DETERMINATION OF IN SITU SHEAR WAVE VELOCITIES

AT CABALLO DAM, NEW MEXICO

BY THE SASW METHOD

by

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1. INTRODUCTION

The Spectral-Analysis-of-Surface-Waves (SASW) method was used at
three sites at the toe of Caballo Dam located in Sierra County, New Mexico
on 30 and 31 January, 1989. This method was used to determine the
variation of in situ shear wave velocity with depth.

Results from this study are reported herein, along with a brief
explanation of the field testing procedures and the data analysis.

The work was awarded to the University of Texas at El Paso by the
U.S. Bureau of Reclamation (USBR). The contract officer technical
representative (COTR) for this project was Mr. Phil Sirles of the USBR.
Mr. Ken Skipper of the USBR assisted in field testing.

Mr. Phil Sirles was present at the site during SASW field tests and
authorized the location of the three sites. Mr. Phil Sirles and Mr. Ken
Skipper were of great assistance in the collection of the data. The
cooperation of these individuals is greatly appreciated.
2. SPECTRAL-ANALYSIS-OF-SURFACE-WAVES TESTING

2.1 BACKGROUND

The Spectral Analysis of Surface Waves (SASW) method is a method of surface seismic testing which has been developed for determining shear wave velocity and shear modulus profiles at soil sites and Young's modulus profiles at pavement sites (Nazarian and Stokoe, 1986 and 1987). The SASW method is a nondestructive method in which both the source and receivers are located on the ground surface. The source can be either a transient vertical impact, a steady state vibrator or a random noise generator. Each of these seismic sources generates a group of surface waves of various frequencies which the medium transmits. Two vertical receivers located on the surface monitor the propagation of surface wave energy past them. By analysis of the phase information of the cross power spectrum for each frequency determined between the two receivers, phase velocity, shear wave velocity and finally elastic moduli are determined.

The key points in SASW testing are generation and measurement of surface waves (Rayleigh waves). Rayleigh wave phase velocity, $V_{ph}$, is constant in a homogeneous half-space and independent of the frequency. Each frequency, $f$, has a corresponding wavelength, $L_{ph}$, according to:

$$V_{ph} = f \cdot L_{ph}$$  \hspace{1cm} (1)

Rayleigh wave (R-wave) phase velocity and shear wave (S-wave) velocity are related by Poisson's ratio of the material through which the wave energy propagates. Ideally, in an isotropic elastic half-space, the ratio of R-wave phase velocity to S-wave velocity increases as Poisson's ratio
increases. However, the change in this ratio is small, and it can be assumed that the ratio is approximately equal to 0.90 without introducing an error larger than five percent (Nazarian and Stokoe, 1987).

If the stiffness of a site varies with depth, then the velocity of the R-wave will vary with frequency. The variation of R-wave phase velocity with frequency (wavelength) is called a dispersion. A dispersion curve, phase velocity versus wavelength, is developed from phase information of the cross power spectrum. This information provides the relative phase between two signals (two-channel recorder) at each frequency in the range of frequencies excited during SASW testing. For a travel time equal to one period of the wave, the phase difference is 360 degrees. Thus, for each frequency the travel time between receivers can be calculated by:

\[ t(f) = \frac{\phi(f)}{360 \cdot f} \]  

(2)

where:

\( f \) = frequency

\( t(f) \) = travel time for a given frequency, and

\( \phi(f) \) = phase difference in degrees for a given frequency.

The distance between the receivers (geophones), \( D \), is a known parameter. Therefore, phase velocity of surface waves at a given frequency, \( V_{\text{ph}}(f) \), is simply calculated by:

\[ V_{\text{ph}}(f) = \frac{D}{t(f)} \]  

(3)
and the corresponding wavelength is equal to:

\[ L_{ph}(f) = \frac{V_{ph}(f)}{f} \]  

(4)

By repeating the procedure outlined in Eqs. 2 through 4 for every frequency, the phase velocity corresponding to each wavelength is computed, and the dispersion curve is derived.

Surface wave phase velocities determined by this method are not actual velocities of the layer but are apparent velocities. Existence of a layer with high or low velocity at the surface of the medium affects measurement of the velocities of the underlying layers. As such a method for determination of shear wave velocities from phase velocities is necessary in SASW testing.

Inversion of the dispersion curve, or (in short) inversion\(^1\), is the procedure used for determining a shear wave velocity profile. Inversion involves determination of the depth of each layer and the actual shear wave velocity of each layer from the dispersion curve.

The inversion process used herein is based upon a modified version of Thomson's (1950) and Haskell's (1953) matrix for elastic surface waves in a layered solid media. To simplify the process of inversion, some assumptions were made. These assumptions include: 1) the layers are horizontal, 2) the velocity within each layer is constant and does not vary with depth, and 3) the layers are homogenous and linearly elastic.

---

\(1\) note that the method described herein is properly named forward modelling (also known as system identification or backcalculation). However it is a common denomen in Civil Engineering to call this process "inversion".
The inversion process is an iterative process in which a shear wave velocity profile is assumed and a theoretical dispersion curve is constructed. The experimental (field data) and theoretical (assumed) curves are compared and appropriate changes are made in the assumed shear wave velocity profile until the two curves (experimental and theoretical dispersion curves) match within a reasonable tolerance.

Once the shear wave velocity for each layer is determined, the following formulae are used to calculate shear and Young's moduli for that layer:

\[ G = \rho \cdot v_s^2 \]  
\[ E = 2G(1+\nu) \]  

where:

- \( G \) = shear modulus,
- \( E \) = Young's modulus,
- \( \rho \) = mass density, and
- \( \nu \) = Poisson's ratio.

**2.2 PROCEDURE**

The general configuration of the source, receivers, and recording equipment is shown in Figure 1. Two 1-Hz geophones (velocity transducers) were used as receivers. The common receiver midpoint (CRMP) geometry (Nazarian and Stokoe, 1986) was used for testing. With this geometry the two receivers were moved away from an imaginary centerline midway between
Figure 1. General Configuration of SASW Testing

Figure 2. Schematic of Experimental Arrangement for SASW Tests.
the receivers at an equal pace, and the source was moved so that the distance between the source and near receiver was equal to the distance between the two receivers. In addition, the location of the source was reversed for each receiver spacing so that forward and reverse profiles were run. This testing sequence is illustrated in Figure 2. Distance between the receivers of 4, 8, 16, 32, 64, 96 and 128\(^2\) feet were utilized.

Different sources were used during this investigation. For close receiver spacings, a 15-lb sledge hammer was used. A 50-lb shaker was utilized for close spacings (i.e. less than or equal to 16 ft); however, due to a malfunction of the shaker this practice was discontinued. Therefore, all the data at close spacings were collected utilizing a sledge hammer. A bulldozer was used as the seismic source for receiver spacings of 32 ft and greater.

The recording device was a Hewlett-Packard 3562A Fourier spectral analyzer. A Fourier analyzer is a digital oscilloscope with a microprocessor which has the ability to directly perform in either time or frequency domain. Fourier analysis is a powerful tool in decomposition of complicated waveforms, and SASW testing could not be performed without such an analysis.

3. PRESENTATION OF RESULTS

3.1 LOCATION OF SITES

The location of the three SASW sites is shown in Figure 3. Three test sites were located along the downstream toe of Caballo Dam. Two of

2) not used at Site 3
Approximate centerline of dam

Downstream Shell materials

Note: 1in. ≈ 60ft.

Figure 3 - Generalized Plan View of the Three SASW Sites, Caballo Dam
the sites were located in the vicinity of three boreholes installed for the purpose of crosshole seismic testing, and a third site was located approximately 200 feet to the east. Sites 1 and 3 were almost parallel to the centerline of the dam, while Site 2 was perpendicular to it. Crosshole seismic testing was performed at the location of the three drill holes a week prior to SAW testing. Shear wave velocity profiles obtained from the crosshole tests were not provided to the University of Texas; however, a general profile of the materials encountered while drilling the middle borehole (of the crosshole triplet) was provided.

3.2 DISPERSION CURVES

Dispersion curves obtained at the three sites are demonstrated in Figures 4 through 6 for Sites 1, 2 and 3, respectively. These dispersion curves were obtained from the phase information of cross power spectra and coherence functions measured at various receiver spacings during SAW testing. All the spectral functions obtained from each receiver spacing and recorded at the three sites are included in Appendices A through C. As reflected in Appendices A and C, the quality of the spectral functions obtained at Sites 1 and 3 was good. In other words, the phase of the cross power spectra could be interpreted very easily.

At Site 2 the phase of the cross power spectra for shorter spacings were of good quality (see Appendix B); however, for longer spacings, the data were of relatively poor quality. For this reason the dispersion curve at Site 2 is extended to only a maximum wavelength of approximately 125 feet. In comparison, the dispersion curves obtained from Sites 1 and 3 were extended to about 190 feet. As previously mentioned, Site 2 was oriented perpendicular to the dam centerline, and two vertical material
Figure 4 - Comparison of Theoretical and Experimental Dispersion Curves from SASW Tests at Site 1, Caballo Dam
Figure 5 - Comparison of Theoretical and Experimental Dispersion Curves from SASW Tests at Site 2, Caballo Dam
Figure 6 - Comparison of Theoretical and Experimental Dispersion Curves from SASW tests at Site 3, Caballo Dam
boundaries (i.e., the downstream shell and construction fill materials, and, construction fill and natural soils) exist perpendicular to this SASW line. In our opinion, the consequence of the existence of these material boundaries resulted in poor quality data. Also, because of space limitations at this site, the source could only be located on one side of the SASW array; therefore, spectral functions for reversed profiles (as described in the CRMP geometry in Section 2.2) were not obtained. SASW tests for the close spacings were performed on the construction fill materials.

Dispersion curves generated for the three sites are presented again with an expanded scale in Appendices D through F for Sites 1, 2 and 3, respectively. The amount of scatter in the data is relatively small for Sites 1 and 3. Some scatter can be detected in the dispersion curve for Site 2 in the range of wavelengths between 50 and 95 ft. It should be mentioned that dispersion curves shown in Figures 4 through 6 and those presented in Appendices D through F are correspondingly the same curves but of different scales.

3.3 SHEAR WAVE VELOCITY PROFILES

Shear wave velocity profiles obtained after inversion of the dispersion curves are presented in Figures 7 through 9, where the values are listed in Tables 1 through 3 for Sites 1 through 3, respectively. A total of 18 layers were used during the inversion process at each site. The first twenty feet of the profiles were divided into ten, two-foot-thick layers. Seven four-foot-thick layers were used between the depths of 20 and 48 feet. During the inversion process, values for Poisson's ratio of 0.35 and 0.45 were assumed for the materials above and below the water
Figure 7 - Shear Wave Velocity Profile Obtained from SASW Tests at Site 1, Caballo Dam
Figure 8 - Shear Wave Velocity Profile Obtained from SASW Tests at Site 2, Caballo Dam
Figure 9 - Shear Wave Velocity Profile Obtained from SASW Tests at Site 3, Caballo Dam
Table 1 - Variation of Shear Wave Velocity and Shear Modulus with Depth at Site 1, Caballo Dam

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<td>1213.</td>
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<td>125</td>
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<td>0.45</td>
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<tr>
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<td></td>
<td></td>
<td>1882.</td>
<td>0.45</td>
<td>125</td>
</tr>
</tbody>
</table>
table, respectively. The water table was reported at a depth of approximately 20 feet. Total unit weights of 110 and 125 pcf were assumed for layers above and below the water table, respectively. As indicated before, mis-estimation of Poisson's ratio and total unit weight have a minimal effect on the final shear wave velocity profile.

Theoretical dispersion curves obtained after completion of the inversion process are compared with experimental dispersion curves obtained from field tests in Figures 4 through 6 for Sites 1 through 3, respectively. It can be seen that the two curves (experimental and theoretical dispersion curves) follow on another very closely for Site 1 (Figure 4) and Site 3 (Figure 6). The theoretical and experimental dispersion curves for Site 2 are in excellent agreement to a wavelength of 90 feet. The two curves are within 10 percent of one another below this wavelength.

Shear wave velocity profiles obtained at the three sites are compared in Figure 10. In general, each site demonstrates a similar trend to a depth of 18 feet. Below this depth, the shear wave velocity profiles are somewhat dissimilar. At Sites 1 and 3 stiffer layers were detected; however, the stiffer layer was detected at a depth of about 40 feet for Site 1, about 48 feet for Site 3, and it was not detected at Site 2.

4. CONCLUSIONS

In general, the quality of the data obtained from the SASW testing at Caballo Dam is good. Some scatter is present in the data collected at Site 2 because of the two material boundaries encountered within the SASW array. The inversion process was carried out successfully. The shear wave velocity profiles from the three sites agree reasonably well.
Figure 10 - Comparison of Shear Wave Velocity profiles obtained at three sites along the toe of Caballo Dam
5. REFERENCES


6. APPENDIX A

Spectral Functions Measured at Site 1, Caballo Dam
Figure A-1. Spectral Analysis Measurements from SASW tests at Site 1, Caballo Dam (Receiver Spacing of 4 ft)

(Top: Cross Power Spectrum, Record Number 40)
(Bottom: Coherence, Record Number 41)
Figure A-2. Spectral Analysis Measurements from SASW tests at Site 1, Caballo Dam (Receiver Spacing of 4 ft)

(Top: Cross Power Spectrum, Record Number 37)
(Bottom: Coherence, Record Number 38)
Figure A-3. Spectral Analysis Measurements from SASW tests at Site 1, Caballo Dam (Receiver Spacing of 8 ft)

(Top: Cross Power Spectrum, Record Number 34)
(Bottom: Coherence, Record Number 35)
Figure A-4. Spectral Analysis Measurements from SASW tests at Site 1, Caballo Dam (Receiver Spacing of 8 ft)

(Top: Cross Power Spectrum, Record Number 31)
(Bottom: Coherence, Record Number 32)
Figure A-5. Spectral Analysis Measurements from SASW tests at Site 1, Caballo Dam (Receiver Spacing of 8 ft)

(Top: Cross Power Spectrum, Record Number 28)
(Bottom: Coherence, Record Number 29)
Figure A-6. Spectral Analysis Measurements from SASW tests at Site 1, Caballo Dam (Receiver Spacing of 16 ft)

(Top: Cross Power Spectrum, Record Number 25)
(Bottom: Coherence, Record Number 26)
Figure A-7. Spectral Analysis Measurements from SASW tests at Site 1, Caballo Dam (Receiver Spacing of 16 ft)

(Top: Cross Power Spectrum, Record Number 22)
(Bottom: Coherence, Record Number 23)
Figure A-8. Spectral Analysis Measurements from SASW tests at Site 1, Caballo Dam (Receiver Spacing of 32 ft)

(Top: Cross Power Spectrum, Record Number 13)  
(Bottom: Coherence, Record Number 14)
Figure A-9. Spectral Analysis Measurements from SASW tests at Site 1, Caballo Dam (Receiver Spacing of 32 ft)

(Top: Cross Power Spectrum, Record Number 10)
(Bottom: Coherence, Record Number 11)
Figure A-10. Spectral Analysis Measurements from SASW tests at Site 1, Caballo Dam (Receiver Spacing of 64 ft)

(Top: Cross Power Spectrum, Record Number 16)
(Bottom: Coherence, Record Number 17)
Figure A-11. Spectral Analysis Measurements from SASW tests at Site 1, Caballo Dam (Receiver Spacing of 64 ft)

(Top: Cross Power Spectrum, Record Number 7)
(Bottom: Coherence, Record Number 8)
Figure A-12. Spectral Analysis Measurements from SASW tests at Site 1, Caballo Dam (Receiver Spacing of 96 ft)

(Top: Cross Power Spectrum, Record Number 19)
(Bottom: Coherence, Record Number 20)
Figure A-13. Spectral Analysis Measurements from SASW tests at Site 1, Caballo Dam (Receiver Spacing of 96 ft)

(Top: Cross Power Spectrum, Record Number 4)
(Bottom: Coherence, Record Number 5)
Figure A-14. Spectral Analysis Measurements from SASW tests at Site 1, Caballo Dam (Receiver Spacing of 128 ft)

(Top: Cross Power Spectrum, Record Number 1)
(Bottom: Coherence, Record Number 2)
7. APPENDIX B

Spectral Functions Measured at Site 2, Caballo Dam
Figure B-1. Spectral Analysis Measurements from SASW tests at Site 2, Caballo Dam (Receiver Spacing of 4 ft)

(Top: Cross Power Spectrum, Record Number 31)
(Bottom: Coherence, Record Number 32)
Figure B-2. Spectral Analysis Measurements from SASW tests at Site 2, Caballo Dam (Receiver Spacing of 4 ft)

(Top: Cross Power Spectrum, Record Number 28)
(Bottom: Coherence, Record Number 29)
Figure B-3. Spectral Analysis Measurements from SASW tests at Site 2, Caballo Dam (Receiver Spacing of 8 ft)

(Top: Cross Power Spectrum, Record Number 25)
(Bottom: Coherence, Record Number 26)
Figure B-4. Spectral Analysis Measurements from SASW tests at Site 2, Caballo Dam (Receiver Spacing of 8 ft)

(Top: Cross Power Spectrum, Record Number 22)
(Bottom: Coherence, Record Number 23)
Figure B-5. Spectral Analysis Measurements from SASW tests at Site 2, Caballo Dam (Receiver Spacing of 16 ft)

(Top: Cross Power Spectrum, Record Number 19)
(Bottom: Coherence, Record Number 20)
Figure B-6. Spectral Analysis Measurements from SASW tests at Site 2, Caballo Dam (Receiver Spacing of 16 ft)

(Top: Cross Power Spectrum, Record Number 16)
(Bottom: Coherence, Record Number 17)
Figure B-7. Spectral Analysis Measurements from SASW tests at Site 2, Caballo Dam (Receiver Spacing of 32 ft)

(Top: Cross Power Spectrum, Record Number 13)
(Bottom: Coherence, Record Number 14)
Figure B-8. Spectral Analysis Measurements from SASW tests
at Site 2, Caballo Dam (Receiver Spacing of 64 ft)

(Top: Cross Power Spectrum, Record Number 10)
(Bottom: Coherence, Record Number 11)
Figure B-9. Spectral Analysis Measurements from SASW tests at Site 2, Caballo Dam (Receiver Spacing of 96 ft)

(Top: Cross Power Spectrum, Record Number 7)
(Bottom: Coherence, Record Number 8)
Figure B-10. Spectral Analysis Measurements from SASW tests at Site 2, Caballo Dam (Receiver Spacing of 128 ft)

(Top: Cross Power Spectrum, Record Number 4)
(Bottom: Coherence, Record Number 5)
8. APPENDIX C

Spectral Functions Measured at Site 3, Caballo Dam
Figure C-1. Spectral Analysis Measurements from SASW tests at Site 3, Caballo Dam (Receiver Spacing of 4 ft)

(Top: Cross Power Spectrum, Record Number 31)
(Bottom: Coherence, Record Number 32)
Figure B-11. Spectral Analysis Measurements from SASW tests at Site 2, Caballo Dam (Receiver Spacing of 128 ft)

(Top: Cross Power Spectrum, Record Number 1)
(Bottom: Coherence, Record Number 2)
Figure C-2. Spectral Analysis Measurements from SASW tests at Site 3, Caballo Dam (Receiver Spacing of 4 ft)

(Top: Cross Power Spectrum, Record Number 28)
(Bottom: Coherence, Record Number 29)
Figure C-3. Spectral Analysis Measurements from SASW tests at Site 3, Caballo Dam (Receiver Spacing of 8 ft)

(Top: Cross Power Spectrum, Record Number 25)  
(Bottom: Coherence, Record Number 25)
Figure C-4. Spectral Analysis Measurements from SASW tests at Site 3, Caballo Dam (Receiver Spacing of 16 ft)

(Top: Cross Power Spectrum, Record Number 22)
(Bottom: Coherence, Record Number 23)
Figure C-5. Spectral Analysis Measurements from SASW tests at Site 3, Caballo Dam (Receiver Spacing of 16 ft)

(Top: Cross Power Spectrum, Record Number 19)
(Bottom: Coherence, Record Number 20)
Figure C-6. Spectral Analysis Measurements from SASW tests at Site 3, Caballo Dam (Receiver Spacing of 32 ft)

(Top: Cross Power Spectrum, Record Number 10)
(Bottom: Coherence, Record Number 11)
Figure C-7. Spectral Analysis Measurements from SASW tests at Site 3, Caballo Dam (Receiver Spacing of 32 ft)

(Top: Cross Power Spectrum, Record Number 7)
(Bottom: Coherence, Record Number 8)
Figure C-8. Spectral Analysis Measurements from SASW tests at Site 3, Caballo Dam (Receiver Spacing of 64 ft)

(Top: Cross Power Spectrum, Record Number 13)
(Bottom: Coherence, Record Number 14)
Figure C-9. Spectral Analysis Measurements from SASW tests at Site 3, Caballo Dam (Receiver Spacing of 64 ft)

(Top: Cross Power Spectrum, Record Number 4)
(Bottom: Coherence, Record Number 5)
Figure C-10. Spectral Analysis Measurements from SASW tests at Site 3, Caballo Dam (Receiver Spacing of 96 ft)

(Top: Cross Power Spectrum, Record Number 16)
(Bottom: Coherence, Record Number 17)
Figure C-11. Spectral Analysis Measurements from SASW tests at Site 3, Caballo Dam (Receiver Spacing of 96 ft)

(Top: Cross Power Spectrum, Record Number 1)
(Bottom: Coherence, Record Number 2)
9. APPENDIX D

Dispersion Curves Obtained at Site 1, Caballo Dam
Figure D.1 - Dispersion Curve Obtained from SASW Tests at Site 1, Caballo Dam. (Range of Wavelengths of 0 to 50 ft)
Figure D.2 - Dispersion Curve Obtained from SASW Tests at Site 1, Caballo Dam. (Range of Wavelengths of 50 to 125 ft)
Figure D.3 - Dispersion Curve Obtained from SASW Tests at Site 1, Caballo Dam. (Range of Wavelengths of 100 to 175 ft)
10. APPENDIX E

Dispersion Curves Obtained at Site 2, Caballo Dam
Dispersion Curve, fps

Figure E.1 - Dispersion Curve Obtained from SASE Tests at Site 2, Caballo Dam. (Range of Wavelengths of 0 to 50 ft)
Figure E.2 - Dispersion Curve Obtained from SASW Tests at Site 2, Caballo Dam. (Range of Wavelengths of 50 to 125)
Figure E.3 - Dispersion Curve Obtained from SASW Tests at Site 2, Caballo Dam. (Range of Wavelengths of 100 to 175 ft)
11. **APPENDIX F**

Dispersion Curves Obtained at Site 3, Caballo Dam
Figure F.1 - Dispersion Curve Obtained from SASW Tests at Site 3, Caballo Dam. (Range of Wavelengths of 0 to 50 ft)
Figure F.2 - Dispersion Curve Obtained from SASW Tests at Site 3, Caballo Dam. (Range of Wavelengths of 50 to 125 ft)
Figure F.3 - Dispersion Curve Obtained from SASW Tests at Site 3, Caballo Dam. (Range of Wavelengths of 100 to 175 ft)