# Arrival time and energy density fluctuation of P-wave in heterogeneous media

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## Introduction

When seismic wave propagates through random heterogeneous media, waveform is distorted by scattering due to the underground heterogeneity, causing fluctuations in arrival time and amplitude. Therefore, a study of spatial fluctuations of arrival time and wave energy and their relationship with size of heterogeneity is important in mapping complex subsurface structures. The fluctuations in P-wave amplitude and arrival time were studied to elucidate the statistical characteristics of the underground random heterogeneity (Aki, 1973; Butler, 1984; Frankel and Clayton, 1986; Roth, 1997). Those studies were performed by analyzing the array data or by numerical simulations. Laboratory physical model experiments (Nishizawa et al., 1997; 1998) provide better understanding about the effects of heterogeneity on seismic wave amplitude and arrival time because of known characteristics of heterogeneity in the medium. In order to study the effects of heterogeneity on seismic wave, we made laboratory model experiments using various rock samples and artificial heterogeneous materials made by gypsum. Elastic waves are generated by a piezo-electric transducer and observed by a laser Doppler vibrometer, which accomplishes very accurate measurements. Waveforms were measured by changing the size of heterogeneity or by changing the wave frequency covering the various ratios of heterogeneity scale and seismic wave length.

In physical model experiments, the estimation of the arrival times should be accurate. Takanami and Kitagawa (1991) have demonstrated that a method based on autoregressive (AR) modeling and Akaike Information Criterion (AIC) provides better estimates of P- and S- arrivals. We implemented their method and evaluated its performance by analyzing various waveform data obtained in our experiments. Arrival times of the longitudinal wave (P-wave) is estimated by searching the best-fit AR-models that divide the waveform into two different time series, noise and signal, in terms of AIC. This method yields reliable P-wave arrival times (Sivaji et al., 1999). We also studied spatial fluctuations of wave energy by using the amplitude data in the time window starting from the onset of P-wave and ending at the coda part. The statistical distributions of arrival time fluctuation and energy fluctuation were analyzed in order to find the relationships between these fluctuations and the scale length of random heterogeneity.

## Results and discussion

We measured arrival time fluctuations of seismic waves propagating through a steel block and two crystalline rock samples, Westerly and Oshima granite, which show different scales of heterogeneity. We also measured the waveforms through artificial heterogeneous medium made by gypsum and rock granules. For gypsum samples, we changed frequency of input signal to study the relationship between the scale length of heterogeneity and the wave length. Here, we show the results obtained for gypsum, Westerly and Oshima granite samples.

Figures 1-a and 1-b show the frequency distribution and fitted Gaussian probability density function(PDF) of observed arrival time for a homogeneous medium made by gypsum and a heterogeneous medium having a heterogeneous layer in gypsum, respectively. The heterogeneous layer is 5 mm in thickness, consisting of rock granules with the diameter 0.85-2 mm. Figures 1-c and 1-d show the observed frequency distributions and fitted PDF of arrival time and log energy for the homogeneous and heterogeneous samples, respectively. The arrival time and log energy distributions for Westerly

(Fig.1e,1g) and Oshima (Fig.1f,1h) granites are also shown.

The histograms represent the observed probability density function obtained by computing derivative of cumulative distribution function. This is then matched with Gaussian PDF computed with sample mean and variance as parameters. Actually, the histograms of the travel time fluctuation, and log energy fluctuation indicate that the arrival time and the energy distributions are skewed, and deviate slightly from the Gaussian PDFs. The distribution of log energy (Figs. 1c,1d,1g and 1h) exhibits less skew and matched closely with Gaussian PDF. The best-fit distributions can be obtained by fitting various PDFs to the data. However, to elucidate the effect on variance due to heterogeneity, we first discuss by adopting the Gaussian PDF.

The parameters of the PDFs indicate that the variance is larger for the heterogeneous sample compared to that for the homogeneous Gypsum sample. The distributions for Oshima exhibit larger variance than those of Westerly granite. This relationship holds for both arrival time and log energy. The increase of variance from homogeneous to heterogeneous (Gypsum) and Westerly to Oshima granites depicts that there is a positive correlation between variance of statistical distribution of arrival time (and energy) and the scale of heterogeneity. Most of the analyses in geophysics and geophysical explorations are done by assuming that the travel time fluctuation is Gaussian. However, our results suggest that the distribution of travel time fluctuation is skewed and may be represented by best fit distribution other than Gaussian. These characteristics are of basic importance when we analyze the seismic waveform for estimating underground structure and heterogeneity.

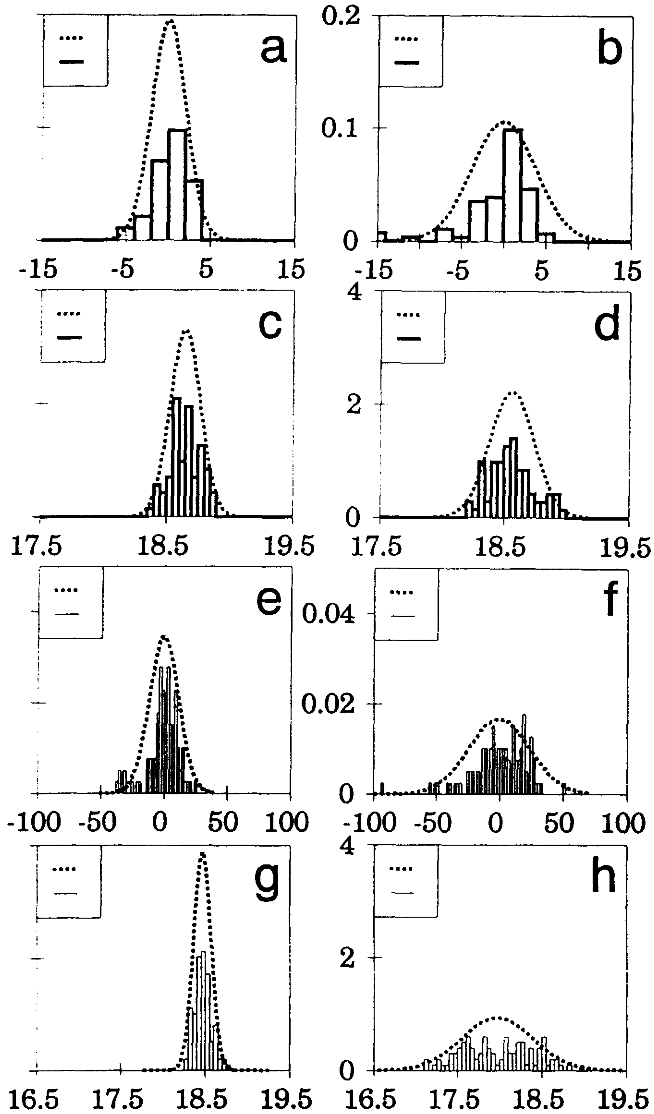


Figure 1. The observed frequency distribution and fitted PDFs of arrival time and log energy for homogeneous (1a, 1c) and heterogeneous(1b, 1d) gypsum, Westerly (1e, 1g) and Oshima(1f, 1h) samples. The dashed curves represent the Gaussian PDF and histogram represent derivative of cumulative distribution function.

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