THE RESPONSE OF STRUCTURES TO TRAVELING BODY AND SURFACE WAVES

by

S.D. Werner[I] and L.C. Lee[II]

SUMMARY

A new methodology has been developed to analyze the three-dimensional response of structures subjected to traveling seismic waves. To demonstrate basic phenomena related to traveling wave effects on the response of structures, the methodology is used in this paper to analyze a simple bridge structure on an elastic half-space subjected to incident P-waves and Rayleigh waves that propagate along the bridge span. The results demonstrate how the bridge response is influenced by the wavelength of the incident wave, the wave type, and the vertical angle of incidence of the P-waves.

INTRODUCTION

In most analyses of the response of structures to earthquake ground motions, the seismic excitation is assumed to be identical at all points along the base of the structure. However, this assumption only approximates the excitation actually applied to the structure, since it does not account for the spatial variations of the incident seismic waves. These spatial variations cause different locations along the structure foundations to be subjected to excitations that differ in both amplitude and phase. Such excitations can have an important effect on the structural response.

This paper presents some results from a research program that investigated how traveling seismic waves influence the three-dimensional response of structures. To carry out the investigation, a new methodology was developed and used to analyze a simple bridge structure on an elastic half-space subjected to traveling body and surface waves with arbitrary wavelength and direction of incidence (Refs. 1 to 4). Sample results of the analyses are provided herein to show some basic phenomena associated with traveling seismic wave effects on structural response.

METHODOLOGY

The methodology used to conduct this study (Fig. 1) computes the three-dimensional dynamic response of one or more arbitrarily configured, elastic, aboveground structures. Each structure is supported on any number of rigid foundations of arbitrary shape that are bonded to the surface of an elastic half-space representation of the soil medium. Input motions correspond to any combination of harmonic body and surface waves with arbitrary excitation frequencies, amplitudes, phase angles, and angles of incidence (denoted by θ_H and θ_V in Fig. 1).

[I] Principal Engineer, Agbabian Associates, El Segundo, CA, U.S.A.

[II] Senior Staff Engineer, Agbabian Associates.

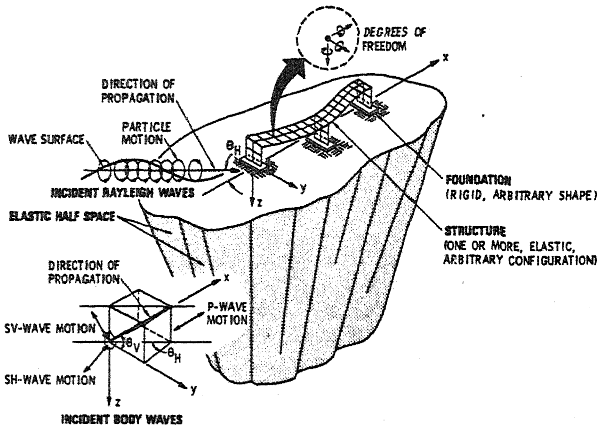
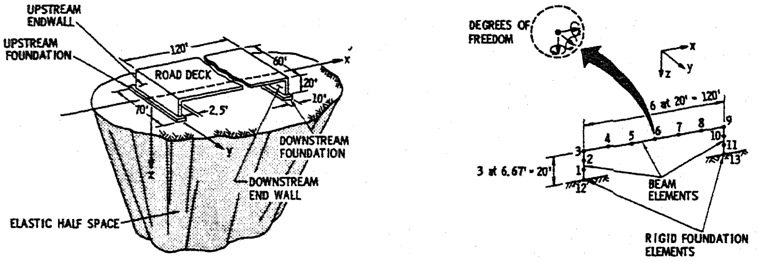


FIGURE 1. SOIL/STRUCTURE SYSTEM CONSIDERED BY METHODOLOGY

In the methodology, each aboveground structure is represented by a finite element model in which a wide variety of element types can be used (Ref. 1). This model defines the mass, stiffness, and damping matrices of each structure, along with its fixed-base mode shapes and frequencies. Interaction between the foundations and the soil medium is represented using a continuum solution; this solution uses Green's functions for an elastic half-space to compute foundation/soil impedance matrices and driving force vectors (Ref. 5). The structure and foundation/soil systems are coupled at their interface through the use of compatibility and equilibrium requirements; then, the steady-state response of this coupled system is computed using an extension of a procedure described in Ref. 6. Ref. 1 provides the formulation of this analysis procedure and a detailed description of the methodology.

BRIDGE MODEL AND EXCITATION

The bridge considered in this analysis is shown in Fig. 2a to be 120 ft long, 60 ft wide, and 20 ft high. It is modeled using a system of undamped beam elements (Fig. 2b) whose section and material properties are given in



(a) Configuration

(b) Model

FIGURE 2. BRIDGE CONFIGURATION AND MODEL

Refs. 1 and 2. The soil medium is represented as an elastic half-space with a shear wave velocity of 500 fps and a Poisson's ratio of 1/3.

Refs. 1 to 4 describe the response of this bridge to harmonic excitations from P-, SV-, SH-, and Rayleigh waves. This response has been computed for vertically incident and nonvertically incident body waves and horizontally incident Rayleigh waves propagating normal to the bridge span (θ_H = 90 deg in Fig. 1), parallel to the bridge span (θ_H = 0 deg), and oblique to the bridge span (θ_H = 45 deg). Sample results are described herein for the cases that involve P-waves and Rayleigh waves propagating parallel to the bridge span (θ_H = 0 deg). In these, the excitation frequency (wavelength) of each wave type and the angle of vertical incidence of the P-waves only are varied. The resulting bridge response is presented as displacement amplitude vs. dimensionless frequency curves and as time-dependent deformed shapes of the bridge at particular frequencies. The dimensionless frequency parameter used to represent these results is denoted as R_{Lx} and defined as

$$R_{Lx} = \frac{\ell}{\lambda} = \frac{\ell\omega}{2\pi V}$$

where ℓ is the span length of the bridge, λ is the wavelength of the incident wave along its propagation path, V is the wave velocity, and ω is the circular frequency of the excitation.

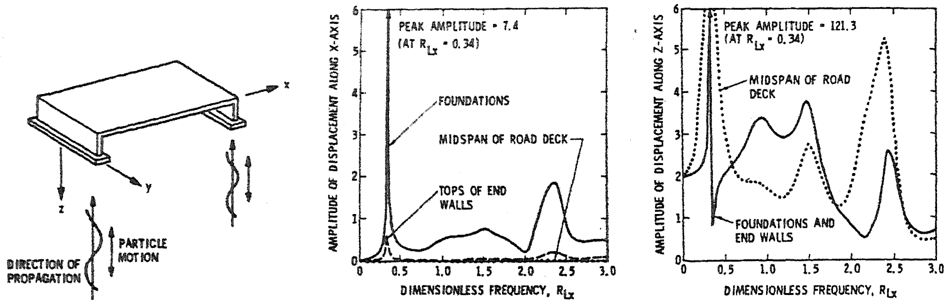
P-WAVE RESULTS

Vertically Incident Waves

When vertically incident P-waves are propagating in the vicinity of the bridge, the ground surface excitations are directed along the z-axis; furthermore, because of the infinite apparent wavelength of the incident waves, these excitations are identical all along the two foundations (Fig. 3a). The resulting bridge response (Figs. 3b and 3c) consists of displacements along the z-axis, with accompanying displacements along the x-axis that are antisymmetric about the midspan of the bridge (Ref. 2). These z-displacements are symmetric about the midspan of the bridge and, at certain resonant frequencies, exhibit very large values at the midspan of the road deck (Fig. 3d).

Nonvertically Incident Waves

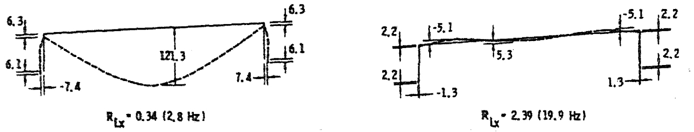
When the P-waves are nonvertically incident, excitation components directed along both the x- and z-axes are applied (Fig. 4a). Also, because the waves now have a finite apparent wavelength, there is a phase difference between the excitations applied to each foundation. The resulting bridge response, shown in Figs. 4b and 4c for θ_V = 45 deg, consists of displacements along the x- and z-axes. This response exhibits the same low-frequency resonant frequency peak in the z-displacements as was induced by the vertically incident waves (Fig. 4d). However, other features of the bridge response are now much different. One such feature is a significant peak in the x-displacement vs. frequency curves that corresponds to a sidesway resonant response of the bridge (Fig. 4d) and occurs at a frequency quite close to that of the above z-displacement peak. Also, the response of the bridge



(a) Excitations from incident wave

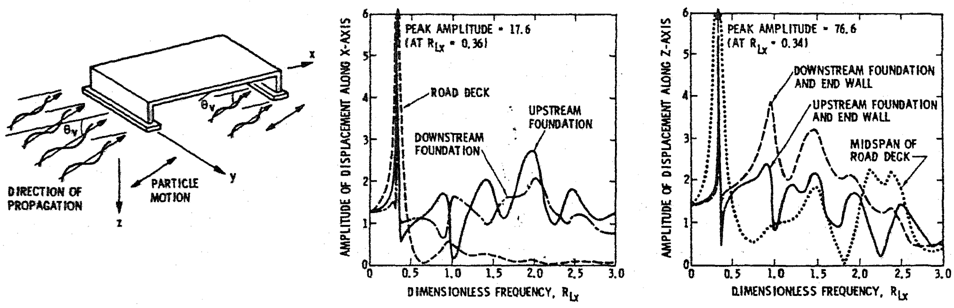
(b) Displacements along x-axis

(c) Displacements along z-axis



(d) Deformed shapes at times of peak resonant response

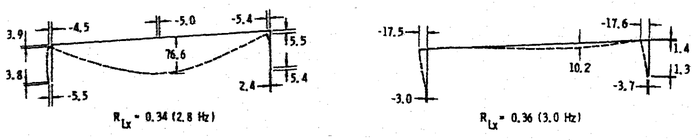
FIGURE 3. BRIDGE RESPONSE TO INCIDENT P-WAVES WITH θ_V = 90 DEG



(a) Excitations from incident wave

(b) Displacements along x-axis

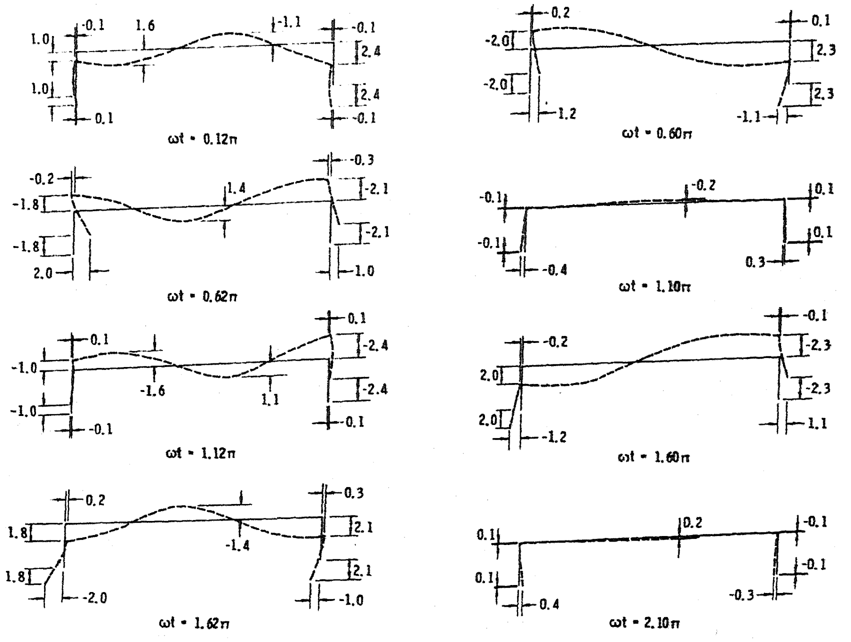
(c) Displacements along z-axis



(d) Deformed shapes at times of peak resonant response

FIGURE 4. BRIDGE RESPONSE TO INCIDENT P-WAVES WITH θ_H = 0 DEG AND θ_V = 45 DEG

is now dependent on the phasing of the excitations applied to the two foundations. This is clearly shown by the significant differences that exist between the time-dependent deformed shapes of the bridge for the following two sets of wavelengths: (1) wavelengths that result in excitations of equal amplitude and equal phase at the two foundations (Fig. 5a) and (2) wavelengths that result in excitations of equal amplitude and opposite phase at the two foundations (Fig. 5b).*



(a) Excitations of equal amplitude and equal phase at the two foundations $\left(R_{Lx} = \frac{1.0}{\cos 45\ \text{deg}} = \sqrt{2}\right)$

(b) Excitations of equal amplitude and opposite phase at the two foundations $\left(R_{Lx} = \frac{0.5}{\cos 45\ \text{deg}} = 0.5\sqrt{2}\right)$

FIGURE 5. DEFORMED SHAPES OF BRIDGE SUBJECTED TO INCIDENT P-WAVES WITH $\theta_H = 0$ DEG AND $\theta_V = 45$ DEG

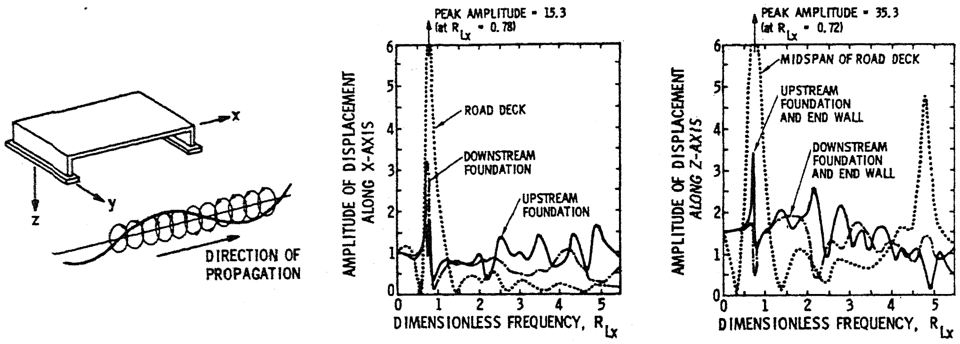
RAYLEIGH WAVE RESULTS

Rayleigh waves that propagate along the span of the bridge induce elliptic retrograde ground surface excitations whose phasing at the two foundations is dependent on the wavelength of the incident wave relative to

---

*Free-field excitations of equal amplitude and equal phase at the two foundations (Fig. 5a) occur when the ratio of the bridge span length to the apparent wavelength of the incident wave is 1.0, 2.0, 3.0, etc, (i.e., $R_{Lx} \doteq \sqrt{2}$, $2\sqrt{2}$, $3\sqrt{2}$, etc., for $\theta_V = 45$ deg). Excitations of equal amplitude and opposite phase at the two foundations (Fig. 5b) occur when the ratio of the bridge span length to the apparent wavelength of the incident wave is 0.5, 1.5, 2.5, etc., (i.e., $R_{Lx} = 0.5\sqrt{2}$, $1.5\sqrt{2}$, $2.5\sqrt{2}$, etc., for $\theta_V = 45$ deg).

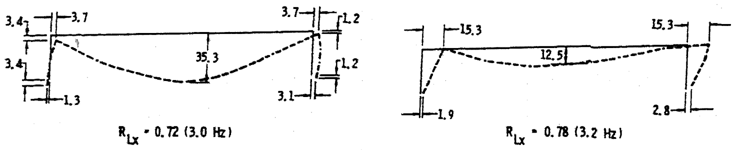
the span of the bridge (Fig. 6a). The significant bridge response components induced by such excitations are displacements along the x- and z-axes; the frequency-dependent displacement amplitudes and phase angles for these components are given in Figs. 6b and 6c and in Ref. 2, respectively. An important feature of this response is the significant peaks in the x-displacements and z-displacements that occur at frequencies of R_{Lx} = 0.78 (3.2 Hz) and 0.72 (3.0 Hz), respectively. These peaks correspond to resonant responses involving sidesway of the bridge in the x-direction and vertical displacements of the midspan of the road deck (Fig. 6d). Similar resonant responses were induced by the nonvertically incident P-waves at nearly the same frequencies.



(a) Excitations from incident waves

(b) Displacement along x-axis

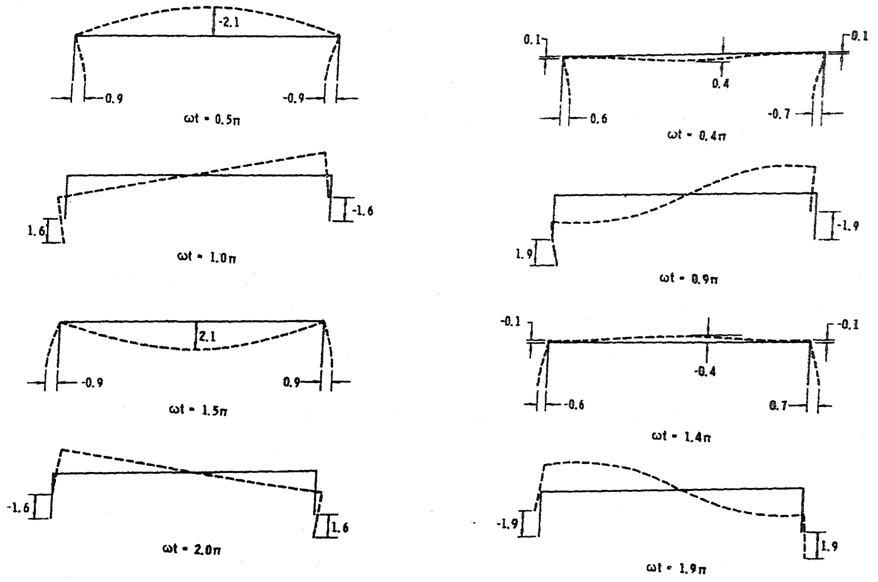
(c) Displacement along z-axis



(d) Deformed shapes at times of peak resonant response

FIGURE 6. BRIDGE RESPONSE TO INCIDENT RAYLEIGH WAVES WITH θ_H = 0 DEG

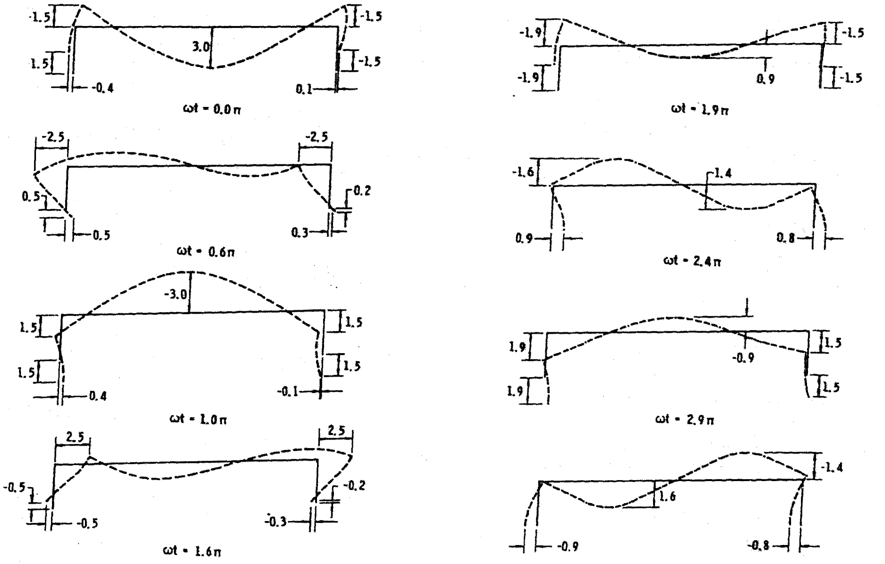
A second important feature is the effect of the phasing of the Rayleigh wave excitations applied at the two foundations. To illustrate this, deformed shapes are presented for two different sets of wavelengths. The first set involves excitations that are of equal amplitude and opposite phase at the two foundations, whereas the second set involves excitations that are identical in amplitude and phase at each foundation. For horizontally incident waves, these sets correspond, respectively, to frequencies of R_{Lx} = 0.5, 1.5, 2.5, etc., and R_{Lx} = 1.0, 2.0, 3.0, etc. Time-dependent deformed shapes (Figs. 7 and 8) show that the bridge response is quite different for these two sets of excitations--a direct result of the differences in phasing of the Rayleigh wave excitations at the two foundations. In addition, the bridge response is seen to change markedly during each



(a) R_{Lx} = 0.5

(b) R_{Lx} = 1.5

FIGURE 7. RESPONSE TO RAYLEIGH WAVE EXCITATIONS OF EQUAL AMPLITUDE AND OPPOSITE PHASE AT THE TWO FOUNDATIONS (θ_H = 0 DEG)



(a) R_{Lx} = 1.0

(b) R_{Lx} = 2.0

FIGURE 8. RESPONSE TO RAYLEIGH WAVE EXCITATIONS OF EQUAL AMPLITUDE AND EQUAL PHASE AT THE TWO FOUNDATIONS (θ_H = 0 DEG)

response cycle, in a manner that is a consequence of the 90-deg phase difference between the horizontal and vertical components of the Rayleigh wave ground surface motion. Finally, as R_{Lx} is increased within each set of excitations, the bridge response becomes more complex due to the increased influence of wave diffraction and scattering and higher modes of vibration at these higher excitation frequencies (Refs. 2 and 3).

CONCLUSIONS

These sample results from a comprehensive study of the response of a single-span bridge to traveling seismic waves show two important trends. First, nonvertically incident P-waves induced bridge response characteristics that differ markedly from those induced by vertically incident waves; in this sense, the P-wave results typify the results from the other body waves considered in the study. Second, the wave type and wavelength (or frequency) of the incident wave have an important effect on the nature of the bridge response.

ACKNOWLEDGMENTS

These calculations were conducted by Agbabian Associates as part of a multiyear research program funded from grants by the National Science Foundation. M.D. Trifunac and H.L. Wong of the University of Southern California were consultants to Agbabian Associates during the program.

REFERENCES

1. Werner, S.D. et al. An Evaluation of the Effects of Traveling Seismic Waves on the Three-Dimensional Response of Structures, R-7720-4514, Agbabian Associates, El Segundo, CA, Oct 1977.

2. Werner, S.D. and Lee, L.C. The Three-Dimensional Response of a Bridge Structure Subjected to Traveling Rayleigh Waves, SV-Waves, and P-Waves, R-7911-5008, Agbabian Associates, El Segundo, CA, Mar 1980.

3. Werner, S.D. and Lee, L.C., "The Three-Dimensional Response of Structures Subjected to Traveling Rayleigh Wave Excitation," Proc. of the 2nd U.S. National Conference on Earthquake Engineering, Stanford, CA, Aug 1979.

4. Werner, S.D., et al. "Structural Response to Traveling Seismic Waves," J. of the Struct. Div, ASCE, 105:ST12, Dec 1979, pp. 2547-2464.

5. Wong, H.L. Dynamic Soil/Structure Interaction, EERL-75-01, California Institute of Technology, Pasadena, CA, May 1975.

6. Clough, R.W. and Penzien, J. Dynamics of Structures, McGraw-Hill Book Company, New York, NY, 1975.