Annual Project Summary – Year 1

Determination of in-situ S wave attenuation in the sediments of the Mississippi embayment using existing boreholes and validation of refraction techniques for the determination of Q_s

External Grant Award Number: 03HQGR0036

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Non-technical summary

Reliable determination of attenuation in the sedimentary cover of the Mississippi embayment is critical for reliable hazard prediction. Because our current knowledge in this area is very limited, the goal of our research is a detailed analysis of attenuation using data to be collected in ten 60-m deep boreholes drilled in western Tennessee by the State of Tennessee Dept. of Transportation. In addition, because drilling and casing of boreholes is expensive, a second goal of our research is to establish whether refraction data, which are easy to collect, can be used to determine reliable estimates of attenuation.

Background

As is well known (e.g. Field, 2000, and references therein), unconsolidated or poorly consolidated sediments amplify the ground motion caused by seismic waves significantly, thus increasing the damage they cause. This is one of the reasons why structures built in sedimentary basins are at a higher risk than those built on hard rock. On the other hand, seismic wave attenuation in sediments can be high, which would contribute to a decrease in ground motion amplitudes. Therefore, a reliable estimate of the seismic attenuation in this kind of environments is necessary for a realistic assessment of seismic hazard. This is particularly true for the New Madrid seismic zone, which is covered by the sediments of the Mississippi embayment, with a thickness of about 1 km near Memphis, Tennessee.

Attenuation is usually quantified in terms of the inverse of the quality factor Q, and because most of the damage to buildings and structures in an earthquake arises from horizontal forces, for seismic risk studies the quantity of interest is the Q for shear waves (Q_s). In addition, because the determination of attenuation is based on variations of seismic wave amplitudes and shapes, establishing reliable values of Q_s requires the use of data recorded in boreholes. However, a drawback of borehole attenuation studies is the cost of drilling and casing and for this reason the number of values of Q_s determined for near-surface materials is small. A review of results from California and Japan (see Pujol et al., 2002) shows that in most cases Q_s is around 10 for depths around 100 m. On the other hand, our own results from three boreholes in the vicinity of Memphis show values of Q_s between 18 and 44 for depths reaching up to 60 m. The difference between these numbers and those obtained by other researchers is significant, as can be seen from Fig. 1, which shows the spectral ground motion amplification for a 100 m deep layer for the case of no attenuation and for two different values of Q_s, 10 and 30. Clearly, for some periods a Q_s of 10 will significantly reduce the amplification due to the presence of the layer, while a Q_s of 30 will not.

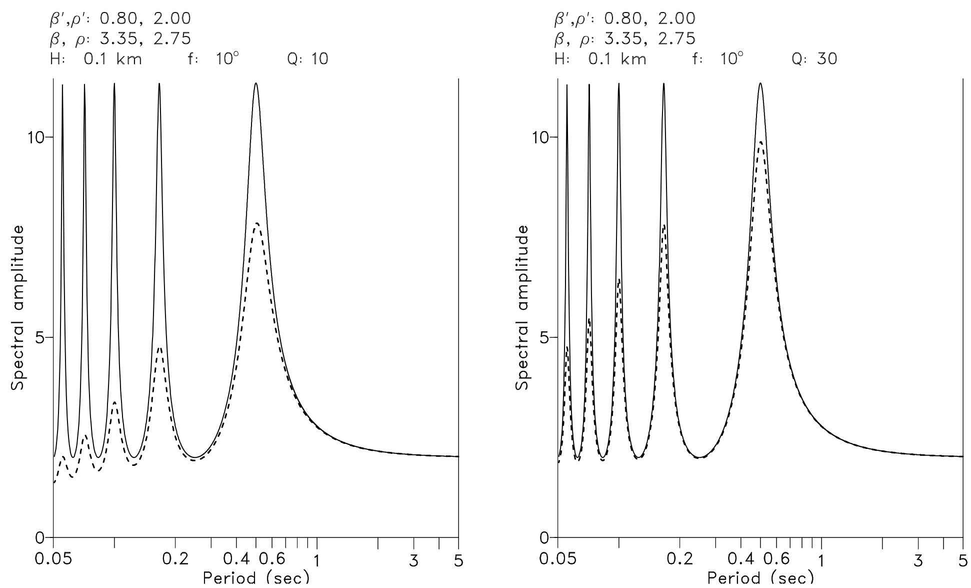

Figure 1. LEFT: Spectral amplitude vs. period for SH waves for a layer-over-halfspace model with velocity and density in the layer and in the half space (β', ρ', β, ρ) equal to 0.80 km/s and 2.00 gm/cm^3 and 3.35 km/s and 2.75 gm/cm^3, respectively. The layer thickness is 0.1 km. These values roughly represent the unconsolidated sediments of the Mississippi embayment and the underlying Paleozoic rocks near the northern end of the embayment. The incidence angle is 10°. The solid and dashed lines correspond to propagation in a medium without attenuation and with a Q_s equal to 10, respectively (from Pujol et al., 2002). RIGHT: Similar to the figure on the left with Q_s equal to 30.

Proposed research

Because our values of Q_s were considerably larger than expected from other researches, and because of the variability we had observed, we proposed to collect data in ten boreholes 60 m deep drilled along western Tennessee by the Department of Transportation as part of a different project (Pezeshk et al., 1998). In addition, our earlier results were determined for frequencies between 10 and 50 Hz because the results for lower frequencies were not reliable. These results had been obtained using a 10 Hz three-component commercial geophone, and to make sure that we would be able to get reliable values of Q_s for frequencies less than 10 Hz we proposed to modify the commercial system by adding a 4.5 Hz three-component geophone, which entailed a complete upgrade of our acquisition system. Finally, as noted above, borehole attenuation studies are not common because of high costs, and for these reason there have been attempts to determine Q_s using shallow SH wave refraction data(e.g., Wang et al., 1994). It is not clear, however, whether the values thus obtained really measure

Q_s, and for this reason we also proposed to collect refraction data at each borehole site and to estimate Q_s using the two data sets. In this way it will be possible to establish whether the refraction data can be used instead of borehole data.

Design and construction of the 4.5 - 10 Hz borehole geophone system

The 4.5 Hz geophones were attached to the 10 Hz borehole commercial instrument by means of the housing shown in Fig. 2. Using 2-inch inner diameter hollow PVC pipe, a 38-inch piece was cut in half longitudinally for a distance of 24.5 inches. The rest of the pipe was kept in its original state to house the 4.5 Hz geophones. The borehole instrument was then attached to the cut section of the pipe with the clamping device directed toward the open cut section. The backside of the 10 Hz system lays flat against the PVC pipe and is held in place by clamps. This allows for the clamping device to hold the system flat against the borehole in a vertical position.

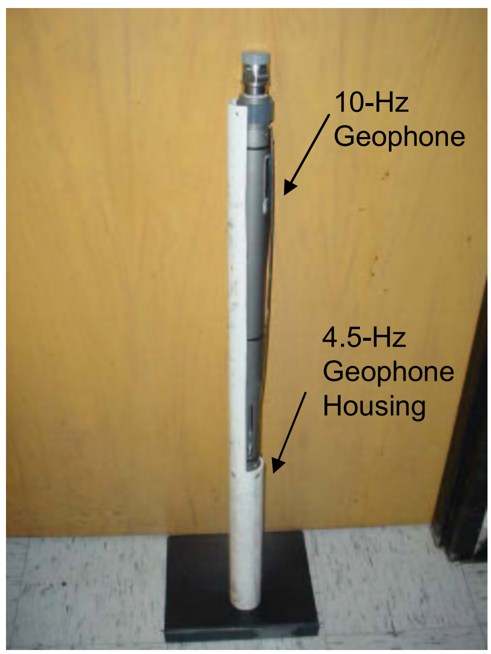

Figure 2. Modified borehole instrument.

The 4.5 Hz geophones were placed into a solid piece of 2-inch PVC that had three sections milled out for the geophones, one vertically, and two horizontally. The geophones were inserted into the millings and hot wax was then poured over them to create a watertight seal. The solid section was then inserted into the bottom of the PVC housing and secured so that the horizontal 4.5 Hz geophones were aligned with the 10 Hz horizontal geophones. This section was then waterproofed with solid PVC inserts placed on both top and bottom with an inch of hot wax poured over them.

The top insert has a waterproof wire pass connection on it that allows for the wire from the 4.5 Hz geophones to pass through the insert. This wire then runs along side the 10 Hz systems to a waterproof connection about 8 inches above the top of the 10 Hz system. This connection was constructed of schedule 80 PVC (this is a high-pressure and temperature PVC). A six-pin circular male-female connector was modified and placed inside the schedule 80 PVC connector. The connector is kept in place by an insert that threads into the connector and allows for the waterproof wire pass connector to be threaded into it. Once the two halves of the connector are pushed together, an outer locking ring tightens and creates a waterproof seal.

The analog signals coming from the geophones are digitized and amplified using a 16-panel board. Each panel consists of 10 separate settings each amplifying the signal by a power of 2. The signals are then transferred to a terminal screw panel. Two separate screw panels were installed, one digital and the other analog although only the latter is actually used. From there the signals are sent to a DT9800 data acquisition box manufactured by Data Translation. The DT9800 then connects to a field PC via a USB plug. Once in the computer, the data are processed with the VEE Pro 6.1 software, which is produced specifically for the DT9800 by Agilent Technologies in cooperation with Data Translation. The software allows for the collection, organization, and display of raw data.

Shear-wave seismic source

The seismic source we use in the borehole experiments is a shear wave generator similar to that described by Liu et al. (1996, 1997). Basically, it consists of a compressed-air driven hammer that slides on low-friction tracks. The hammer impacts on two anvils located on both sides of the hammer. The two impacts correspond to the forward and retracting motions of the hammer. The weight of a truck on the source gives a good coupling to the ground. The source was built by personnel of the Department of Civil Engineering at The University of Memphis using blueprints provided by Dr. Liu. This source is very repeatable, although in a previous experiment we have observed an increase in amplitude for the higher frequencies as the depth increases. Because the experiment was conducted from the surface down and the source position was unchanged, the amplitude increase for the higher frequencies is probably the result of a source-ground coupling that kept improving as the experiment proceeded. To account for these (slight) source variations we use a “source monitor”, which is a three-component geophone at a fixed position on the surface to record the waves generated each time that the source is activated.

Method used to determine Q_s

The determination of attenuation is based on the standard assumption of exponential amplitude decay in the frequency domain. For the the case of borehole data and a seismic source close to the borehole the variation in wave amplitudes can be represented by the following relation:

$$A_z(f) = (G_o/G_z)\, e^{-\alpha f} A_o(f) \tag{1}$$

where $A_o(f)$ is the amplitude of a reference wavelet at depth z_o, $A_z(f)$ is amplitude of a wavelet at depth z, α is the attenuation coefficient, and G_o and G_z are frequency-independent geometric spreading factors for depths z_o and z. A number of factors that may affect wave amplitudes and shapes are discussed in Pujol et al. (2002). The data recorded with the source monitor described above is used to extract A_o.

When the medium is homogeneous α is given by

$$\alpha = \pi\delta z/Qv; \qquad \delta z = z - z_o \tag{2a, b}$$

where v is the velocity of wave propagation in the medium. If α is independent of frequency, then one way to estimate Q is to fix z, to divide (1) by A_o and then to take logarithms on both sides. This gives

$$\ln \frac{A_z(f)}{A_o(f)} = -\alpha(z)f + \ln \frac{G_o}{G_z} \tag{3}$$

which is the equation of a straight line in f. In this context α is a function of z, known as cumulative attenuation, and can be determined by fitting a least squares line to the observations. Once $\alpha(z)$ has been computed, Q as a function of depth can be estimated using (2a). However, as scatter in the data may preclude the determination of reliable values of Q, we fit a straight line to $\alpha(z)$ for a range of values of z. Let k be the slope of the best-fit line. Then, from (2a) we get

$$k = \frac{\pi}{vQ} \tag{4}$$

so that

$$Q = \frac{\pi}{vk} \tag{5}$$

and

$$\alpha = k\delta z \tag{6}$$

The Q determined using (5) is an average value, and if $\alpha(z)$ is an approximately piecewise linear function of z, there will be a pair of values k and Q for each segment. Together with Q_s we also compute its standard deviation σ_Q (Pujol et al., 2002).

This method is based on Hauge (1981) and is convenient because it is not necessary to know the true amplitudes of the waves. When the assumption that α is independent of f is not valid, an alternative method is to fix f and let z vary (Pujol and Smithson, 1991). In this case it is critical to account for the geometric spreading correctly.

Data and preliminary data analysis

Our first data set was collected in August 2003 in a 60-m borehole in Bartlett, Tennessee, about 10 miles to the north of Memphis. The borehole was drilled in 1998, cased with 3-inch diameter PVC pipe and grouted. The modified borehole instrument was used with a 1.5 m (5 ft) depth interval. The time sampling interval was 0.67 ms. The shear-wave source described above was located about 1 m from the borehole. A surface 4.5 Hz three-component geophone was placed about 1 m from the source for monitoring purposes. For each depth four traces were recorded, two for each of the hammer directions. The traces corresponding to one of the horizontal components for the 4.5 Hz geophone and the respective monitor traces are shown in Fig. 3. The traces have been normalized so that the largest amplitude in each trace is one.

Figure 3 also shows the traces after windowing and time shifting. The spectra of the windowed data and monitor traces are shown in Fig. 4. The effect of attenuation on the spectral content of the traces is a reduction in the amplitude of the higher frequencies, and a shift of the peak frequencies to lower values as the depth increases, in agreement with the attenuation model. The spectral ratios (Fig. 4) show a linear relation between about 7 and 56 Hz. The deviation from a straight line for lower frequencies is puzzling and will be investigated further.

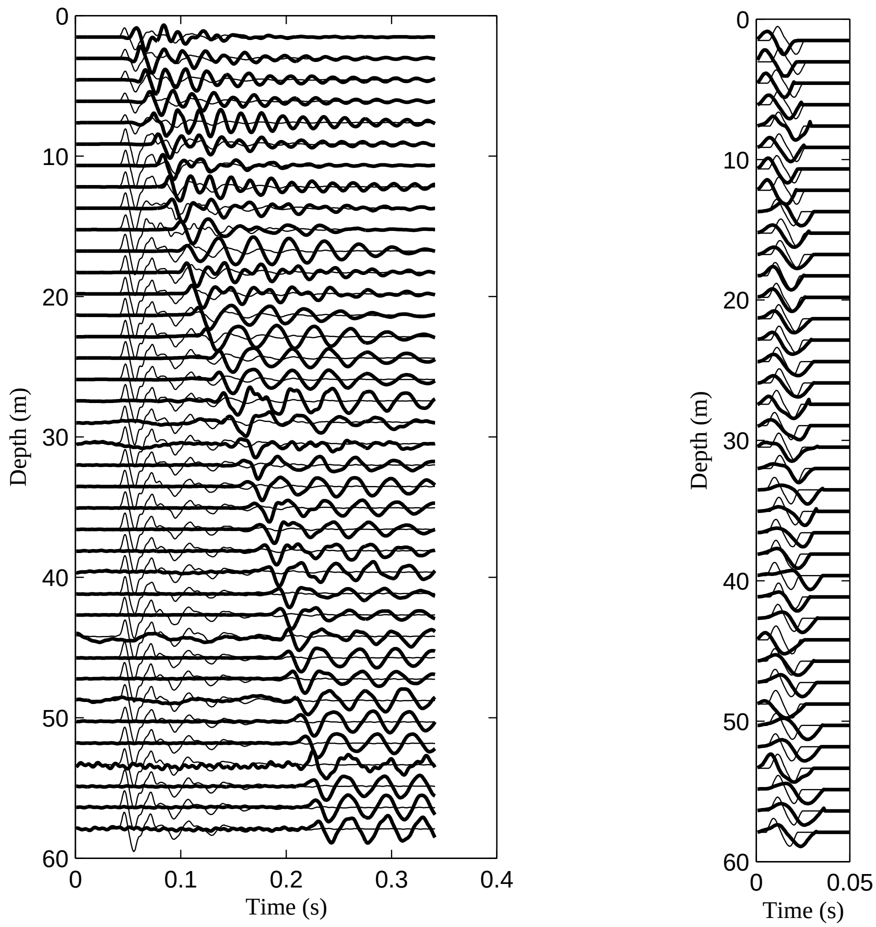

Figure 3. LEFT: Data recorded in the Bartlett, Tennessee borehole using a 4.5 Hz geophone (bold lines) and corresponding surface monitor traces (thin lines). RIGHT: first cycles of the traces on the left used for the attenuation analysis.

The slopes of the straight lines fitted to the attenuation curves (see Fig. 4) are plotted versus depth in Fig. 5. As expected, there is an increasing trend with depth, with the observed scatter caused by one or more of the various factors affecting wave shapes. From the slope of the best-fit line and using Eq. (5) with an average velocity of 350 m/s we get a Q_s of 23, which has a standard deviation σ_Q of 4. These values are only preliminary because Fig. 5 shows that at about 30 m depth there is a marked difference, which corresponds to a change in the slope of the first arrivals in Fig. 3 (left). Although the lithology log does not indicate a change in the composition of the soil at that depth, the blow count is more than doubled at about 27 m, which indicates that the soil becomes stiffer. Therefore, it is reasonable to expect that attenuation will be less, as Fig. 5 suggests. To investigate this question in more detail we will use synthetic seismograms (e.g. Pujol and Smithson, 1991).

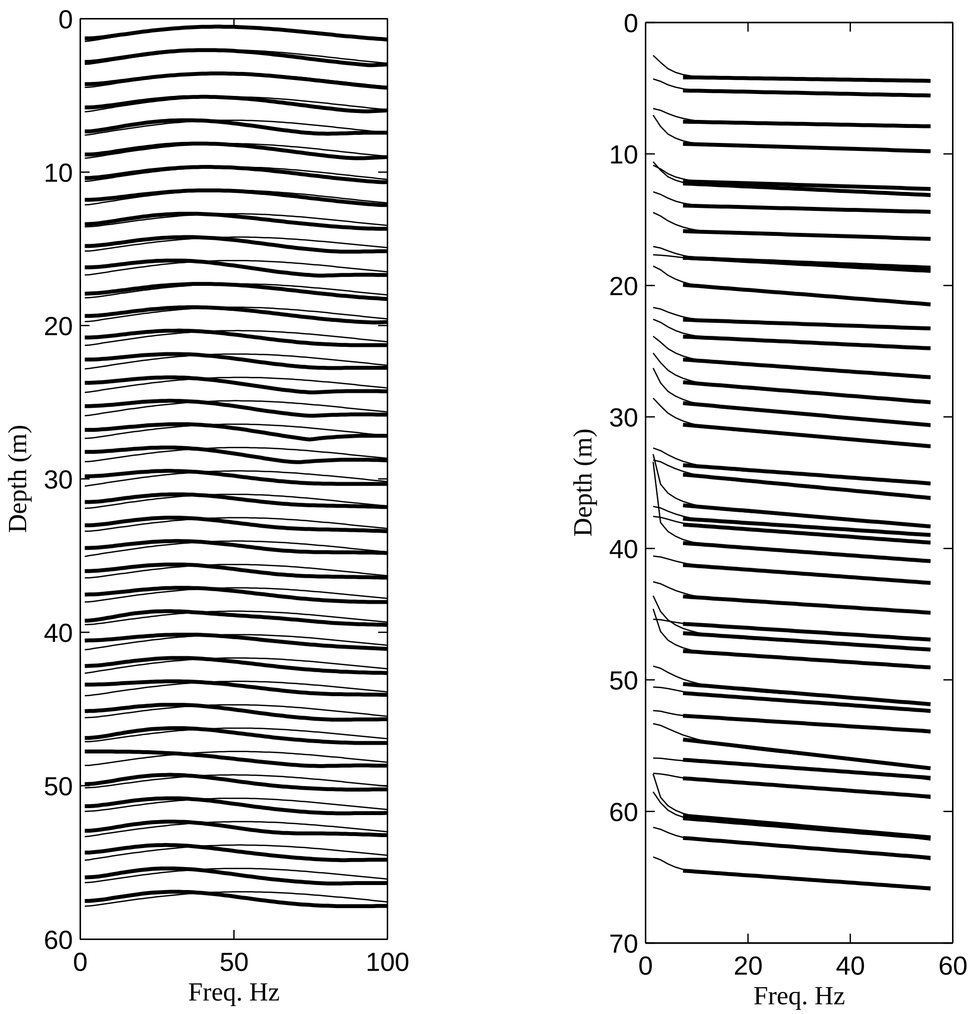

Figure 4. LEFT: Normalized spectra for the data on the right of Fig. 3. RIGHT: Spectral ratios for the pairs of spectra on the right. The best-fit lines between 7 and 56 Hz are shown in bold.

Data availability

The borehole data are available in ASCII format from Dr. S. Pezeshk (phone: 901-678-4727; email: spezeshk@memphis.edu).

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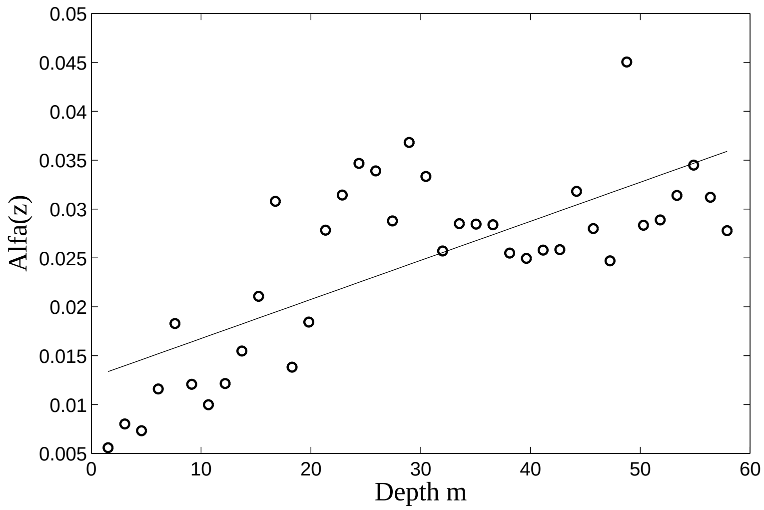

Figure 5. Attenuation curve for the Bartlett data. Circles represent the cumulative attenuation α derived from Fig. 4. The best-fit line is also shown.

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