SEISMIC DESIGN

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IMPORTANCE OF ACCURATE SHEAR WAVE VELOCITY IN SEISMIC EVALUATION OF BRIDGES

Yegian, M.K
Northeastern University, U.S.A.

Jain, S.K, Kishore, K., and Patel, J.
NYCDOT, U.S.A.

Abstract

Seismic evaluation of bridges is challenging, particularly when investigating existing bridges. If an existing bridge is deemed to be vulnerable, costly repair and strengthening of the structure might be required. In order to avoid over-conservatism, it is essential that the seismic geotechnical evaluation of a bridge is performed with advanced analytical techniques using accurate input parameters, thus leading to a realistic assessment of the seismic vulnerability and potential need for bridge retrofit. One of the most important soil parameters used in various seismic geotechnical investigations of a bridge is the shear wave velocity of the soils encountered at a site. Often, shear wave velocities of different types of soils are estimated using empirically based relationships that use field measured SPT (Standard Penetration Test), N-values. However, there are significant uncertainties in such estimated shear wave velocities. More accurate shear wave velocities can be measured using in-situ geophysical tests. This paper demonstrates, through the use of two bridge case studies, the importance of using reliable values of shear wave velocities in seismic investigations. The case studies include comparative analyses, which show the benefits of using in-situ measured shear wave velocities in the seismic analysis of the example bridges.

1. Introduction

Seismic vulnerability assessment of a bridge, especially of an existing bridge, can be a major challenge if a safe and cost-effective design is to be achieved. Whereas for a new bridge, a certain level of conservatism can be readily adopted without prohibitive cost consequences. Such conservatism for an existing bridge may lead to a retrofit design that is so costly that an owner may opt to replace the bridge rather than retrofit.

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Realistic assessment of the potential vulnerability of a new or existing bridge requires a rational critical investigations in the fields of seismology, and geotechnical and structural engineering. Geotechnical earthquake engineering plays a crucial role not only in establishing the earthquake motions but also in contributing to the modeling and analysis of the soil-foundation-bridge system. Figure 1 depicts two areas of seismic investigations that are within the realm of geotechnical earthquake engineering. The first area, relates to efforts aimed at characterizing the site conditions at a bridge location, which is then incorporated into ground motion analysis to develop the earthquake input motions for the seismic analysis of the bridge. The second area shown in Figure 1 relates to the development of soil-foundation-bridge models that are needed in the seismic analysis of the bridge.

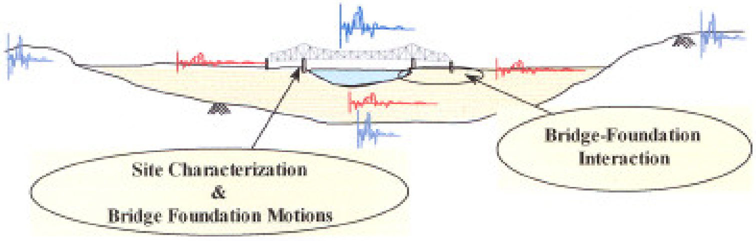

Figure 1: Two areas of geotechnical earthquake engineering selected for the case studies.

One of the most important material properties used in the two areas of geotechnical investigations described is the shear wave velocity, V_S, of the various soil layers and of the bedrock encountered at a bridge site. Shear wave velocity of a medium characterizes the speed of shear waves propagating through the medium, and can be related to the shear modulus, G, and mass density, ρ, of the medium by $V_S = (G/\rho)^{0.5}$. In geotechnical engineering practice, empirical procedures are often employed that can provide estimates of shear wave velocities for different soils. However, the results of such procedures can be highly uncertain or at times erroneous. More accurate estimates of shear wave velocities can be obtained using field geophysical tests.

This paper presents two bridge case studies, which demonstrate the importance of accurate characterization of a bridge site and the use of measured versus estimated shear wave velocities, V_S in the seismic analysis.

2. Case study 1: site characterization and spectral responses

Figures 2a and 2b show the soil profiles at the site of the Northbound Whitestone Expressway in Queens, N.Y. Generally, the soil profiles to the south and north of the Flushing River, over which the expressway crosses, are quite similar. Two crosshole geophysical tests were conducted to obtain in-situ measurements of V_S.

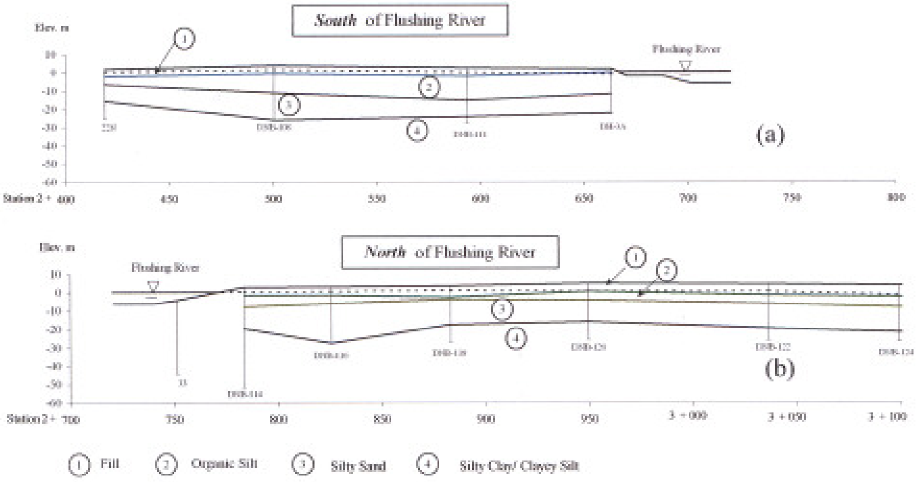

Figure 2: Soil profiles (a) South of Flushing River, and (b) North of Flushing River in the region of the Northbound Whitestone Expressway, Queens, N.Y.

Figures 3a and 3b show the two crosshole test results one in the south and the other in the north of the Flushing River, respectively.

Figures 3a and 3b include the subsurface soil profiles at the locations of the two crosshole tests, and the SPT, N-values recorded. For purposes of comparison, the V_S values for the soils at the site were also computed using the SPT, N-values and the empirical procedures of Sykora and Koester (1988), and Seed et al. (1986), even though the authors recognize that use of correlations between V_S and undrained shear strength or cone point resistance would generally yield more accurate V_S for soft soils. It is interesting to note that for the soils on the south of the Flushing River, the empirical procedure overestimates the V_S, while for soils on the north of the river it underestimates the V_S values. These inconsistent predictions made from the empirical procedure is attributed to the fact that on the south side, the sands are gravelly, thus the N-values are high, and on the north side the sands are more silty, thus the N-values are relatively low. It is not surprising that empirical procedures, which are based on N-values and do not account the effect of grain size distribution, at times yield erroneous results.

A comparative study was performed to demonstrate the differences in the site characterization and design response spectra that result in using measured versus empirically based V_S values. In the 1998 NYCDOT seismic guidelines for bridges, generic soil spectra are provided for use in seismic analysis of non-critical bridges. Each soil spectrum corresponds to a site class defined by NEHRP (2003). Figures 4 and 5 show the spectral values, from the 1998 NYCDOT seismic guidelines, as a function of selected structural periods and $V_S(30m)$, which is the average shear wave velocity of the top 30m of the soil profile defined according to NEHRP.

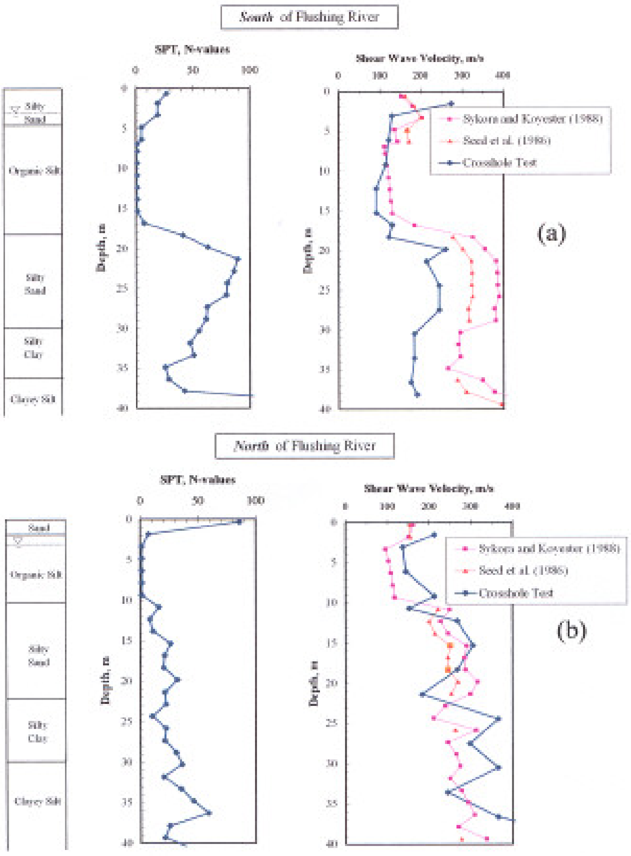

Figure 3: Crosshole test results (a) South of Flushing River, and (b) North of Flushing River.

Based on ranges of $V_S(30m)$, sites are classified as A, B, C, D, E, and where there is peat or highly organic or high plasticity clays or liquefiable cohesionless soils, F. Sites that are classified as F require site specific analysis and generic spectra are not provided for this site class. For the purpose of demonstrating the importance of shear wave velocities, the parameter $V_S(30m)$ was calculated for the south and north profiles using measured and estimated V_S values. Based on the calculated $V_S(30m)$, the soil profile to the south of the Flushing River is classified as E, if the V_S values that were measured in the crosshole tests are used, and is classified as D, if the V_S values estimated by the empirical procedure are used. Therefore, for the soil profile to the south of the Flushing River, the empirical procedure leads to an *underestimation* of the spectral accelerations.

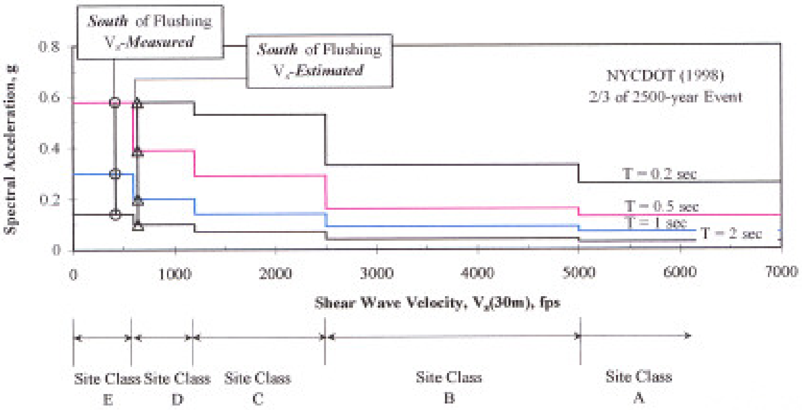

Figure 4: Comparison of spectral accelerations predicted using measured and estimated V_S values from the south of Flushing River, and based on the 1998 NYCDOT seismic guidelines.

Similar calculations made for the soil profile to the north of the Flushing River (Figure 5) lead to the conclusion that using the measured V_S values the profile is classified as D, and using the empirically estimated V_S values the profile is classified as E, the reverse trend observed for the south profile. In this case, the empirical procedure leads to an *overestimation* of spectral accelerations.

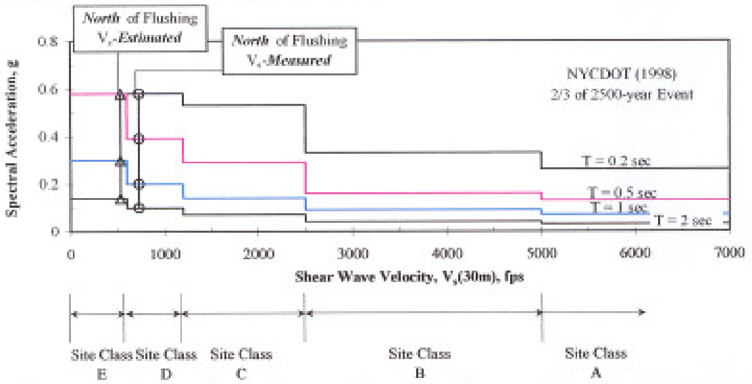

Figure 5: Comparison of spectral accelerations predicted using measured and estimated V_S values from the north of Flushing River, and based on the 1998 NYCDOT seismic guidelines.

It is evident that without having measured V_S values, using empirically based V_S values and generic spectra can lead to uncertain outcomes with regards to design level seismic forces. In this bridge project, the measured V_S values were used and site-specific ground motion analyses were performed to obtain reliable estimates of spectral accelerations and seismic loads.

The borehole logs of the field geotechnical investigations showed significant spatial variability in the SPT, N-values, particularly in the silty sand, and silty clay layers as shown in Figure 6.

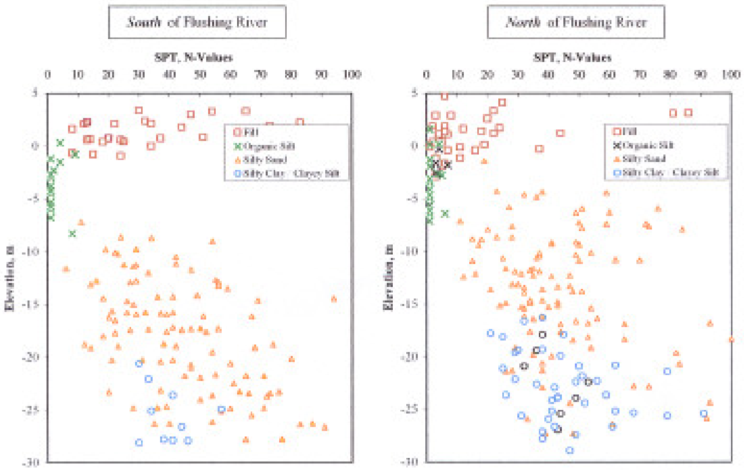

Figure 6: Spatial variability in the densities of the soils encountered at the project site.

The crosshole tests that were performed at two locations provided accurate shear wave velocities of the soil layers encountered at these locations. The spatial variability of these V_S values was considered by incorporating the variability in the N-values on the average V_S measured from the crosshole tests. Figure 7a shows one of the soil columns that represent the soil profile to the north of the Flushing River. This soil column was used to generate ground motions. Included in Figure 7a are ranges of V_s values that are based on the measured crosshole test results. The ranges of V_s incorporate the spatial variability in the site condition.

Figure 7b presents the response spectra of the computed motions from SHAKE analyses for the longitudinal and transverse components, for the lower and upper bound V_S values. The effect of V_S on the spectral accelerations is very pronounced. In the period range smaller than 1.5 sec, using the upper bound V_S values results in significantly larger spectral accelerations than using the lower bound V_S. The reverse is true for periods larger than 1.5 sec.

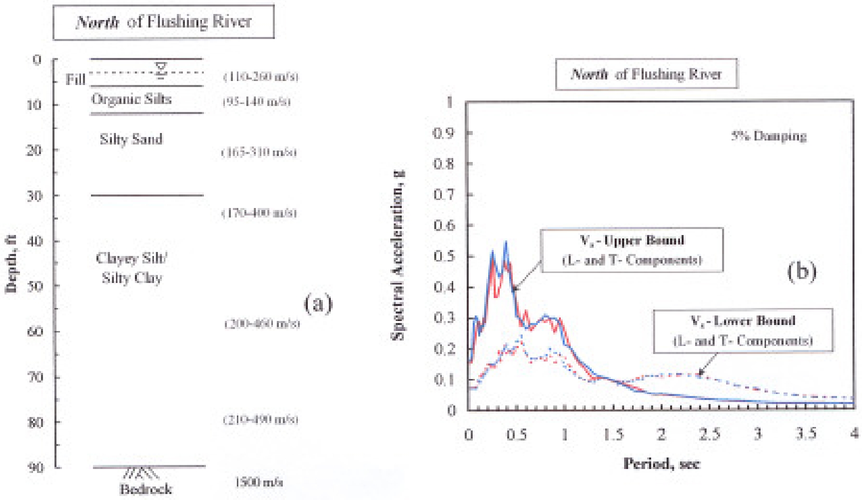

Figure 7: Soil column and V_s values used, and the computed acceleration spectra for the soil profile to the north of the Flushing River.

In summary, this case study demonstrates that shear wave velocities play an important role in characterizing a site and have a pronounced effect on the magnitude of spectral accelerations. Empirically based estimates can lead to erroneous classification of a site leading to sometimes overestimated and other times underestimated spectral accelerations. In-situ measurements of V_S can avoid such pitfalls and can yield reliable predictions of ground motions and design spectral accelerations.

3. Case study 2: bridge foundation stiffness and response

A second bridge case study is presented to demonstrate the importance of using accurate V_S and advanced analytical procedures for foundation stiffness calculations versus using average V_S and simplified procedures.

Figure 8 shows a longitudinal elevation of the Manhattan Cable Anchorage of the Brooklyn Bridge, in New York. The cable anchorage is founded on a deep deposit of soils as shown in Figure 9. Bedrock is about 175 feet below the ground surface.

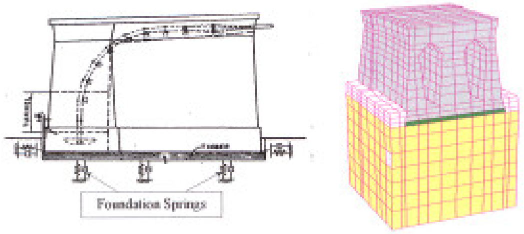

Figure 8: Elevation and computer model of the Manhattan cable anchorage.

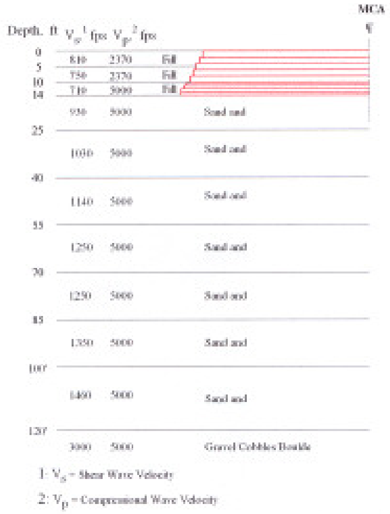

Figure 9: Soil profile and shear wave velocities used in the foundation stiffness calculations for the Manhattan Cable Anchorage.

In the global seismic analysis of the Brooklyn Bridge, soil-foundation-bridge interaction was accounted for through the use of foundation springs and dashpots as shown in Figure 8. When reliable information on the site characteristics and the shear wave velocities with depth are not available, the coefficients of foundation springs and dashpots often are computed using the simple procedure described by Gazetas (1991). In such an approach, typically an average value of V_S with depth of soil profile is used. Figure 10 shows the results of foundation stiffness calculations as a function of excitation frequency obtained using the simple procedure assuming an average V_S with depth.

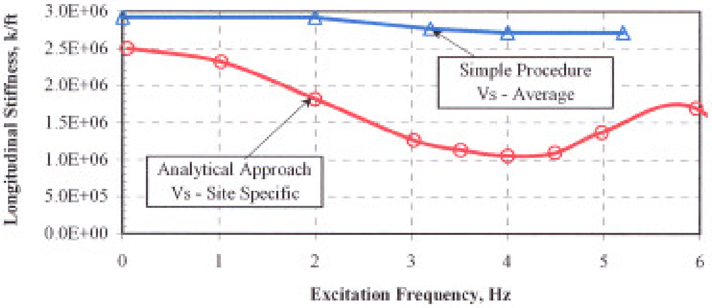

Figure 10: Comparison of stiffness coefficients using average and site-specific V_S.

The results from the simple procedure show that the static longitudinal stiffness coefficient of the cable anchorage is about 2.8E+06 k/ft, and that this coefficient varies little with the frequency of excitation.

In this project, the shear wave velocities of the soils were measured using crosshole tests. Such accurate characterization of the site and V_S permitted the use of advanced analytical approach utilizing the computer program ACS-SASSI, for the calculations of the ground motions as well as the foundation spring and dashpot coefficients for the cable anchorages of the bridge. The computer model used in these calculations is shown in Figure 8. The resulting stiffness coefficients as a function of the excitation frequency are shown in Figure 10. It is noted that the advanced analytical procedure that used accurate V_S yielded significantly smaller stiffness coefficients than those obtained from the simple procedure that used average V_S, especially in the frequency range of relevance in the analysis of the bridge (3 Hz to 4 Hz.).

Since a cable anchorage is a very rigid structure, soil-foundation-structure interaction becomes of major significance. The fundamental period of the system is primarily dictated by the foundation stiffness of the cable anchorage. To evaluate the effect of using average V_S and simple procedures for stiffness calculations on the seismic response of the Manhattan Cable Anchorage, the longitudinal period of the soil-foundation-cable anchorage system using the stiffness coefficients from both approaches were calculated. Using the stiffness coefficients based on average V_S and the simple procedure, the period of the cable anchorage was about 0.25 sec. The period of the cable anchorage calculated based on the stiffness coefficients obtained using accurate, site-specific V_S values and the advanced analytical approach was about 0.36 sec.

Figure 11 shows the response spectrum of the computed foundation motion for the 500-year event. Included in Figure 11 are two points that correspond to the responses of the cable anchorage corresponding to the two periods, 0.25 sec, and 0.36 sec.

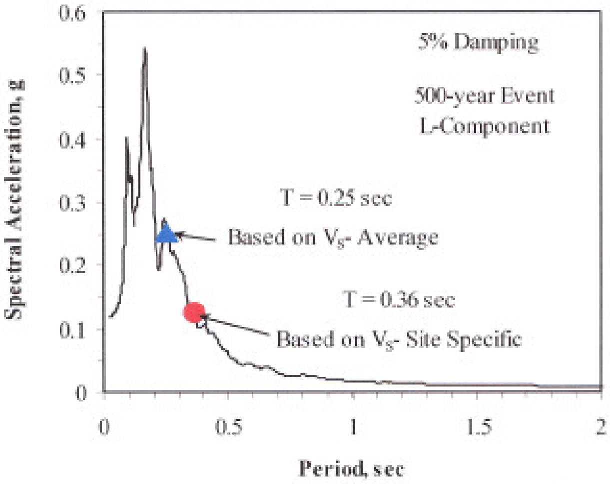

Figure 11: Comparison of spectral responses based on average and site-specific V_S.

The results shown in Figure 11 lead to the conclusion that if an average V_s together with simplified stiffness calculations are made, the estimated spectral acceleration of the cable anchorage is about 0.25g. Using measured V_s values and advanced analytical stiffness calculations yield a spectral acceleration of 0.13g, almost ½ of the spectral acceleration obtained based on average V_S. This case study demonstrates that using average V_s values and the simple procedure for stiffness calculations commonly used in practice, can sometimes lead to significantly overestimated seismic loads on a bridge structure that may result in costly and at times unnecessary retrofit requirements.

4. Summary

Seismic vulnerability assessment of a bridge requires realistic estimations of the ground motions and the modeling of the soil-foundation-bridge system. The shear wave velocities of the soil and rock encountered at a bridge site play a crucial role in such investigations. Through two example case studies, this paper demonstrates the importance of acquiring accurate in-situ measured shear wave velocities and accounting for their spatial variability. The availability of accurate shear wave velocity values also permits the application of advanced analytical methods for the computation of design spectra and for proper modeling of a soil-foundation-bridge system. Use of empirically estimated shear wave velocities and simplified analytical methods can lead to sometimes overly conservative and at other times unconservative seismic response values.

5. Acknowledgments

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