DESIGN OF GEOPHYSICAL SURVEYS IN TRANSPORTATION

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ABSTRACT

Designing geophysical investigations for transportation related projects requires special attention to the constraints imposed by right-of-way, irregular topography, noise from traffic, and the need to avoid the interruption of traffic flow. A geophysical engineer needs to be prepared to consider these design issues that are not addressed in a standard procedure such as ASTM D-5777. The author presents design strategies that address these issues, and illustrates the concepts with case histories taken from bridge and highway projects. Beam steering, broadside shooting, and non-traditional designs that preserve alternative analysis options are presented. Transportation engineers who augment traditional subsurface geotechnical surveys with engineering geophysics are better prepared to avoid costly delays and redesign of projects due to differing site conditions.

INTRODUCTION

Application of geophysical methods to transportation projects falls into three general areas. First, there is the area of subsurface characterization and mapping. The goal is to avoid problems associated with unknown geological conditions which may require costly redesign measures and delays in project completion. Second, there is the location of buried utilities and other man made objects. This area is also known as subsurface utility engineering. Third, there is the field of non-destructive testing of roadways, bridges, and other transportation facilities.

This paper will be limited in scope, and focus only on the first area, characterization of the shallow subsurface geology. Further, it will be limited to seismic methods. The

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principals discussed will be illustrated by reference to case histories on the design of bridge foundations and the problems of slope stability above a roadway.

BEYOND GEOPHYSICAL STANDARDS

Standards, such as those published by the American Society for Testing Materials (ASTM, 1996), do exist for some geophysical methods. Typically, these exist as *guides*. A guide, as defined by ASTM, describes *"a series of options or instructions that do not recommend a specific course of action."* This is quite distinct from a *test method* or a *practice* (both of which do specify definitive procedures). Project engineers should know that ASTM guides are not considered comprehensive, and selection of a guide itself may present challenges to a non-geophysicist.

For example, a project engineer might be interested in mapping the depth to bedrock across a stream channel so that a bridge foundation can be designed. If the engineer specifies that a geophysical survey be conducted according to ASTM D-5777, Standard Guide for Using the Seismic Refraction Method for Subsurface Investigation, (ASTM, 1996), the results *might* be very informative (assuming that bedrock exists below the soil). On the other hand, it is quite possible that critically refracted rays will not be generated, and no interpretable data will be recorded. Being boxed in by the standard, the geophysical contractor will have to argue for a change in scope that permits other methods to be employed (such as reflection or surface wave surveys).

The ASTM guides are not intended to be comprehensive. This paper demonstrates survey design solutions to problems not addressed by the ASTM guides. These problems include noise from traffic and natural sources, and the limitations imposed by a narrow right-of-way.

CASE HISTORY: ATTENUATING NOISE, TRAFFIC AND RIVER FLOW

A common problem encountered in transportation related seismic surveys is traffic generated noise. Due to right-of-way limitations, geophones often are placed close to roadways. The seismic source must compete with noise generated from trucks and other large vehicles. This first example is from a bridge foundation study. Idaho Transportation Department (ITD) contracted a geophysical survey to determine if the soil layer was thick enough to support an H-pile foundation for a replacement bridge. The concern was that bedrock might be very shallow, and this would not permit a sufficient thickness of overburden to support the pile foundation. A detailed account of the results for this project may be found in Michaels (2001). The emphasis here will be on the unpublished design considerations for that geophysical investigation.

The original concept was to either deploy hydrophones in the river, or to plant geophones on the river bottom and up each bank. Explosive seismic sources would be placed at either end of the line of geophones for a reverse profile acquisition similar to the survey design described in ASTM D-5777. The problem with this design was that the swift current generated large amplitude noise on the hydrophones. Placing phones on the river bottom was not possible, since the river flow against the geophone case generated too much noise, and deployment was too risky. On the banks, the phones would have to be placed close to the road to stay in the right-of-way. Traffic included logging trucks and other large vehicles which generated surface waves that would degrade any

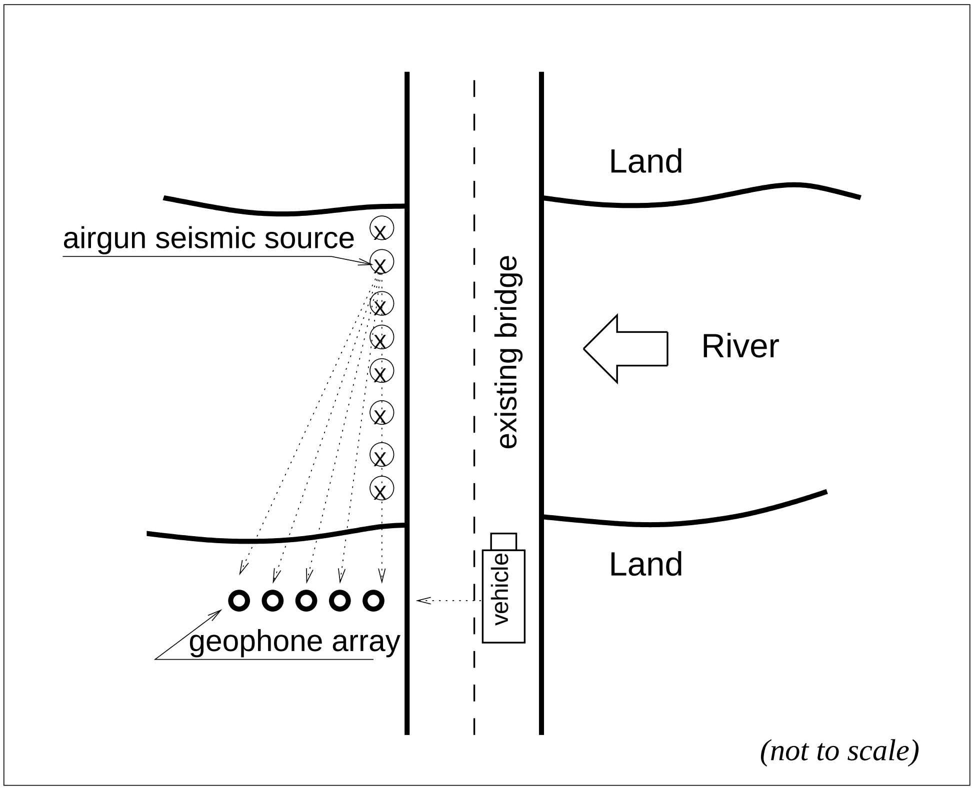

Figure 1 Plan view of geophone array and reciprocal shooting to attenuate noise.

signal from the seismic sources.

To avoid the noise from the river current, the author decided to design a reciprocal survey. The original placement of seismic sources and receivers was reversed. Instead of planting hydrophones across the river, the seismic source would be lowered from the existing bridge where receivers had been planned. The original planned seismic source positions were replaced with geophones. This meant that no water would flow against the geophones, now located on the bank. This greatly reduced the recorded noise.

To deal with traffic noise, a receiver array was deployed at each end of the section to be investigated. Figure 1 is a schematic plan view of the final concept. The geophone array is oriented orthogonal to the road way. The seismic waves from the seismic source positions in the river strike the array at about the same instant, and thus, the signal from the source is summed and enhanced. Waves from the roadway (noise) strike each geophone in the array at a slightly shifted time. When summed by the array, the noise is attenuated. In effect, the receiver array is like a directional antenna.

The original plan was to use explosives for a seismic source. However, we feared that we could easily loose control of a charge lowered into the river. The reason was that an occasional branch or tree limb would flow under the existing bridge, conceivably snapping the charge free from the shot wire. Instead, an air gun was fabricated from PVC tubing, the design of which is given in Michaels (2001). The use of the air gun avoided problems that would result from a lost explosive charge.

GEOPHONE ARRAY DESIGN

A geophone array adds directivity to the receiver of seismic signals. For an array consisting of equally weighted elements, the general rule of thumb will be that apparent wavelengths less than or equal to the physical length of the array will be rejected. The apparent wavelength depends on the true wavelength of the signal and the angle of arrival for that particular wavefield. Figure 2 illustrates the situation. The apparent wavelength is given by

$$\lambda_{app} = \frac{\lambda_{true}}{sin(\theta)} \tag{1}$$

where λ_{app} is the apparent wavelength, λ_{true} is the true wavelength, and θ is the angle of incidence as shown in Figure 2. Spatial frequency, or wavenumber, k, is defined as

$$k = \frac{2\pi}{\lambda} \tag{2}$$

where the units are radians per meter. Applying the definition of equation 2 to equation 1, we have

$$k_{app} = k_{true} sin(\theta) \quad . \tag{3}$$

We design the array to attenuate the traffic noise, and these are waves arriving from the roadway ($\theta = 90^o$), where the apparent wavelength equals the true wavelength. For a preliminary design of the array shown in Figure 1 we require the shortest and longest wavelengths radiated from the traffic sources. The minimum wavelength is used to determine the maximum element spacing, Δx, that will not be spatial aliased is given by

$$\Delta x \leq \frac{\lambda_{min}}{2} \tag{4}$$

where λ_{min} is the shortest wavelength (maximum wavenumber) expected from the roadway traffic. The other constraint is the maximum noise wavelength to be attenuated. A rule of thumb is to make the array physical length, L, equal to this maximum noise wavelength. Thus, the number of geophone elements is approximately given by

$$N = \frac{\lambda_{max}}{\Delta x} + 1 \tag{5}$$

where λ_{max} is the maximum expected wavelength.

To obtain values for λ_{min} and λ_{max}, one may choose to lay out a noise spread. A noise spread consists of a large number of closely space geophones placed on the ground where the array is to be located. One can trigger the recorder during a period of heavy traffic, or use an artificial source, like a sledge hammer, to observe the range of wavelengths likely to be recorded from traffic. The required wavelengths can be obtained from the slowest and fastest traffic generated wavefields,

$$\lambda_{min} = \frac{V_{min}}{f_{max}} \tag{6}$$

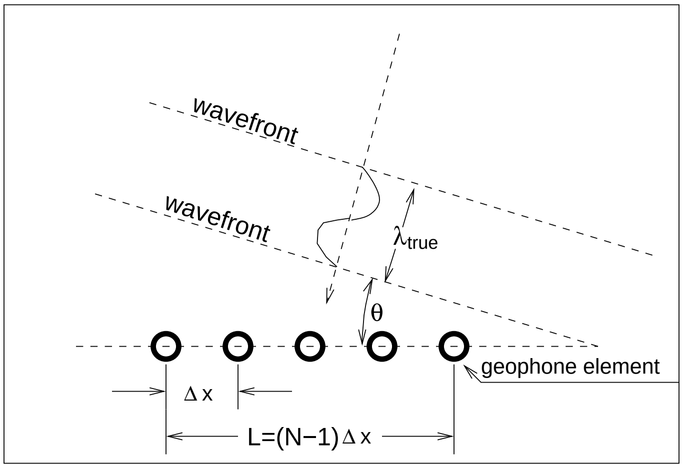

Figure 2 Wave arriving at angle θ to a geophone array.

$$\lambda_{max} = \frac{V_{max}}{f_{min}} \tag{7}$$

where the velocities are given by V_{min} and V_{max}, and the dominant frequencies are given by f_{min} and f_{max}. A more comprehensive design strategy is to compute the 2-dimensional Fourier Transform of the noise spread data. This is known as an F-K, frequency wavenumber plot. This is often worth while, since few noise spreads are reduced to the few measurements required for the right hand side of equations 6 and 7 above.

COMPUTING THE ARRAY RESPONSE

Once the preliminary array design is determined by the above procedure, one can then compute the array response and superimpose it on the F-K plot. This will reveal the location of leaks due to the side lobes of the array. For an array with N elements spaced Δx apart, the Z-transform is given by

$$F(Z) = \frac{1}{N}\left(1 + Z^{+1} + Z^{-1} + Z^{+2} + Z^{-2} + \cdots + Z^{(N-1)/2} + Z^{-(N-1)/2}\right) \tag{8}$$

and the spatial frequency response is given by substituting $Z = e^{-jk\Delta x}$into equation 8

$$F(k) = \frac{2}{N}\left[\frac{1}{2} + cos(k\Delta x) + cos(2k\Delta x) + \cdots + cos\left(\frac{(N-1)}{2}k\Delta x\right)\right] \quad . \tag{9}$$

Employing the relationship (see p. 248, EQA.9, Hsu (1970))

$$\frac{1}{2} + \sum_{n=1}^{M} cos(nx) = \frac{sin\left(\left(M + \frac{1}{2}\right)x\right)}{2sin\left(\frac{x}{2}\right)} \quad , \tag{10}$$

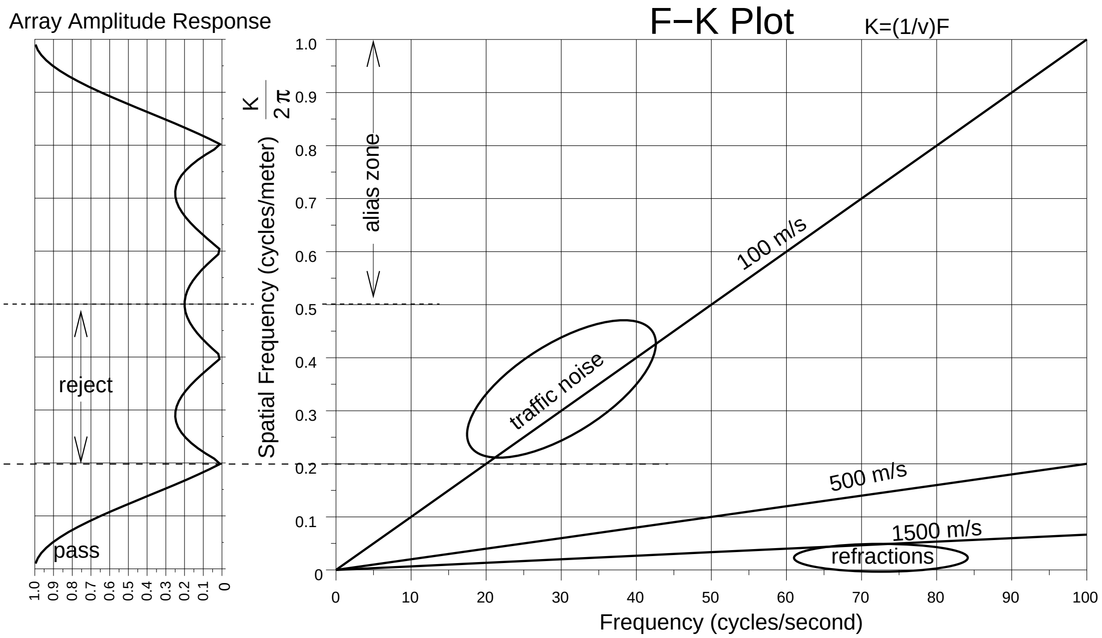

Figure 3 Array amplitude response plotted parallel to wavenumber, K, axis of F-K plot.

we may simplify the array response of equation 9, yielding

$$F(k) = \frac{sin\left(\frac{Nk\Delta x}{2}\right)}{N \cdot sin\left(\frac{k\Delta x}{2}\right)} \quad . \tag{11}$$

COMBINING THE ARRAY RESPONSE WITH THE F-K PLOT

A convenient way to summarize the concepts of the array response and F-K transform is shown in Figure 3. The array response is plotted parallel to the K-axis, and the units are in cycles/meter, ($\frac{k}{2\pi}$). The element spacing, Δx, for this is example is 1 meter. That establishes a Nyquist frequency of 0.5 cycles per meter. Should an F-K transform of the noise spread indicate that shorter wavelengths are present, then a smaller element spacing is required (see equation 4). In this simplified drawing, the traffic noise (indicated by the ellipse) is band-limited between 15-45 Hz, and the wavelengths are limited between 5 and 2 meters (wavenumbers between 0.2 and 0.5 cycles per meter respectively), and the choice of Δx is satisfactory. Further, in this example, the refractions are indicated to be band-limited between 60 and 85 Hz, with the wavelengths falling between ∞ and 20 meters (wavenumbers between 0 and .05 cycles per meter). The desired signal (refractions in the pass-band of the array) is enhance with respect to the traffic noise.

CASE HISTORY: LIMITED RIGHT OF WAY

In this second case history (Michaels, 1999), the problem was to evaluate the soil profile on the steep slope on one side of a roadway. The depth to bedrock was re-

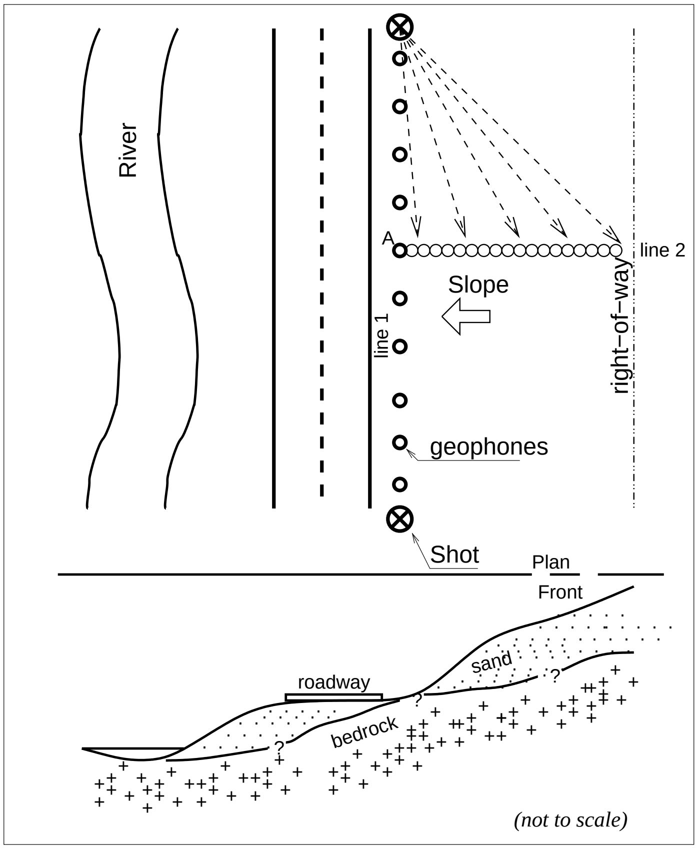

Figure 4 Broadside shooting applied to limited right-of-way conditions.

quired to assess the feasibility of adding a passing lane (which would require cutting into the slope), and then to evaluate the risk of potential landslides into the roadway. The right-of-way on the slope above the road only extended about 70 meters, severely restricting the range of offsets available for a refraction survey conducted up the slope. Furthermore, even if the permits had been obtainable to go beyond the right-of-way, the topography was very steep, and a drill could not be placed on the slope for shot holes. On the down-slope side of the road, the topography dropped sharply into the Payette River, and was even more difficult to investigate. On the other hand, a conventional reverse profile refraction survey was quite feasible on the shoulder, parallel to the road. Shot holes were easy to drill on the shoulder, and there were no restrictions on offset.

To solve the problem, the survey was designed in two phases, a sample of which is shown in Figure 4. First, line 1 (5 meter geophone spacing) was shot along the shoulder, and the refracted first arrivals were analyzed by the a delay time method (Michaels, 1995). The delay time for the geophone labeled “A” in Figure 4 was noted and then saved for use in the second phase. The second phase consisted of closely spaced (1 meter) geophones that ran up the slope (only one of several such lines is shown in the figure). Shots points on line 1 were re-occupied and data were collected broadside (see dashed arrows for one case). Analysis of the broadside shooting for delay times became possible because a solution had already been obtained for line 1. The refractor velocity, shot delay times, and the delay time at location “A” were all available to constrain what would otherwise be an under-determined system of equations. The trick to this type of design is to make sure that the broadside shot locations are far enough away from the line running up slope. The first arrivals need to be a refractions. Thus, the source must be beyond the cross-over distance, such that the first arrival for every geophone on line 2 is a refraction from the top of bedrock.

SUMMARY

Transportation projects present many challenges for those charged with conducting geophysical surveys. While guides, such as ASTM D-5777 are helpful in a general sense, one must innovate to overcome common obstacles imposed by traffic noise and limited right-of-way. There is no one correct or best way to conduct a geophysical survey, just as there is no one best way to design a bridge or roadway. In the case of the bridge investigation, the geophone array and reciprocal shooting geometry made it possible to analyze the data for both refractions and reflections, greatly reducing the risk of differing site conditions in the bridge foundation design (Michaels, 2001). In the other example, the difficulties associated with a steep slope and limited right-of-way were solved by a two phase approach (traditional reverse profiles along the shoulder, and broadside shooting up the slope). The resulting images helped the transportation engineers decide not to locate the passing lane at the investigated site, since the risk of landslide would be increased with further excavations (Michaels, 1999).

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