# A Study of the Geologic Section at Bloomington, Indiana, Using Rayleigh Wave Displacement Amplitude Ratios

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*Abstract*

The elliptic particle trajectories of Rayleigh waves in the frequency of range 0.5 to 2.0 hertz produced by coal mine explosions and recorded at Bloomington, Indiana, were studied to determine whether the particle motion conformed to the theoretical prediction for Rayleigh waves propagating on an elastic, horizontally layered half space and could, therefore, be used to determine the elastic parameters of layers within the sedimentary section beneath the receiver.

Surface waves from two hundred mine blasts were digitized at a sampling rate of 10 points per second and recorded on magnetic tape. The results of analysis show that the phase difference of the horizontal and vertical components is statistically scattered about the value of $\pi/2$, the theoretically predicted value, and that values of the displacement amplitude ratio, defined as the ratio of the magnitude of the horizontal component to the magnitude of the vertical component, can be fitted to values calculated from an elastic parameter model of the geologic section at Bloomington.

It is concluded that structural irregularities have had little noticeable effect on the results and that the observation of displacement amplitude ratios may be a useful means of determining the gross structure of sedimentary basins.

## Introduction

Rayleigh waves are seismic waves which propagate on the surface of the earth with a particle displacement contained by the vertical-radial plane such that the particle trajectory is elliptical and retrograde.

The eccentricity (displacement ratio) of the ellipse of motion is a function of the medium in which the Rayleigh wave is travelling. Layering introduces a frequency dependence. The displacement ratio value is measured as the ratio of the radical to the vertical spectral amplitude of the Rayleigh wave.

$$E(nf) = |A_r(nf)|/|A_v(nf)| \qquad (1)$$

The spectral dispersion of the displacement ratio depends almost solely on the seismic section beneath the recording station and is independent of the travel path or source. The dispersion is a function of density, layer thickness, and compressional (P) wave velocity; and is particularly sensitive to shear (S) wave velocity. The particular attractions of the use of displacement ratios to the study of the structure of geologic layering are that an interpretation is derived from a single point of observation and that the study provides knowledge of S wave velocity, the least accurately determinable body wave.

The use of displacement ratios to study the structure of geologic layering was first done by Lee in the 1930's (6,7); hindered by the burden of the calculation, he was limited to a two layer interpretation. The method has recently been applied to the study of the lower crust-upper mantle of the continental United States (2,10,11) and to the determination of the shear velocity structure at Apollo sites 12, 14, and 15 on the moon (9).

This study is an application to the interpretation of the sedimentary structure of the west flank of the Cincinnatti Arch under Bloomington, Indiana.

## Assumptions

Spectral dispersion for a theoretical model, calculated using the Thompson-Haskell matrix method (4), requires that the model be an infinite half space with perfectly horizontal and planar layers. The west flank of the Cincinnatti Arch has a gentle slope of about 0.5 percent; the interfaces are not planar; and the layers wedge out on the surface of the earth. To apply a modelling method to the inversion of displacement ratio data, the discrepancies between the geologic section and the model requirements must be negligible.

Experiments with the propagation of Rayleigh waves on wedges (5) have demonstrated that the effect of a 5 percent wedge is negligible; however, the presence of surface irregularities is likely to cause complications by the regeneration of seismic energy by the incidence of the original seismic signal on a surface or interface topographic feature. The effect of interfering noise on amplitude and phase modulation has been found to be quite dramatic (2). If the noise is random with respect to the signal, the effect can be diminished statistically, but if the noise correlates with the signal, such as regeneration, the effect may result in irrecoverably altered data.

## Geologic Setting

Because the spectral dispersion of displacement ratios depends only on the strata beneath the receiver, the section immediately beneath Bloomington is of interest. For this study both the geologic and the P velocity control were provided by studies of the Luther Brown test well in Lawrence County. This well is stratigraphically down strike from Bloomington; it is one of only a few wells drilled to the Precambrian in Indiana; and it is the only well with a continuous velocity log from the New Albany Shale to the basement (1,3). The depth to strata surfaces is slightly greater at Bloomington than at the test well; this is reflected in the models which were developed.

Of the parameters other than P velocity and layer thickness needed to calculate the dispersion properties of a model, the average Poisson's ratio is estimated to be 0.33 for sedimentary basins and density was assigned the value 2.5. The modelling process refined the initial estimates somewhat. Shear velocity for a Poisson's ratio of 0.33 is half the P velocity.

## Procedure

Seismic signals are continually recorded digitally onto magnetic tape at the seismic station at Bloomington. The sampling rate is 10 points per second with a resolution of 12 bits for all three components. The signal is amplified and converted from long period Sprengnether seismometers.

The signals analyzed in this study mostly originated from surface coal mines located 45 to 140 kilometers west and southwest of Bloomington (figure 1). The signals are dispersed in the frequency range 0.4

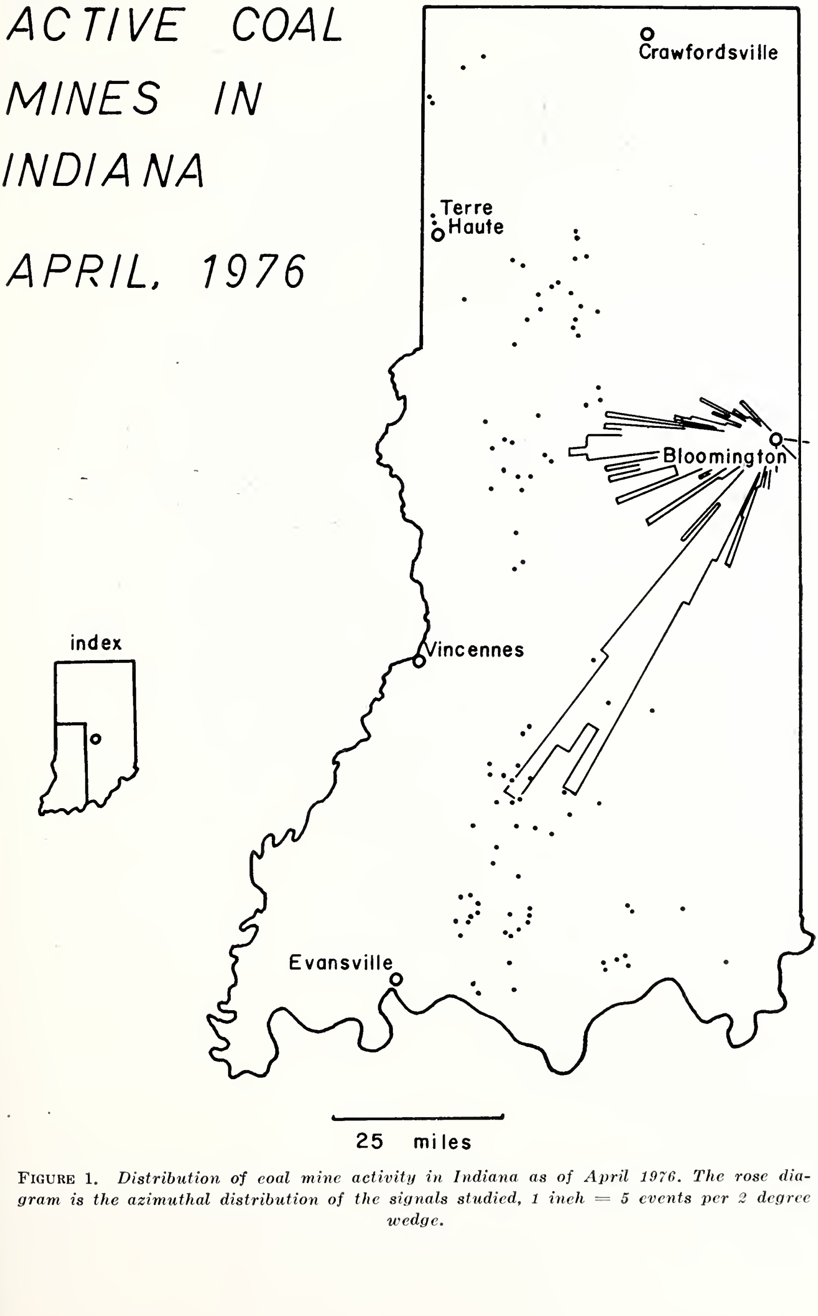


FIGURE 1. *Distribution of coal mine activity in Indiana as of April 1976. The rose diagram is the azimuthal distribution of the signals studied, 1 inch = 5 events per 2 degree wedge.*

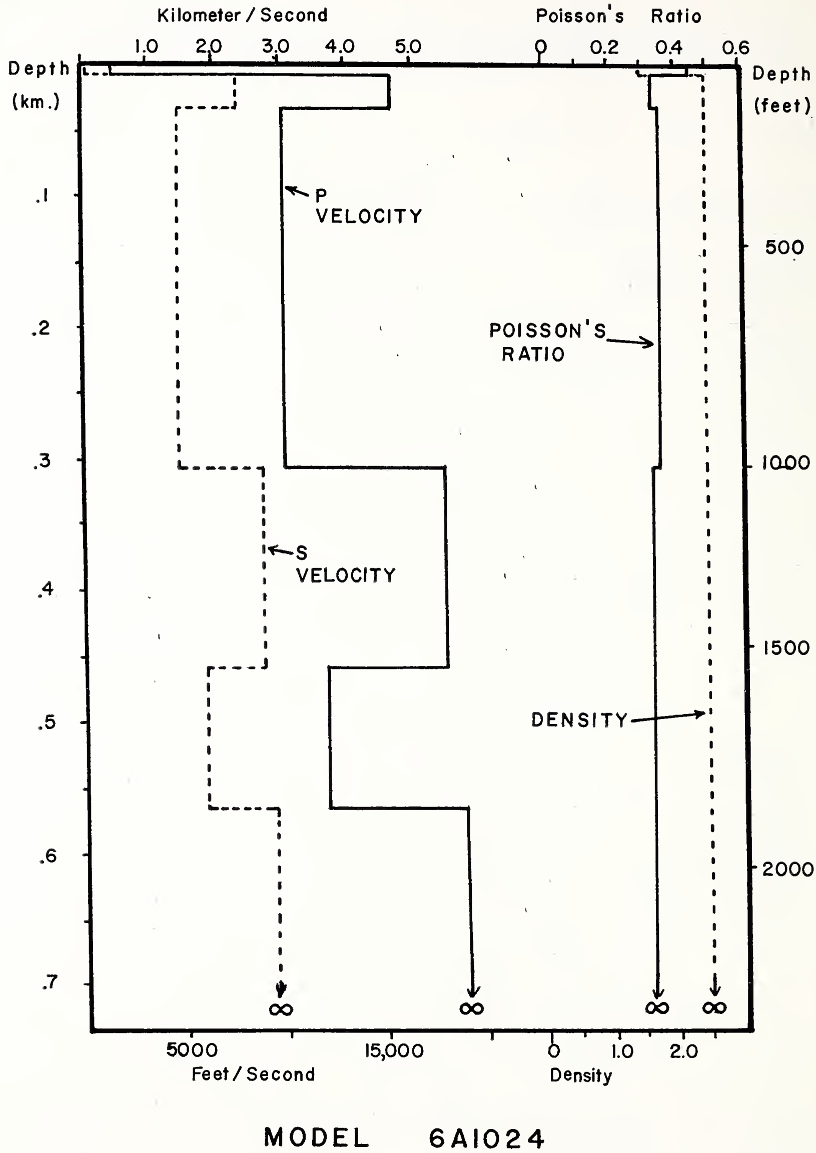


FIGURE 2. *Model 6A1024, a model of the elastic structure of the upper 1.5 kilometers of the geologic section beneath Bloomington, Indiana, which provides a reasonable fit to the data.*

to 2.0 hertz. It is in this frequency range that surface waves are most greatly influenced by the sedimentary section.

Because of the pronounced effect of noise modulation on the signal it was necessary to look at a large number of events so that random noise could be statistically removed. Two hundred events were used. To process the data in a reasonable length of time expedient methods were developed. The desired events are transcribed from a continually recorded tape to a condensed archive tape. Each event is filtered and inspected for acceptance; the source direction is established by correlating the phase shift filtered vertical component with the horizontal component; and the displacement ratio and the phase difference are calculated as functions of frequency for each event. Coalescing all events, the average values of displacement ratio, phase difference, and the vector length are determined. The data is discriminated according to the value of the mean vector length, a measure of data coherence (8). Once the data is evaluated a geologically reasonable model is determined by a trial-and-error process which compares the data with mathematical models.

## Results

A good tentative model for the geologic section is model 6A1024 (figure 2), which fits the data as shown in figure 3. The larger deviations in the data (e.g., at 0.95 hz., 1.05 hz., 1.2 hz.) are due to the interference of correlational noise and cannot be removed statistically. The poorness of the fit above 1.6 hertz has two possible explanations: either the model is not a correct representation, or the data is erroneous at the higher frequencies. Perturbation curves and the trends of the models developed suggests that the first explanation may not be correct.

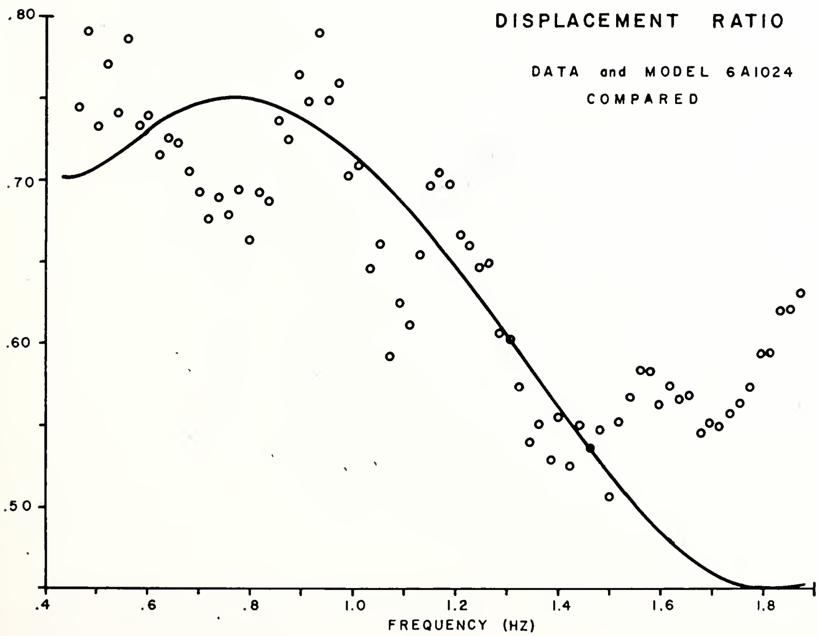


FIGURE 3. *The comparison of the model and the data. The data points are the result of the statistical reduction of over 5000 observations.*

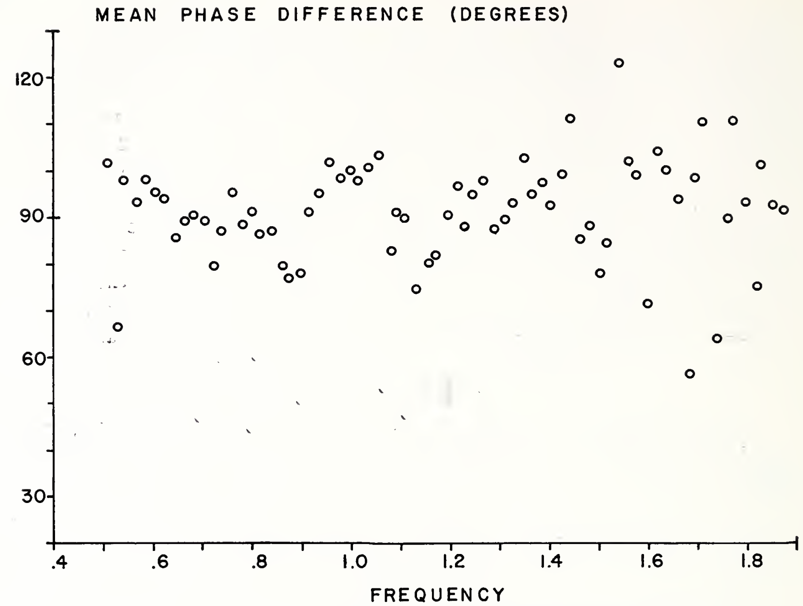


FIGURE 4. *Mean phase difference of the vertical and radial components.*

The scatter at the higher frequencies of the mean phase difference (figure 4) suggests that the Rayleigh wave is not well behaved theoretically above 1.6 hertz, and the low values at the higher frequencies of the mean vector length (figure 5) indicate that the signal is not very coherent above 1.6 hertz. This supports the second explanation.

The randomness and lack of theoretical behavior may be due to the departure of the seismic station geometry from the requirements of the theoretical calculation. The required presence of twenty feet of overburden may be a partial compensation of the effect of the seismic station pier rather than indicating the presence of 20 feet of alluvium in Bloomington.

## Conclusions

The use of displacement ratios is an interesting and novel means of studying the seismic properties of the geologic section in a horizontally layered region. With a systematic method of analysis the derived information is broader than the information derived solely from P wave studies because S velocity, Poisson's ratio, and density information is derived as well as P velocity and layer depths. The method is cheaper than reflection methods, and, in areas with low velocity layers, is more accurate than refraction methods.

The method would be most advantageously used in conjunction with a surface wave velocity analysis technique because the observations are independent and results would have a greater resolution. A tripartite station arrangement with stations 2-5 kilometers apart is suggested. It appears that the observations in this study exceeded the upper frequency limit of the Bloomington seismic station and that the seismometers should be set at bedrock level to study high frequency Rayleigh waves.

It is felt that the effect of correlational noise while quite noticeable in the data had a rather minimal effect on the interpretation of the data.

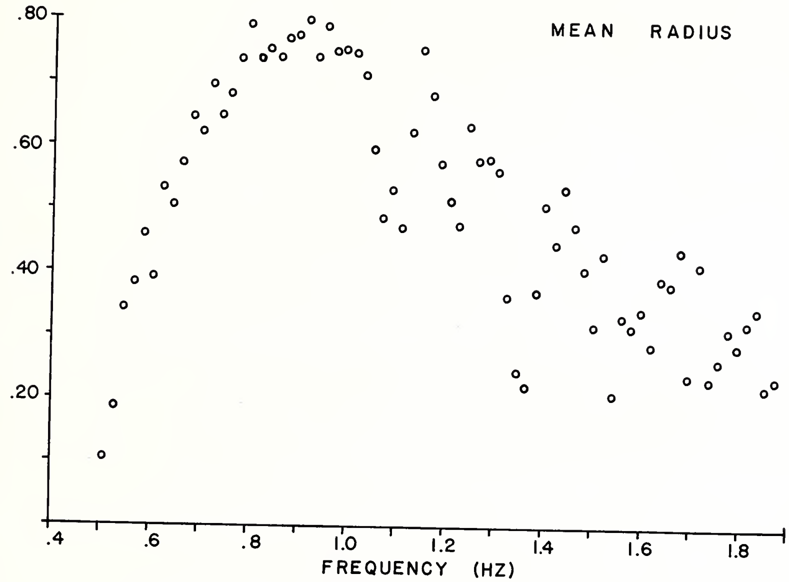


FIGURE 5. *Mean vector length (radius) of the phase vector.*

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