Geotechnical Factors Influencing the Spatial Variability in Ground Motions for Bridges

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Abstract: Spatial variability in ground motions along the longitudinal axis of a bridge can be of significant importance for its seismic response. Differences in the geotechnical site conditions along the bridge axis, including sharply dipping base rock, can lead to significantly different ground motions at the various bridge supports. This paper presents a case study of a bridge for which spatially variable ground motions were generated. Ground surface motions, generated at the bridge foundation locations, from one and two-dimensional wave propagation analyses are presented and discussed. Two-dimensional dynamic site response analysis yields reasonable ground motions that vary in magnitude and frequency along the bridge axis because of differences in the underlying soils. One-dimensional wave response analysis is shown to be inadequate.

Introduction

Seismic safety evaluation of existing bridges continues to receive increased attention nation and world-wide. In the northeastern U. S., there are many important bridges that are old and potentially vulnerable to earthquake-induced damage. Often, the seismic safety evaluation of these bridges, and the development of cost effective retrofit schemes require advanced analytical approaches. Three-dimensional dynamic response analysis of a bridge superstructure can provide realistic assessment of the performance of the bridge under the design ground motions. In such an analysis, foundation springs and damping coefficients can be used to account for the soil-structure interaction effects. Furthermore, potential variability in the ground motion at the different support locations of the bridge can

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also be incorporated. Such spatial variability in the ground motion can significantly influence the magnitude of the dynamic forces induced in the bridge superstructure and its foundation supports.

Spatial variability in ground motion can be due to differences in the rock motion along the longitudinal axis of a bridge. This may be the case especially for long span bridges. However, differences in the ground motions at bridge support locations, due to differences in the geotechnical site conditions, including sharply dipping base rock along the bridge axis, can play important role even for relatively short span bridges.

This paper presents a case study of the Madison Avenue Bridge over the Harlem river in New York City, for which spatially variable ground motions were generated and used in the dynamic response analysis of the bridge.

The Madison Avenue Bridge

The Madison Avenue Bridge is a swing bridge centrally supported on a large pier (Center Pier, CP). The two ends of the bridge rest on piers, hereafter referred to as the Manhattan Rest Pier, MRP, and the Bronx Rest Pier, BRP. These three piers are founded on 12 inch diameter timber piles driven to refusal. Figure 1 shows a schematic drawing of the bridge and its foundation.

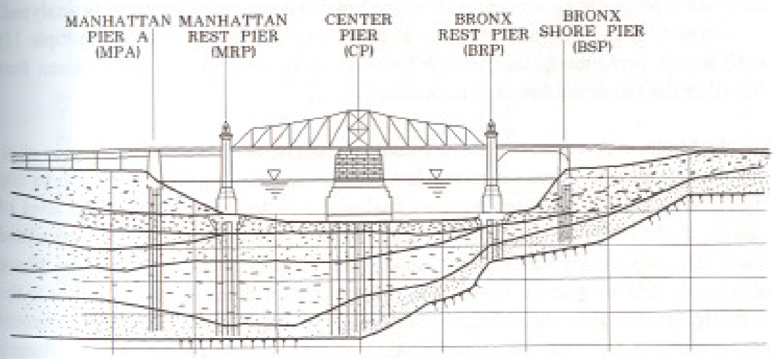

Fig. 1 The Madison Avenue Bridge over the Harlem River in New York.

Geotechnical Site Condition

Figure 2 shows a geotechnical profile along the longitudinal axis of the bridge. This cross section was developed based on boring information gathered from 1907, 1994 and 1996 field investigation programs. It is clearly evident that the soil profile at the bridge site is quite heterogeneous. It is also noted that, within a distance of 500 feet, the depth to bedrock changes from about thirty feet, near the Bronx Shore Pier, to about 100 feet, near the Manhattan Rest Pier.

To asses realistically the influence of this spatially variable site condition upon the earthquake rock motions, the finite element method was employed. In situ shear wave velocities were obtained using geophysical procedures. Cross hole tests were conducted at two locations: one near the Manhattan Pier A and the other near the Bronx Shore Pier. The shear wave velocities, obtained from the cross hole tests and from the Standard Penetration Test results, were used in wave propagation analyses to asses the influence of the site condition upon the rock motions.

Wave Propagation Analysis

It is now well recognized that the local site conditions can have important effects upon the propagating earthquake waves. Typically, in geotechnical engineering practice, one-dimensional, (1D) wave propagation analysis is performed in which a shear wave propagating vertically from the base rock to ground surface is analyzed. To account for the spatial variability in the site condition, commonly, multiple 1D analyses are performed, one for each location of interest, using a soil column that describes the site condition at that location.

For the Madison Avenue Bridge, such analysis was deemed inadequate. Yegian et al. (1994) have shown, based on earthquake damage analysis and its correlation to site conditions, that 1D wave propagation analysis grossly underestimates the level of shaking if the bedrock is sharply dipping. Furthermore, ground motions calculated from 1D analyses for the various bridge pier locations will not have the phase differences that are associated with the different arrival times of the waves due to the spatially variable geotechnical site conditions. For these reasons, the finite element procedure (the computer program QUAD4M) was used to determine the influence of the site condition upon the rock motions.

Figure 3 shows the two-dimensional (2D) finite element mesh used. Since the cross hole tests showed the presence of decomposed base rock, the finite element mesh includes a 30-ft layer of this soft rock. Shear wave velocities of the soils were estimated using the cross hole data. Non-linear dynamic response of the soils were also considered using strain dependent moduli and damping values. The rock

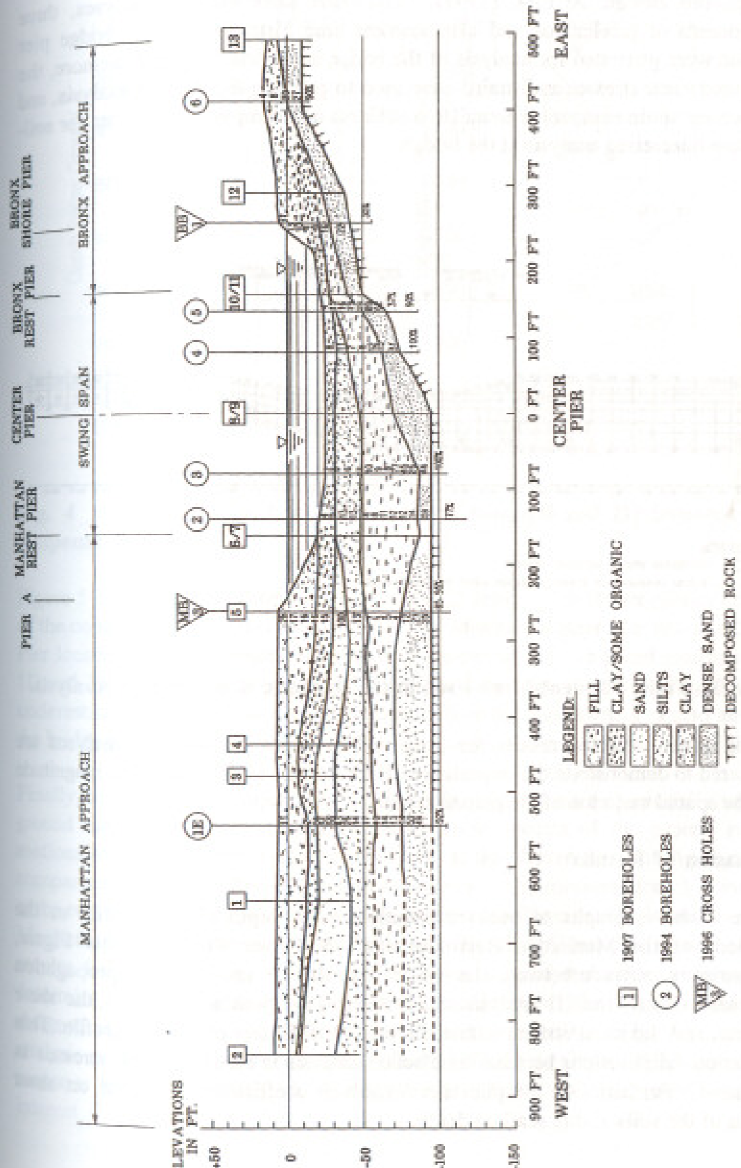

Fig. 2 Geotechnical Profile Along the Longitudinal Axis of the Madison Avenue Bridge.

motions assigned at outcrop were those used in the seismic analysis of the Queensboro Bridge, NCEER (1995). From the finite element analyses, three components of acceleration and displacement time histories for each bridge pier location were generated for analysis of the bridge superstructure. Furthermore, the computed shear stresses and strains were used to perform liquefaction analysis, and to calculate strain compatible foundation stiffness and damping coefficients for soil-structure interaction analysis of the bridge.

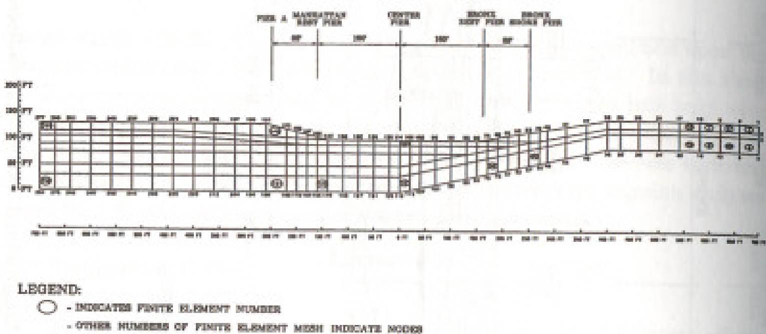

Fig. 3 Finite Element Mesh Used in the Dynamic Site Response Analysis.

In this paper, selected results are presented in which 2D and 1D analyses are compared to demonstrate the importance of 2D analysis in estimating the magnitude and the spatial variation of the ground motion.

Discussion of Results

Figure 4 shows graphs of peak accelerations with depth of soil profile at the locations of the Manhattan Rest Pier and the Center Pier. In this Figure, comparisons are made between the results from the 1D and 2D wave propagation analyses. Clearly the 1D analysis underestimates the peak accelerations, the shear stresses, and the shear strains within the top 40 to 50 feet of the soil profile. This has serious implications because liquefaction analysis is based on shear stresses in this zone. Furthermore, the pile lateral stiffness coefficients are based on shear strains of the soils at this shallow depth.

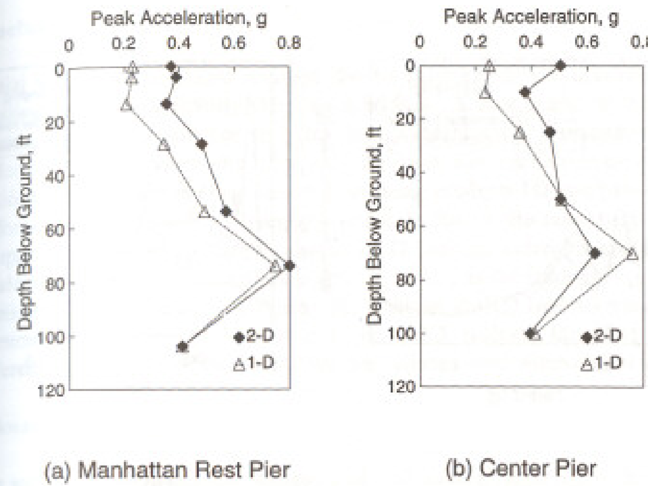

Fig. 4 Comparisons of Peak Accelerations from 1D and 2D Dynamic Site Response Analyses.

Figure 5 illustrates the influence of 1D versus 2D analysis on the frequency content of the computed ground surface motions at the Manhattan Rest Pier and the Center Pier locations. In this Figure, the response spectra of the computed motions from 1D and 2D analyses are compared. The results show that 1D analysis significantly underestimates the spectral responses, especially in the fundamental period range of the bridge (0.4 - 0.5 sec).

Finally, to illustrate the importance of 2D analysis in determining spatially variable ground motions, Figure 6 compares the response spectra of the ground surface motions at the Manhattan Rest Pier with those at the Center Pier. In Figure 6 (a) a comparison is made between the response spectra of the motions from 1D analysis at the two pier locations. As expected, since the soil columns at the locations of the Manhattan Rest Pier and the Center Pier are similar, the 1D analysis yielded similar results for the two piers. Hence, if multiple 1D analyses were performed to determine ground motions at these two bridge pier locations, the two piers would be assigned identical motions, i.e. there is no spatial variability. However, the 2D analysis results presented in Figure 6 (b) clearly indicate significant differences in the response spectra at the two pier locations - again, especially in the period range of interest, 0.4 to 0.5 sec.

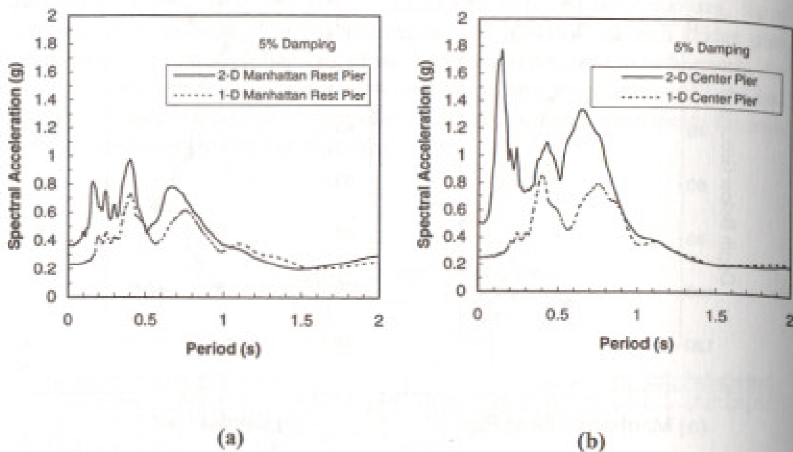

Fig. 5 Comparisons of Response Spectra from 1D and 2D Dynamic Site Response Analyses. (a) Manhattan Rest Pier location, (b) Center Pier Location.

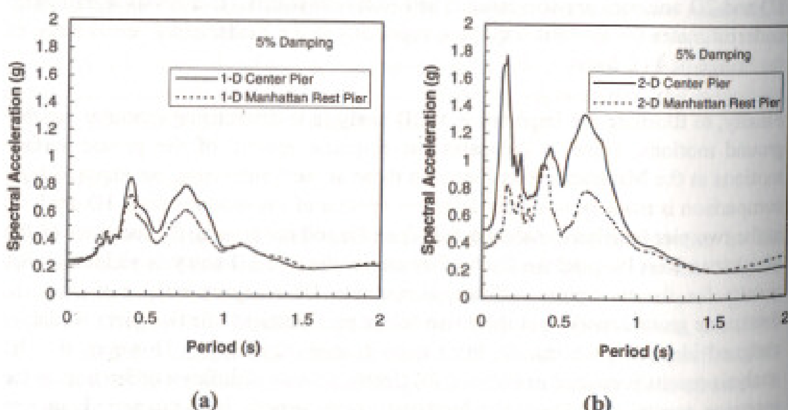

Fig. 6 Differences Between the Ground Motion Spectra of the Manhattan Rest Pier and the Center Pier, from 1D and 2D Dynamic Site Response Analyses.

Conclusions

Spatial variability in ground motions due to geotechnical site conditions can be significant even for relatively short span bridges. A case study of the Madison Avenue Bridge demonstrates that 2D finite element wave propagation analysis, performed to incorporate the effects of the local site conditions upon the rock motions, yields more realistic results than using multiple 1D analysis commonly performed in geotechnical engineering practice. In fact, in the case study presented, compared to 2D wave propagation analysis, 1D analysis underestimated the ground accelerations, shear stresses and shear strains, as well as the response spectra at the locations of the bridge piers. Furthermore, whereas, the 1D analysis yielded almost identical ground motions for the two piers, 2D analysis identified significant differences in the ground motions of the two adjacent piers discussed in this paper.

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