Geophysical Research Abstracts
Vol. 13, EGU2011-7085, 2011
EGU General Assembly 2011

Analysis of the high-frequency noise field recorded by a vertical borehole array in Taiwan 1: General properties, and the direct arrival of the ambient noise cross correlation

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We analyze properties of the high-frequency noise field (>1 Hz) recorded by a vertical borehole array consisting of 7 sensors between 950 and 1280 m depth situated in the formation hosting the Chelungpu fault zone, Taiwan. The examination of sub-hourly sampled spectrograms reveals the anthropogenic character of noise amplitude pattern in the frequency range between 1 and 20 Hz. Amplitudes differ by a factor of 4 between day- and night-time hours, and day time amplitudes during weekends are reduced with respect to working days. Several sharp amplitude peaks at frequencies between 7 and 15 Hz, also exhibiting a distinguished day/night pattern, suggest industrial origins. Furthermore, spectral analysis of daily sampled minimum noise amplitudes around 5 Hz constructed from the 2 years of continuous records yields a distinguished 7-day periodicity, which is also preserved in the frequency content of daily constructed cross correlation functions (C1) computed between individual sensor pairs. In contrast to the cultural components of the noise field, features observed in the amplitude spectrum at yet higher frequencies suggest to be more likely of natural origin. In particular, significant increases in the noise level between 5 and 40 Hz coincide with strong rainfall recorded in the vicinity of the borehole. The main arrival of the Z-Z C1 functions—whose computation has become a standard diagnostic tool in ambient noise processing—shows an upward propagation of the direct wave; no energy is seen at opposite time lags corresponding to the downgoing wave, although surface-reflected P-phases can clearly be identified in earthquake seismograms. We find, however, that correlation of the positive part of the coda (corresponding to the downward propagating wave field) of the C1 function—dubbed C3pp—exposes the downgoing direct wave. Similarly, the C3nn function—the correlation of only the negative coda lags—reproduces the upgoing wave. This indicates that information on the coherent downward propagating energy is contained in the positive-lag coda of the C1 function, but that this energy is small compared to the upgoing wave field that dominantes C1. A similar conclusion is reached by analyzing wave speed and incidence angle using beamforming techniques. We find that the dominant part of the coherent wave energy at 1-5 Hz forms an angle of <45 degree with respect to vertical down, i.e. it arrives from below. Nevertheless, some energy can be recovered arriving from above. The observation of a culturally dominated wave field passing the array around 1000 m depth in a predominantly upward motion is consistent with its generation west of the site, i.e. in the densely populated lowlands of Taiwan. Travel paths are compared to waves emanating from shallow, local and regional seismicity in the same azimuthal range. We develop a technique to process covariance matrices composed of intercomponent and -station C1 (and possibly C3) functions with standard polarization techniques. This allows us to circumvent the lack of radial resolution of the beamforming analysis owed to the vertical array geometry, and thus to constrain the source areas that dominate the high-frequency noise field at different times. Our comprehensive analysis of the noise wave field anatomy over the course of 2 years in the frequency range of 1-5 Hz clearly reveals the dominant anthropogenic character of the noise sources; very strong rainfall events are found to leave their footprints in noise amplitude measurements at the target depth; hence, the analysis of potential temporal changes of subsurface properties utilizing ambient noise has to be evaluated for possible effects associated with variable contributions from different sources.