EFFECT OF SEISMIC WAVE INCLINATION ON STRUCTURAL RESPONSE

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ABSTRACT

A new procedure is developed using the computer program SASSI to evaluate the effects of inclined propagating shear waves on three-dimensional (3-D) seismic soil-structure interaction (SSI) response. An example of an offshore gravity structure is used to illustrate the procedure. Using the recorded motions from the two-dimensional (2-D) dense strong motion array in Taiwan (SMART-1), the angle of incidence of incoming shear waves is estimated at 20 degrees. SSI analyses are performed for the same input motion using vertical as well as inclined wave propagation. The results show an increase of up to 50 percent in the horizontal response of the structure using the inclined wave assumption as opposed to the vertically propagating wave assumption.

INTRODUCTION

In the past, seismic SSI analyses of nuclear power plants, offshore platforms, and other important structures have generally been performed using seismic wave fields consisting primarily of vertically propagating body waves (p-, SV- and SH-waves). This assumption may not be valid if, for example, the structure is sited close to a potential seismic source or if it is supported on a sediment-filled basin. During an earthquake, such structures will likely be subjected to strong ground motions due to inclined propagating body waves and surface waves (R- and L-waves). A comprehensive seismic SSI analysis must, therefore, consider appropriate angle of incidence for the seismic waves.

While current methodology for SSI analysis can handle complex seismic wave patterns, little information exists regarding the composition of seismic wave fields. This has resulted from a limited understanding of the effects on strong ground motions of seismic source mechanism and transmission path. Recent recordings of strong ground motion obtained from dense arrays have significantly enhanced our understanding of the properties of seismic wave fields.

We have developed procedures to study the effects of inclined propagating shear waves (SV- and SH-waves) on the three-dimensional seismic SSI response. An example of an offshore gravity platform is used to illustrate this problem. Estimates of the angle of incidence for inclined shear waves were obtained by analyzing the recorded motions from SMART-1, which provided the first recordings of strong

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ground motion made by a dense 2-D array (1). This was done by using the array recordings to measure the slowness of the seismic waves and then applying an understanding of the local velocity structure below the array to estimate the angles of incidence of various wave types.

Comparing the results obtained using the assumption of inclined propagating shear waves with those obtained using the assumption of vertically propagating shear waves, we see a considerable increase in the predicted response of the example offshore structure when the inclined wave assumption is used.

METHOD OF ANALYSIS

The computer program SASSI (4) was used to perform the 3-D SSI analysis. This program uses the flexible volume method, a general finite element substructuring procedure. The method permits true 3-D modeling of soil-structure systems which are subjected to ground motions resulting from inclined propagating body waves and surface waves. The method also allows modeling of structures with multiple foundations of arbitrary shape supported on or embedded in horizontal viscoelastic layers on top of a rigid base rock or a halfspace.

In the flexible volume method, the complete soil-structure system is subdivided into two substructures, namely the foundation and the structure. The foundation is solved first, and the impedance and scattering properties are established at the soil-structure interface. These properties are then input as boundary conditions and load vectors in the dynamic finite element analysis of the structure. In performing the partitioning, the mass and stiffness of the structure are reduced by the corresponding properties of the volume of soil excavated, but are retained within the halfspace. The interaction is thus assumed to occur over a volume rather than at boundaries of the foundation. This greatly simplifies the analysis procedure in that the impedance problem is reduced to a series of axisymmetric solutions for the response of a horizontally layered site to point loads, and the scattering problem is reduced to a free-field problem.

THE CONDEEP PLATFORM

The procedures developed are applied to study the response of the Condeep platform (Figure 1). The structure is a gravity-type platform designed for water depth of 240 meters. The structure consists of a deck, a tower, three legs, and three foundation pads. Its height from seabed to the helicopter deck is 284 m. The foundation pads are approximately 50 m in diameter and 180 m from center to center; each pad includes 12 concrete cells, approximately 15 m in height. The pads are connected to each other slightly above the foundation level.

Site Conditions

The soil profile at the platform site consists of 120 m of dense fine silty sand overlying rock. The sand has total unit weight of 2 tons per cubic foot. Figure 2 shows the variation of low-strain shear modulus of the sand with depth. Poisson's ratio was assumed to be 0.45 for the profile.

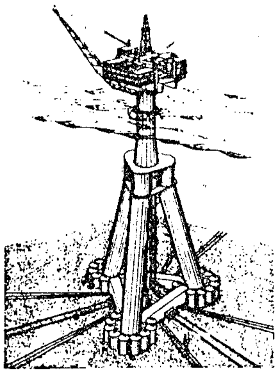


Figure 1. General View of the Condeep Platform

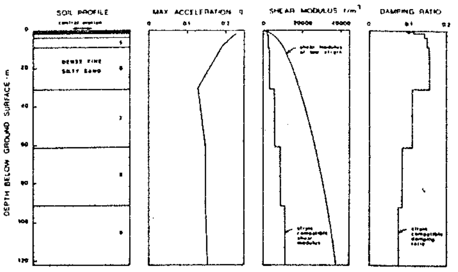
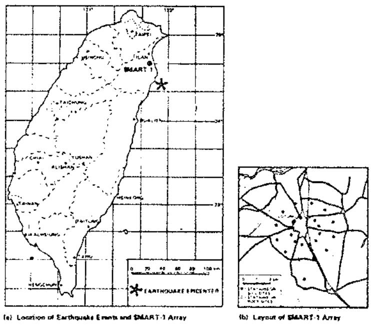


Figure 2. Strain Compatible Soil Properties from Free Field Column Study

Seismic Criteria

Free-field input motion to the SSI analysis was obtained by analyzing the strong ground motion recordings of the January 29, 1981 Taiwan earthquake from the SMART-1 array (Figure 3). The free-field ground motions recorded at central station C-00 were analyzed, and the resulting SH- and SV-wave components with recorded peak ground accelerations of 0.1 and 0.11g were selected as the x- and y-components of the free-field control motion at ground surface for SSI analysis, respectively. The peak horizontal ground acceleration of both components was scaled to 0.25g for analysis. Figure 4 shows the response spectrum of the two selected control motions.



(a) Location of Earthquake Events and SMART-1 Array (b) Layout of SMART-1 Array

Figure 3. Smart-1 Array Location and Configuration

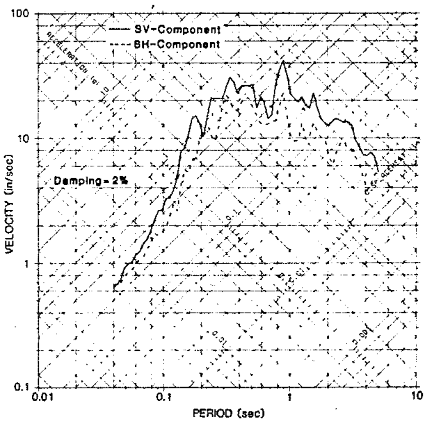


Figure 4. Horizontal Components of Control Motion

The angle of incidence of the shear waves was estimated using frequency-wavenumber analysis (2). Figure 5 shows the S-wave power contours in wavenumber space at 1 Hz. The center of the plot is at zero slowness (infinite velocity) and corresponds to vertical incidence. Moving away from the center of the plot, the slowness increases (apparent velocity decreases), which corresponds to increasing angle of incidence. In Figure 5, the spectral peak labeled "A" indicates that the plane wave is equivalent to an apparent velocity of 3.6 km/sec. Based on measurements of the velocity structure below the array, the apparent velocity of 3.6 km/sec corresponds to an angle of incidence of about 20 degrees. This angle was used as the angle of incidence of shear waves in the underlying rock for the SSI analysis.

The analyses previously performed on this gravity platform indicate that frequencies above 3 Hz are of minor importance for the SSI response of the structure (3). Hence, to save computer time and storage, it was decided to modify the original time history for the interaction analysis by removing all frequencies above 3 Hz. The response spectrum of the modified control motion, SV- and SH-wave components, are shown in Figures 9(a) and 9(c), respectively. The maximum acceleration of the motion did not change significantly for the SV-wave component but dropped about 50 percent for the SH-wave component. P-waves and surface waves were not considered in this study.

Site Response Analysis

A one-dimensional shear wave propagation analysis was performed using the computer program SHAKE (5) to obtain strain-compatible soil properties shown in Figure 2. The y-component of the control motion was used as input motion into the profile.

Three-Dimensional SASSI Analysis

We used the computer program SASSI to perform the SSI analysis. The SASSI procedure assumes that the site is horizontally layered. This assumption may not be appropriate for the region immediately under foundation pads. That is, on one hand, the confining pressure due to the static weight of the structure tends to increase the stiffness of the sand, while on the other hand, high shear strains due to interaction tend to decrease the effective stiffness. Both effects can be approximated by including in the structural model a number of solid elements which span the region over which the irregularities occur. Using this procedure, it is possible to perform the 3-D SASSI analysis at the actual induced soil-strain level (one iteration) and reduce the computational effort.

The increase in confining pressure due to the weight of the structure was determined by static analysis. In making this calculation, it was assumed that the three pads act independently; the stresses were added to those in the free field, and the resulting mean effective confining pressure was used to estimate the low-strain dynamic shear modulus under each pad, as shown in Figure 6. These low-strain dynamic moduli were then adjusted for strain effects due to interaction using a simple 2-D model. The 2-D model includes a single pad and a single damped oscillator with one-third the mass of, and the same fundamental frequency as, the structure. Assuming vertically propagating shear waves with the SV-component of the control motion specified at mud line level, the analysis yielded the approximate strain-compatible shear moduli and damping values for the soil region below each pad, as shown in Figure 7.

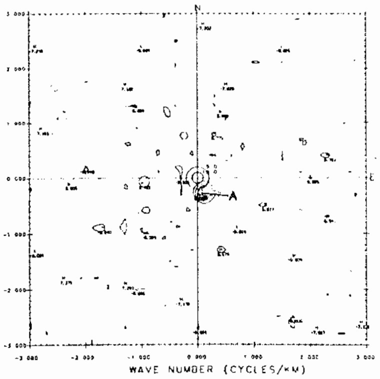


Figure 5. Frequency-Wavenumber Spectrum at 1 Hz

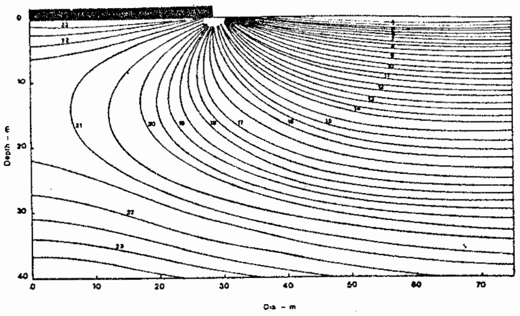


Figure 6. Variation of Low Strain Shear Modulus Beneath a Pad (G_{max}-*10^3 t/m^2)

The 3-D structural finite element SASSI model is shown in Figure 8. The superstructure was idealized using beam elements and lumped masses. The pads and a region of soil beneath each pad were modeled using 8-node solid elements. The latter region was estimated from Figure 7 and was included to account for the weight of the structure and the nonlinear effects in this region, as described previously. The hydrodynamic inertia effects were included in the analysis by using an added mass coefficient, and hydrodynamic damping was added to the structural damping by specifying a constant damping ratio to represent both damping effects. The details of the structural finite element and properties of the model are given in (3). The inclined shear wave assumption considered the waves to propagate in the y-z plane.

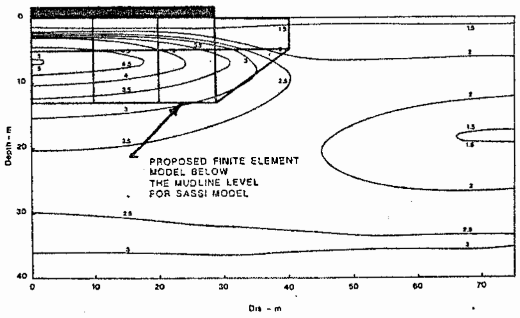


Figure 7. Variation of Strain Compatible Shear Modulus Beneath a Pad (G_{max} - * 10^3 t/m^2)

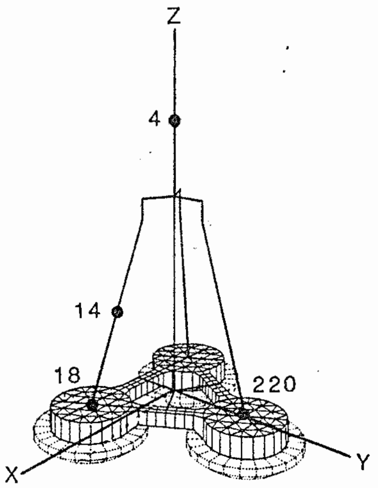
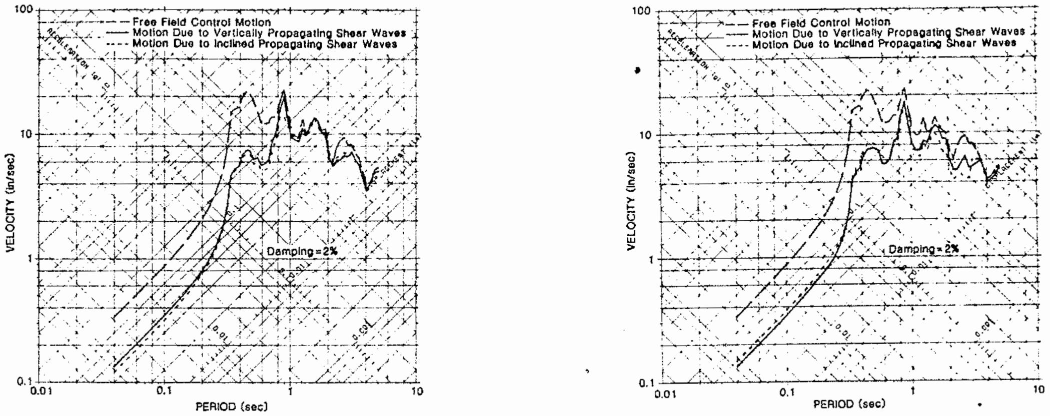


Figure 8. View of Finite Element Model for SASSI Analysis.

ANALYSES, RESULTS, AND DISCUSSION

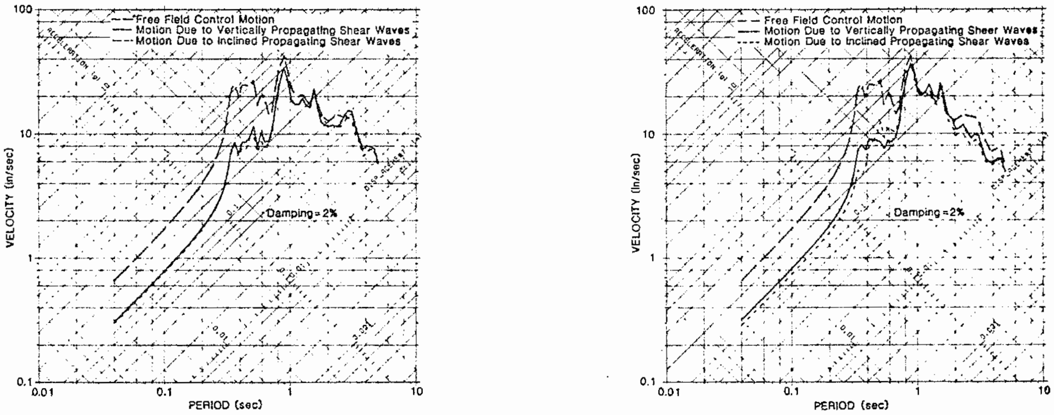
The results of the 3-D SSI analysis using vertically and inclined propagating shear waves are computed at nodes 4, 14, 18, and 220 as shown on Figure 8. The results in terms of 2 percent response spectra are compared in Figures 9 through 10. Figures 9(a) and (b) show the response spectra corresponding to the motions calculated in the x-direction at nodes 18 and 220 on the pads, respectively. Figures

9(c) and (d) show the same results calculated in the y-direction at nodes 18 and 220, respectively. Superimposed on these figures are the spectra of the free-field motion in the x- and y-directions corresponding to the SH- and SV-wave components of the control motion at the mud line level, respectively. Comparing the results obtained assuming vertically and inclined propagating shear waves, we find that both assumptions result in horizontal pad motions which are essentially the



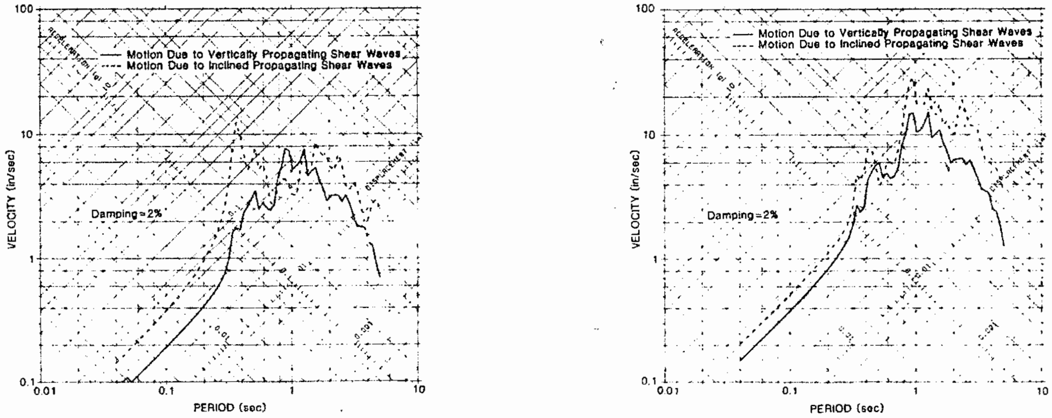
(a) Node 18, X- Direction

(b) Node 220, X-Direction



(c) Node 18, Y-Direction

(d) Node 220, Y-Direction



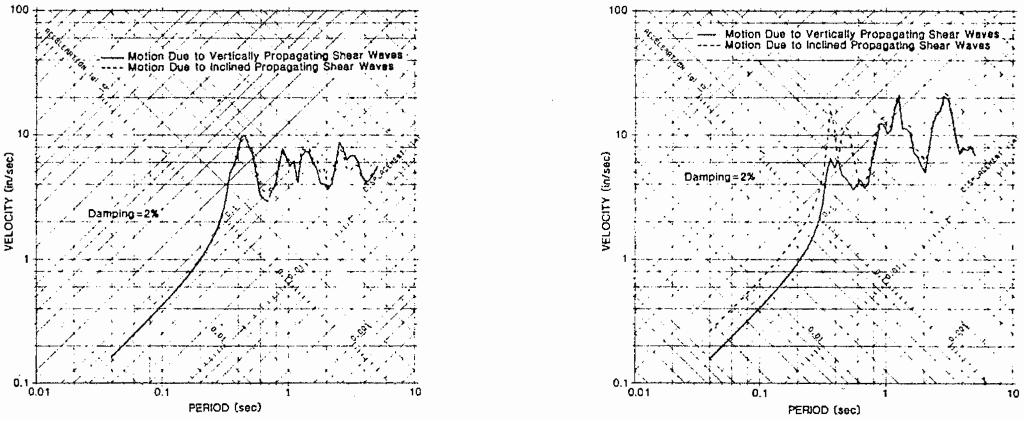
(e) Node 18, Z-Direction

(f) Node 220, Z-Direction

Figure 9. Comparison of Calculated Motions at the Base of the Structure

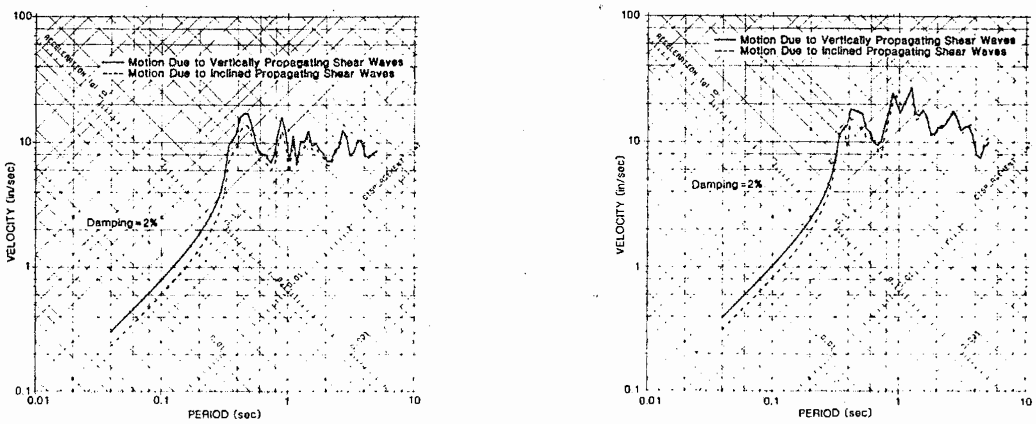
same but are considerably lower than those of the free-field response. The decrease in the structural base motion compared to that of the free-field is on the order of 60 percent at frequencies above 1.2 Hz for both vertically and inclined propagating shear waves; this is attributed to the interaction between the soil and the platform structure. Figures 9(e) and (f) compare the vertical motion of the pads calculated at nodes 18 and 220, respectively. Significant asymmetric rocking of the platform can be seen. The magnitude of rocking, however, is twice as great for the inclined propagating waves as for the vertically propagating waves.

Comparisons of the motions calculated on the superstructure are shown on Figures 10(a) and (b) for node 14 and on Figures 10(c) and (d) for node 4. The acceleration responses calculated near the top of the structure at node 4 in the x- and y-directions are about 10 percent lower at frequencies above 1.2 Hz assuming inclined propagating shear waves, as compared to the responses calculated for vertically propagating shear waves. As shown in Figure 10(b), this difference is more marked on the leg of the platform, where the calculated acceleration response at node 14 is about 50 percent greater than that calculated for vertically propagating shear waves. This considerable increase in the motion is attributed primarily to the higher rocking effects in the structure due to inclined wave propagation and the special geometry of the structural support.



(a) Node 14, X-Direction

(b) Node 14, Y-Direction



(c) Node 4, X-Direction

(d) Node 4, Y-Direction

Figure 10. Comparison of Calculated Motions on the Superstructure

SUMMARY AND CONCLUSIONS

A new procedure is developed using the computer program SASSI and seismic wave-field information obtained from the SMART-1 array to analyze the 3-D SSI response of the Condeep platform subjected to inclined propagating shear waves. Using an angle of incidence of 20 degrees for inclined propagating shear waves in rock, we calculated the SSI response of the platform at foundation and superstructure levels and compared it to the response calculated for vertically progagating shear waves. Comparison of the results leads to the following conclusions.

1. A considerable decrease in the horizontal structural base response results from interaction between the soil and structure using both vertically and inclined wave propagation assumptions.
2. Considerable rocking in the structure results from SSI effects. The magnitude of rocking was approximately twice as great for the inclined as compared to the vertically propagating waves.
3. The computed response of the tower was basically the same for both wave propagation assumptions (difference less than 10 percent). However, the predicted response of the platform legs increased about 50 percent when inclined rather than vertically propagating waves were assumed.

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