Yield Estimation from Surface-wave Amplitudes

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Abstract — Surface-wave amplitudes from explosion sources show less variation for a given event than body wave amplitudes, so it is natural to expect that yield estimates derived from surface waves will be more accurate than yield estimates derived from body waves. However, yield estimation from surface waves is complicated by the presence of tectonic strain release, which acts like one or more earthquake sources superimposed on top of the explosion. Moment-tensor inversion can be used to remove the tectonic component of the surface waves, however moment-tensor inversion for shallow sources is inherently non-unique so the explosion isotropic moment cannot be determined with the necessary accuracy by this means. Explosions on an island or near a mountain slope can exhibit anomalous surface waves similar to those caused by tectonic strain release. These complications cause yield estimates derived from surface waves to be less accurate than yield estimates from body waves recorded on a well-calibrated network with good coverage. Surface-wave amplitudes can be expressed as a surface-wave magnitude $M_s$, which is defined as the logarithm of the amplitude plus a distance correction, or as a path corrected spectral magnitude, log $M'_0$, which is derived from the surface-wave spectrum. We derive relations for $M_s$ vs. yield and log $M'_0$ vs. yield for a large data set and estimate the accuracy of these estimates.

Key words: Surface wave, explosion, yield, magnitude, moment, moment tensor.

Introduction

The Threshold Test-Ban Treaty (TTBT) between the United States and the Soviet Union, which went into effect in 1976, limited the yield of underground nuclear tests to 150 kilotons. Because of this, accurate estimation of explosion yields from seismic data became very important, and a great deal of research was performed to identify all of the factors that caused variations in seismic amplitudes. This caused renewed interest in estimating explosion yields from surface waves. These yield estimates were then used as a consistency check on other phases, or combined with the other estimates to obtain a unified yield (RINGDAL et al., 1992; MURPHY, 1993) using all measurements at the same time.

Surface waves have some advantages and disadvantages for yield estimation compared to other phases. Surface-wave amplitudes exhibit less scatter than other phases, with a network standard deviation in $M_s$ typically about half the standard deviation for $m_b$ (BACHE, 1982). Also, since surface waves are usually measured at periods of about 20 seconds, they are much less sensitive to small-scale variations in

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the earth than short-period regional and teleseismic phases. Since the measured period is considerably longer than the explosion source duration, this also means that surface waves are insensitive to the explosion source function. That is, while surface-wave amplitudes will vary in different materials with source coupling, they are not affected by details of the source spectrum which are flat at periods longer than a few seconds. On the negative side, surface waves cannot be measured to as small a magnitude as \( m_b \). This is particularly true for explosions where \( m_b \) is 1–2 magnitude units higher than \( M_s \). Also, while surface waves are less sensitive to variations in attenuation and scatter than \( m_b \), they are subject to variations due to tectonic strain release and near-source structure that have little effect on \( m_b \). The sources and magnitude of these variations are discussed later in this paper.

Because surface waves are long-period measurements, surface-wave amplitudes are approximately proportional to explosion yield, and the slope of the magnitude yield curve is close to one. That is, we can write \( M_s = \log Y + C \), where \( Y \) is the yield in kilotons (KT) and \( C \) is a constant that may depend on source medium, but is independent of explosion yield. For example, Bache (1982) using data from Marshall et al. (1979), found \( M_s = \log Y + 2.05 \pm 0.21 \). There are a number of other similar relations in the literature. Murphy (1977) found \( M_s = 0.84 \log Y + 2.14 \) and \( M_s = 1.33 \log Y + 1.20 \) for explosions with yield less than and greater than 100 kilotons, respectively. Marshall et al. (1979) found \( M_s = 0.97 \log Y + 2.16 \) for explosions in salt and granite, and \( M_s = 1.06 \log Y + 1.88 \) for all explosions in their data set including poorly coupling events above the water table. In general, however, these relations have been derived as best fits to data including events in different materials with varying depths, and are also consistent with unit slope for explosions in similar materials at comparable depth.

Since an idealized explosion is spherically symmetric, and when embedded in a plane layered structure is cylindrically symmetric, such an explosion should generate no Love waves and should generate Rayleigh waves with the same amplitude in all directions. It is well known, however, that explosions generate Love waves, which can be quite large in some cases, and that the Rayleigh waves not only have a radiation pattern, but can be reversed, as if from an implosive source, in some cases (e.g., Toksöz and Kehr, 1972). Figure 1 shows an example of Rayleigh and Love waves recorded at the same station for two explosions at the Soviet Semipalatinsk test site. The first set of seismograms shows a normal Rayleigh wave and a small Love wave; the second shows a reversed Rayleigh wave and a Love wave comparable in amplitude to the Rayleigh wave. This anomalous radiation can be explained by superposition of one or more earthquake-like sources on top of the explosion source. Explanations for this extra source include tectonic strain release (Archambeau, 1972; Stevens, 1982; Day et al. 1987; Harkrider et al., 1994), earthquake triggering (Aki and Tsai, 1972), and passive block motion (Salvado and Minster, 1980; Masse, 1981). Viecelli (1973) suggested that spall could be a strong generator of surface waves, and a possible mechanism for reversed Rayleigh waves. However