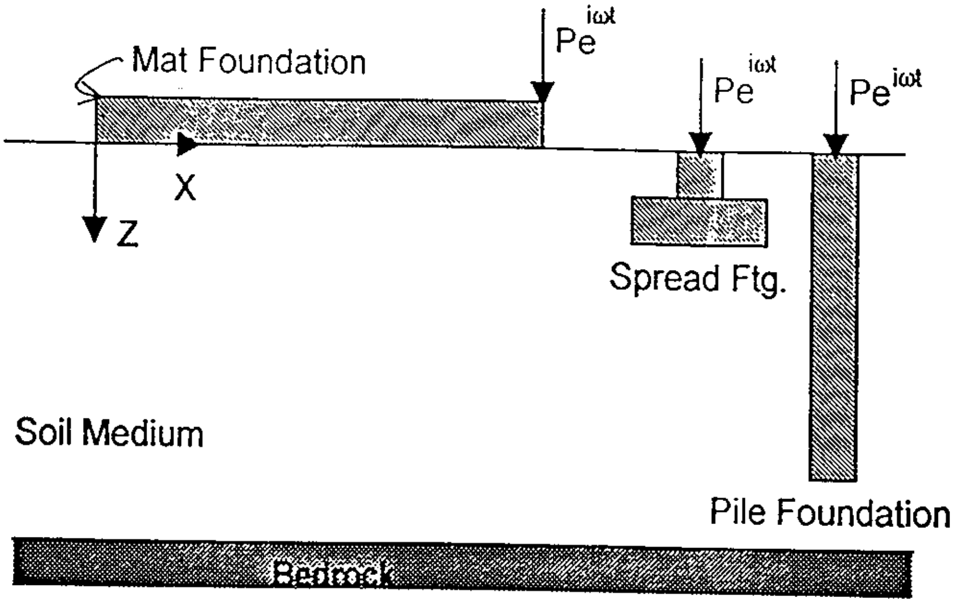


Figure 2. Soil Parametric Study

Weak Soil
γ = 90 pcf
ν = 0.30
$G = 0.144\times10^{6}$ psf
Vs = 226 ft/sec
η = 0.02

Strong Soil
γ = 110 pcf
ν = 0.30
$G = 1.44\times10^{6}$ psf
Vs = 650 ft/sec
η = 0.02

Cases Analyzed:

Case No.	Condition	H
1	Weak soil	40'
2	Weak soil	160'
3	Strong soil	40'
4	Strong soil	160'

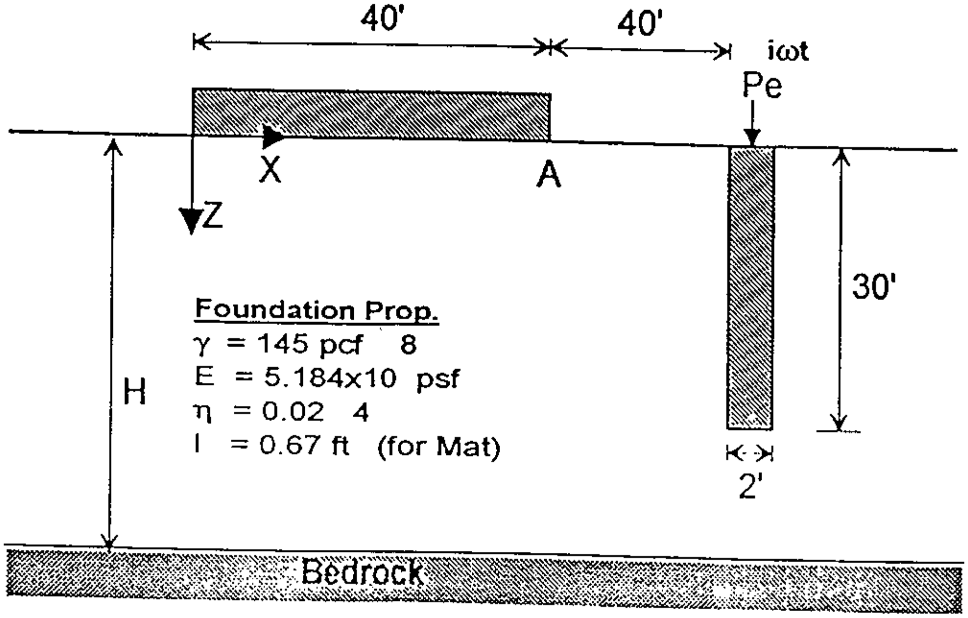


Figure 3: Soil Parametric Study

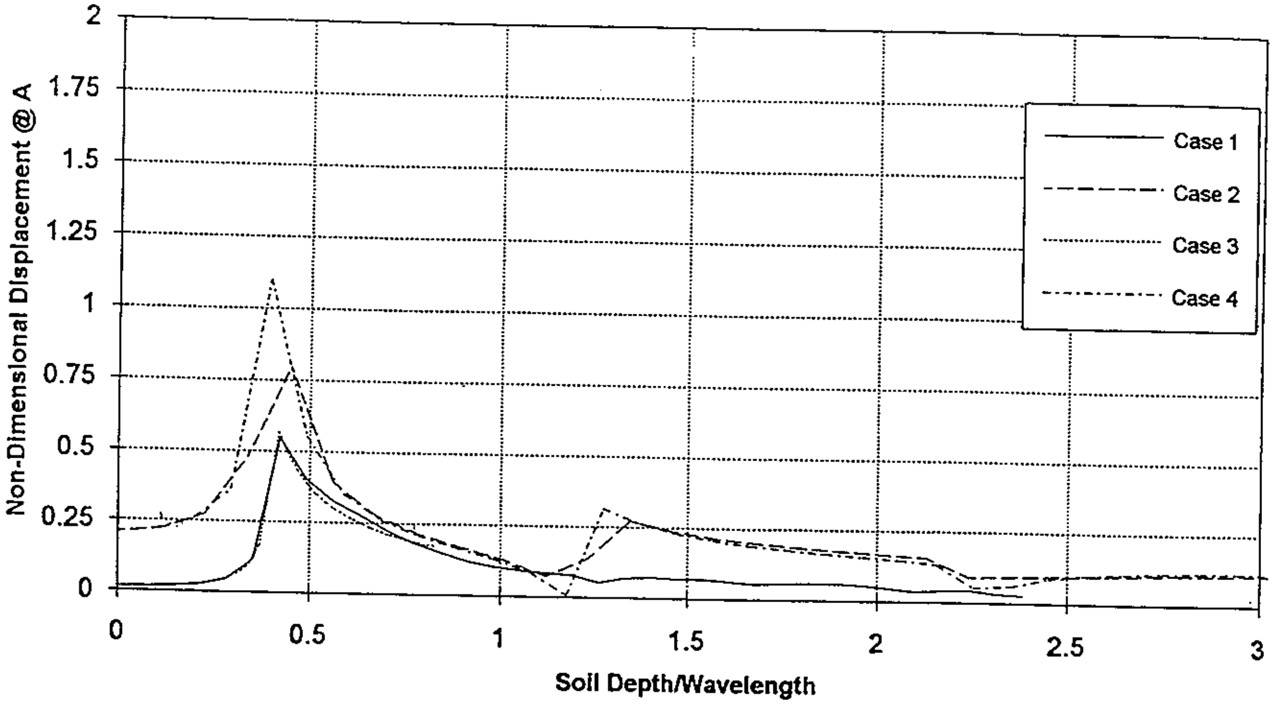
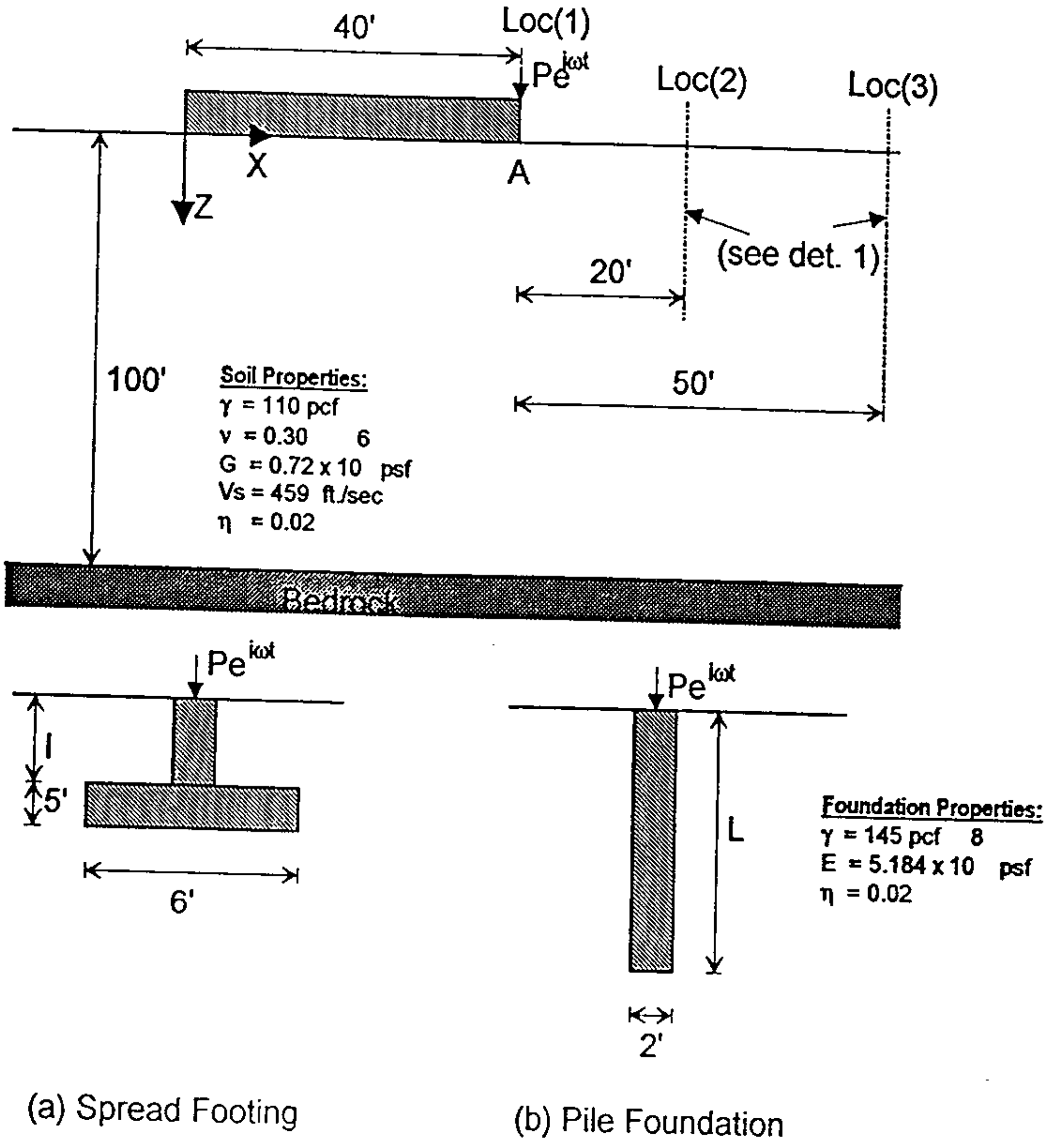


Figure 4. Dynamic Soil-Foundation Interaction (Horizontal Separation)

Cases Analyzed:

Case No.	Load Applied at	L	l
1	Loc(1)	–	–
2a	Loc(2) on Pile	15'	–
2b	Loc(2) on Pile	30'	–
2c	Loc(2) on Spread Ftg.	–	8'
3a	Loc(3) on Pile	15'	–
3b	Loc(3) on Pile	30'	–
3c	Loc(3) on Spread Ftg.	–	8'



Soil Properties:
γ = 110 pcf
ν = 0.30
G = 0.72×10^6 psf
Vs = 459 ft./sec
η = 0.02

Foundation Properties:
γ = 145 pcf
E = 5.184×10^8 psf
η = 0.02

(a) Spread Footing

(b) Pile Foundation

Detail 1

Figure 5: Dynamic Soil-Foundation Interaction
(20' Horizontal Separation)

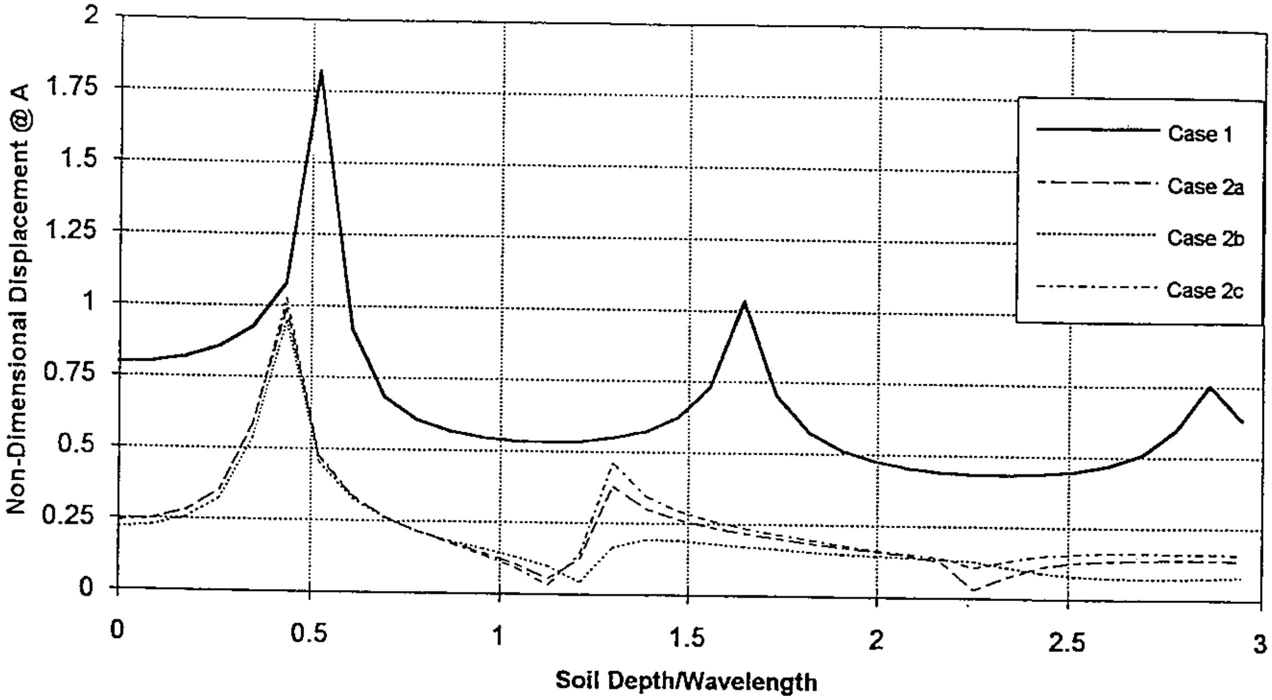


Figure 6: Dynamic Soil-Foundation Interaction
(50' Horizontal Separation)

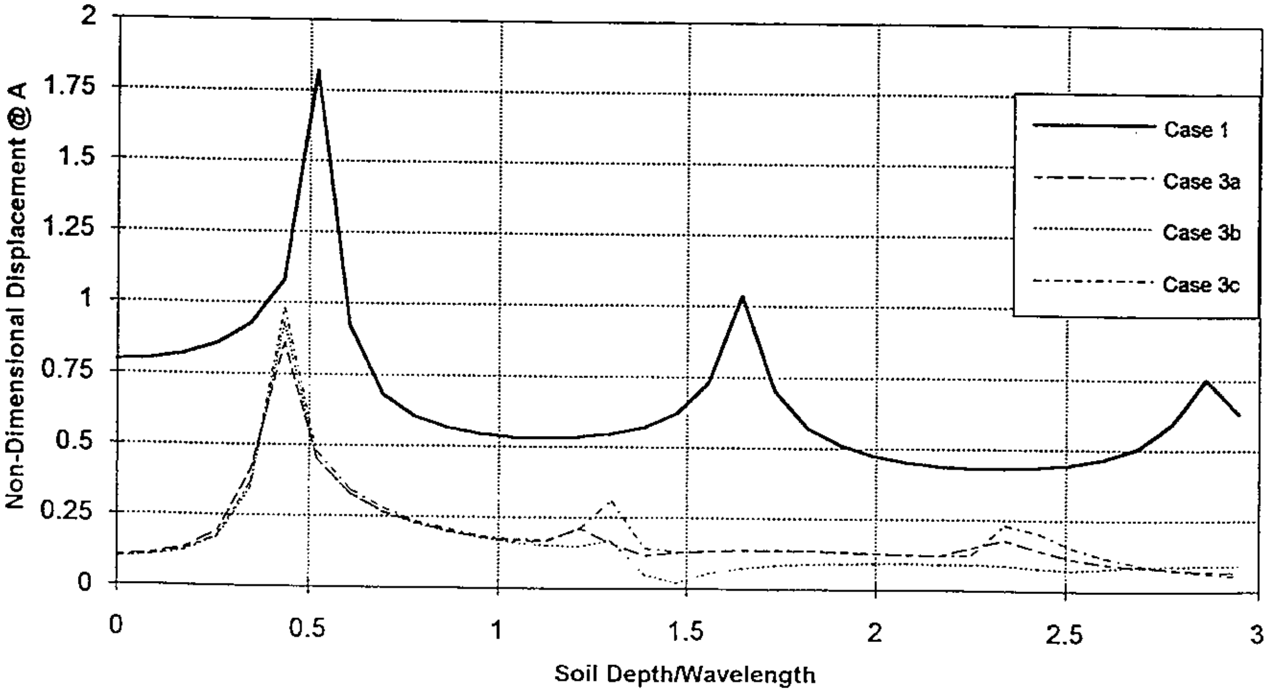
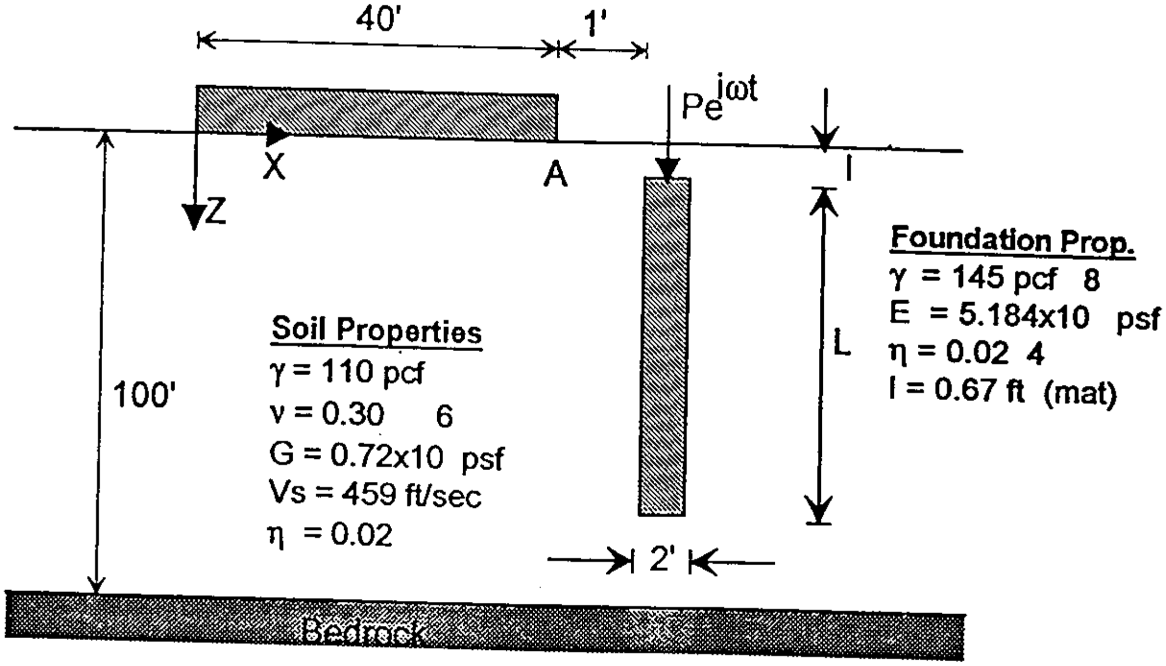
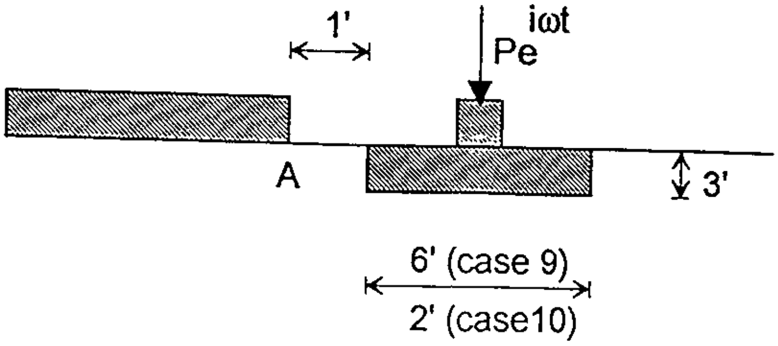


Figure 7. Dynamic Soil-Foundation Interaction (Vertical Separation)

Cases Analyzed:

Case No.	Load Applied at	L	l
1	At Point A on Mat	–	–
2	On Pile	30'	0'
3	On Pile	30'	5'
4	On Pile	30'	10'
5	On Pile	60'	0'
6	On Pile	60'	5'
7	On Pile	60'	10'
8	On Pile	100'	0'
9	On Spread Ftg.	–	–
10	On Spread Ftg.	–	–





Partial Details for Cases 9 & 10

Figure 8: Dynamic Soil-Foundation Interaction (Vertical Separation)
Source Foundation =30' Long Pile

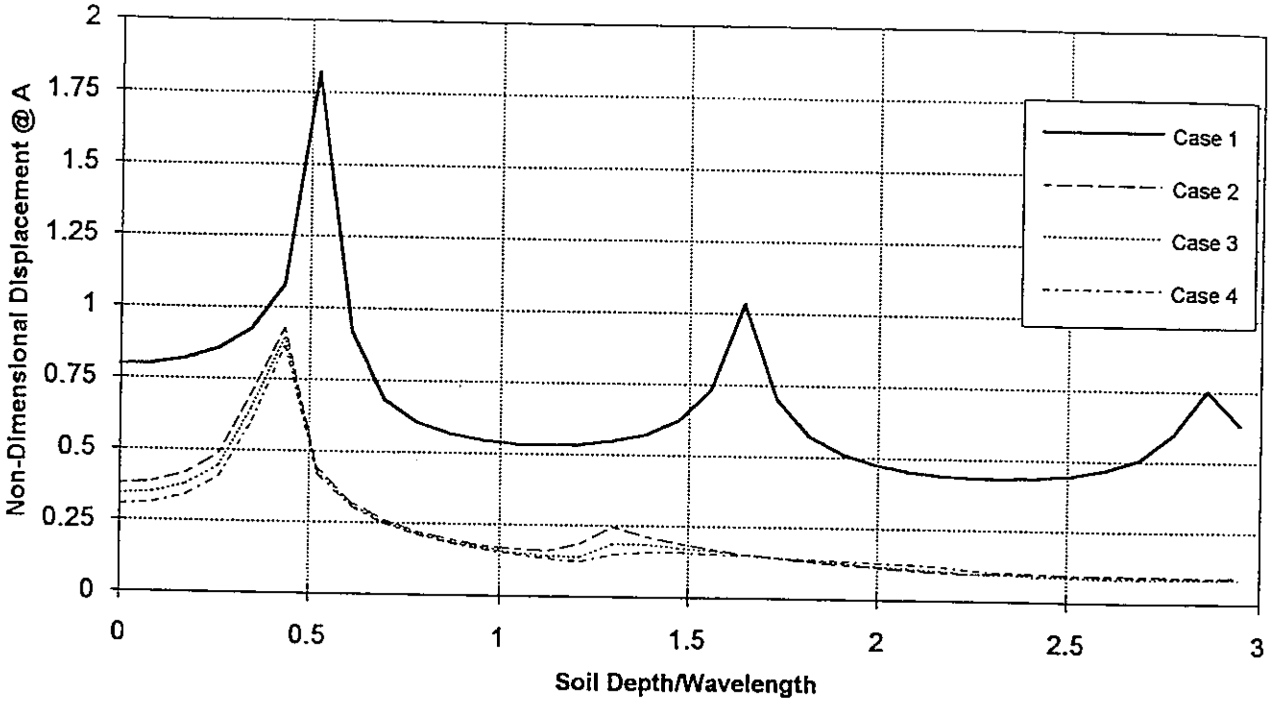


Figure 9: Dynamic Soil-Foundation Interaction (Vertical Separation)
Source Foundation=60'Long Pile

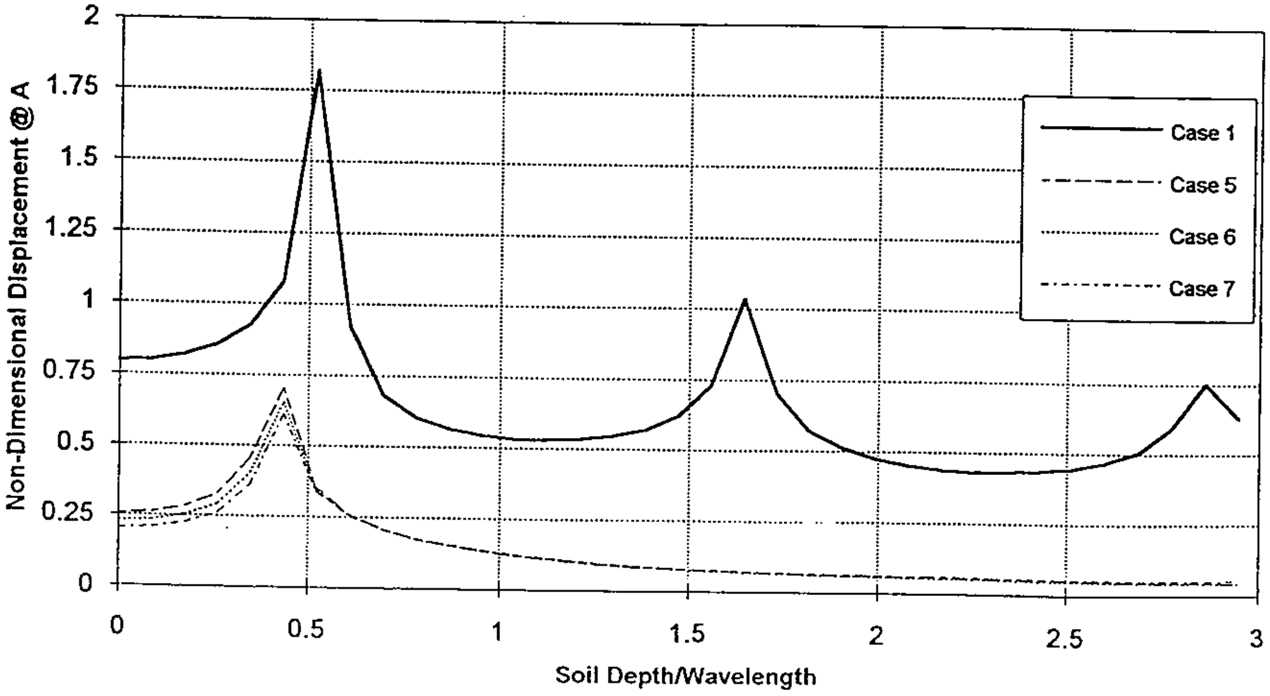


Figure 10: Dynamic Soil-Foundation Interaction (Vertical Separation)
Different Source Foundations