ASSESSMENT OF SEISMIC
WAVE EFFECTS ON SOIL-STRUCTURE INTERACTION*

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SUMMARY

One of the most common hypotheses made for soil-structure interaction analyses is that the earthquake input motion is identical at all points beneath the structure. Several papers have recently shown that this assumption may be overly conservative and that the effect of wave passage is extremely important. These studies typically employ a relatively simple model, namely, the basement is represented by a rectangular rigid foundation resting on top of the soil and connected to the soil by a continuously distributed set of soil springs. The seismic input is applied at the base of the soil springs and is assumed to be traveling at a constant wave velocity across the site. It is possible to improve on the soil/structure model by use of finite element methods; however, little is known about how to model the input seismic energy and typically a simple traveling wave is used. In this paper, we examine the available data to determine: (i) the appropriate wave velocity to use, and (ii) if the currently available analytic models are adequate.

The choice of the appropriate apparent wave velocity to use in the analysis is not simple because in the near field of an earthquake, a number of complex arrivals give rise to the strong motion. These arrivals would be associated with the high apparent wave velocities of the lower layers, whereas, the surface wave arrivals would be associated with the much lower wave velocities of the near surface layers. Because strong motion instruments are triggered at some threshold level, it is not possible to make reasonable estimates of the appropriate wave velocities to use from the available earthquake data. Considerable data exists from underground nuclear explosions. This data was analyzed and shows that the appropriate velocity to use relative to wave passage as observed by various surface accelerometers is much higher than the near surface values. This high apparent wave train velocity is observed out to at least 10 times the depth of energy release.

The adequacy of the currently proposed methods of analysis was qualitatively determined by comparing the overall response of structures to real traveling waves to that predicted qualitatively by the various models. Although few cases exist of strong motion recorded both in buildings and nearby in the free field, there are a number of cases where groups of buildings with different basement areas have recorded data. By comparing buildings in the same general area with different basement areas, the lack of free field motion is minimized. The adequacy of current theoretical models is obtained by contrasting the differences in foundation level spectra between structures of different basement areas to the variation predicted by the currently available methods.

The results are mixed. If the apparent seismic wave velocity is taken to be that of the upper layers (approximately 2000 ft/s) then the theory predicts considerable difference in response for buildings with different basement areas. If, as suggested by the data from underground nuclear explosions, the apparent wave velocity is much higher than the upper layers, then the theory predicts only small changes in the spectra between buildings of different basement areas. Actual comparisons of the foundation level spectra between buildings is also mixed. It appears we are seeing many complex effects that clearly cannot be lumped together in a simple averaging scheme.

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1. INTRODUCTION

It is normally assumed in the seismic analysis of structures that the free-field motion which is used as input is the same for all points on a given level beneath the foundation mat. This represents a simplification, as not all particles of soil describe the same motion simultaneously. As the foundation mat of the structure is rigid in the horizontal direction, it will tend to average the ground motion. Abandoning the assumption of the uniformity of the input motion may lead to a reduction of the translational motion which a foundation mat will experience, as the displacement components will cancel each other to a certain extent. This is of considerable interest for the design of nuclear power plants which are very stiff, large structures.

To investigate these effects, the extremely complex phenomenon of the passage of a seismic wave has to be simplified considerably. Typically, the basemat is assumed to be rigid, and the soil is represented by simple soil springs, e.g., Scanlan [1] shows that averaging a passing compressive wave for which the directions of wave propagation and seismic motion coincide results in a different effective "single-point" earthquake, which shakes the structure in the classical manner used for seismic analysis.

Newmark [2] and Yamahara [3] use slightly different approaches to derive at the same basic results as Scanlan. Both Newmark and Yamahara present some data to support their basic results. Because of the potential importance of wave passage and the fact that a number of simplification must be introduced into the analysis, it would be useful to determine if the phenomenon actually exists. It is the purpose of this paper to determine if wave passage effects can be determined from the simplified analyses currently used.

2. REVIEW OF BASIC THEORY AND RESULTS

A number of slightly different approaches have been used to develop the basic theory. Scanlan [1] is the most complete and reasonably typical. Hence, his model and results can be used to identify the main simplifying assumptions common to most models and to obtain an order of magnitude estimate of the reduction of the free-field ground motion projected by the theory.

In Scanlan's [1] model, the basemat is represented by a rectangular rigid foundation resting on top of the soil and connected to the soil by a continuously distributed set of soil springs. The seismic input is applied at the base of the soil springs and is assumed to be of the form

$$u(t) = \sum A_n \cos \left( \omega_n t + \phi_n - \frac{\omega_n}{C_s} \right)$$

where

$$\sum A_n \cos (\omega_n t + \phi_n) = \text{Fourier expansion of surface accelerogram}$$

$$C_s = \text{appropriate wave train velocity.}$$

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The term $\omega_n^2 x/C$ in eq. (1) approximates the fact that the wave train is traveling across the site.

Scanlan considers two cases: the first case is when the soil particle motion is in the same direction as the wave is traveling; and the second case is when the soil particle motion is transverse to the direction of the wave motion. Scanlan shows that the traveling wave can be replaced by an averaged time history applied simultaneously at the base of the soil springs. Scanlan found that for both cases that

$$\bar{u}(t) = \sum A_n \cos \left( \omega_n t + \phi_n - \psi_n \right)$$

(2)

where

$$A_n = \frac{2(1 - \cos \theta_n)}{R_n^2}^{1/2} \quad A_n$$

$$R_n = \frac{\omega_n L}{C_s}$$

$$\tan \psi_n = \frac{1 - \cos \theta_n}{\sin \theta_n}$$

$C_s$ = appropriate wave velocity

$L$ = foundation dimension

A plot of $A_n/A_n$ is shown on Figure 1. The important thing to note from Figure 1 is that the theory predicts that the net effect of the traveling wave is to effectively reduce the "higher frequencies." High frequencies in this case are defined relative to the average traveling wave train velocity and the foundation dimension $L$.

In addition, Scanlan found that a torsional motion would be excited even in symmetric structures. This torsional motion is generally not included in typical soil structure interaction analysis. For the symmetric case, there is of course, no torsional motions induced when the same motion is input at every point under the structure. Thus, it is not possible to come up with an expression completely equivalent to eq. (2). However, Scanlan shows that torsional behavior is very similar.

3. CHOICE OF AN APPROPRIATE WAVE VELOCITY

It is seen from eq. (2) and Figure 1 that the assumed wave train velocity is an extremely important parameter. If the important part of the ground motion is from surface waves, then the appropriate average velocity can be obtained. However, in the reasonably near field of an earthquake, a number of complex arrivals give rise to the strong motion. Thus, many of the arrivals recorded at two nearby instruments would be associated with the high apparent wave velocities of the lower layers.

Because strong motion instruments are typically triggered at some threshold level, little data exists from actual earthquakes which can be used to estimate the wave velocities associated with the strong motion. Considerable data exists from underground nuclear explosions which can be used to make reasonable estimates of the apparent wave train velocity.
Tamura et al. [4] and Tsuchida et al. [5] published results obtained from two different arrays of accelerometers located on soft alluvial ground. For both arrays, the apparent wave velocity was computed by obtaining the time lags from a cross-correlation of the records recorded at the various instruments. Tamura et al. [4] estimated a wave velocity of nearly 3km/sec as the wave velocity. Tsuchida et al. [5] obtained a somewhat greater variation in their results in that the wave velocity varied between 2.6 to 5.3 km/sec. It should be noted that these velocities are much larger than the wave velocities of the near surface layers.

Very similar results are obtained if data obtained from underground nuclear explosions is used. In this case, the recording arrays have a common time base. A number of different sets of data were examined and all gave similar results as obtained for the available earthquake data - namely the apparent wave velocity of the traveling wave train is much higher than the wave velocities of the near surface layers.

4. ANALYSIS OF AVAILABLE DATA

A number of assumptions were made in the various analyses of the wave passage effect, such as, Scanlan's model. The validity of many of these assumptions are difficult to determine. This suggests that it would be useful to assess the overall effect of wave passage on the response of structures. This can be done by qualitatively comparing the overall response of structures to real traveling waves to that predicted qualitatively by equation (2) to determine if it is important. There are at least two ways to do this. First, the most ideal case is to compare a free-field measurement with a measurement obtained in a building. Because so few cases where this is possible exist, we must also use a second method of comparing the response of an accelerometer located at the basemat of various groups of nearby buildings with different basemat areas. By comparing these to the theory, we should be able to determine if the effect is important.

One of the few useful cases is the comparison between the recording in the parking lot and in the Hollywood storage building during the San Fernando earthquake. Newmark [2] used this example as evidence for wave passage effects. Figure 2 gives a plot of the ratio of the Fourier Spectral amplitude of the parking lot motion divided by the motion recorded in the basement of the Hollywood storage building. Newmark [2] was able to predict the difference between the two spectra by using a wave velocity of 0.6 km/sec. The value of wave velocity used by Newmark is very low as compared with the experimentally obtained wave velocities discussed above.

Although few additional cases exist of strong motion recorded both in buildings and nearby in the free-field, there are a number of cases where groups of buildings with different basemat areas have recorded data. We can use eq. (2) to obtain an estimate of the effect various basemat areas. Figure 3 illustrates the averaging as a function of frequency that would be expected for an average wave velocity of $C_s = 0.6$ km/sec and 3 km/sec for structures of effective length of 100' and 300'. The ratio of the Fourier coefficients of the effective time histories for the two different structures is shown. From this figure, we see that the choice of $C_s$ is very important. If, as indicated in Section 3, the appropriate wave velocity is that of the deeper layers (>3 km/sec) then wave passage is not very important. On the other hand, if the value of $C_s$ used by Newmark is appropriate, then wave passage effects should be important and observable.

Figure 4 shows the location of a group of buildings in the Los Angeles area used in
this study, as well as, the basemat areas for these buildings. Figure 5 shows the ratio of the 2% damped relative velocity spectral amplitude of each building to that of the largest basemat [the 3411 Wilshire Building]. There are only slight differences between the two different components recorded at each site. Only the envelope of the data is shown because we are primarily interested in the overall trend of the data rather than the fine structure of the spectral ratio. The 2% damped spectra was chosen to smooth out some of the violent fluctuations observed in the Fourier spectra and simplify interpretation.

In the high frequency end, (greater than 3 Hz) we would expect -- on the basis of Figure 3 -- that the ratio would be much larger than unity if Newmark’s choice of 0.6 km/sec for the wave velocity is correct. Clearly this isn’t the case, as the only significant change in the ratio is between 1 and 3 Hz. However, the response shown on Figure 5 is consistent with the choice of a higher wave velocity for frequencies greater than 3 Hz. The 3411 Wilshire Building seems to have filtered the ground motion between 1 and 3 Hz as compared to the other buildings.

5. DISCUSSION AND CONCLUSIONS

Space limitations preclude the presentation of other similar data. E.g., a record was obtained in a 14-story building within 2 km of the Hollywood storage building. This spectra was very similar to that recorded in the parking lot at the Hollywood storage building and showed no evidence of averaging. Data obtained at the Humboldt Bay Nuclear Power Plant showed a considerable difference between the free-field and that recorded in the refueling building. Seed, et al. [6] were able to account for this difference [for frequencies greater than 3 Hz] by a soil structure interaction analysis neglecting any wave passage effects.

The main conclusions that can be reached from this, is that we need to actually measure the wave velocity to associate with the traveling wave. The available data seems to suggest that this velocity is much larger than the wave velocity of the near surface layers. In addition, comparisons with theory are mixed in that some cases appear to support the theory and others do not. But any interpretation is difficult because the wave velocity is unknown and has such an important effect on the phenomenon. It appears we are seeing many complex effects that clearly cannot be lumped together in a simple averaging scheme.

6. ACKNOWLEDGMENTS

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References


Figure 1. Wave Amplitude Reductions vs. Wave Number $R_n$. 

![Wave Amplitude Reductions vs. Wave Number $R_n$.](image-url)
Figure 2. Ratio of 2% Damped Relative Velocity Spectral Amplitude - (Parking Lot/Hollywood Storage Building).

Figure 3. Predicted Effect on the Ratio of the Fourier Amplitude for a Building of an Effective Length $L = 100'$ divided by a Building of $L = 300'$. 
Figure 4. Relative Location and Basemat Areas of Buildings Compared in Figure 5.
Figure 5. Ratio of 2% Damped Relative Velocity Spectra Obtained in the Basement of the Buildings Shown on Figure 4 to that Obtained in the Basement of the 3411 Wilshire Building

A 3550 Wilshire
B 3470 Wilshire
C 616 S. Normandie
D 3345 Wilshire
E 3407 W. 6th.