Seismic ground-velocity prediction based on shot distance, shot size, and shotpoint site environment in Ethiopia (EAGLE Project)

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Abstract

Accurate prediction of ground velocity is essential in determining seismic shot sizes which minimize risk to nearby human-made structures yet still ensure acceptable signal-to-noise ratios at large distances. In our study, ground-velocity data from the 2003 Ethiopia-Afar Geoscientific Lithospheric Experiment (EAGLE) were compared with the semi-empirical “Oriard” formula. Though the “Oriard” formula does not distinguish between different shot environments, we used the categorization of previous ground-velocity studies and divided the EAGLE shot environments into “wet unconsolidated material”, “dry unconsolidated material”, “wet solid rock”, “dry solid rock”, and lake shots. At moderate and large distances (beyond ~200m), the Oriard formula predicted velocities well for wet unconsolidated material and wet solid rock shot environments, but overpredicted velocity for dry solid rock and underpredicted velocities for lake shots. We therefore recommend the use of the maximum Oriard formula to calculate shot size for wet solid rock, wet unconsolidated material, and lake shots. For dry solid rock the charge size calculated from the Oriard formula could be doubled without compromising the safety of nearby structures. We lack sufficient data for dry unconsolidated material to draw conclusions. All EAGLE data at very short offsets (scaled distances less than .003 km/kg$^{1/2}$ or ~100m for a 1 ton shot) showed lower velocities than predicted by the Oriard model. Preliminary analysis of data from the 1999 Los Angeles Region Seismic Experiment (LARSE II) shows the same low ground velocities as the EAGLE data at short scaled distances. More accurate prediction of velocities at these small offsets would permit the use of larger shot sizes without increased risk to structures.

Introduction

In January 2003, as part of the EAGLE program (Maguire et al., 2003; this volume), we used 20 large chemical explosions up to 2200 kg in shot weight in a refraction survey of the Main Ethiopian Rift. 1003 RefTek "Texans" with 4.5 Hz geophones and 97 broadband (6-TD) instruments were active during our experiment (Maguire et al., 2003; this volume). Prior to each shot, the distances between shots and the nearest structure—usually unreinforced mud-and-wood houses, occasionally concrete irrigation ditches or bridges—were measured. Semi-empirical formulae derived from mining blasts by Hendron & Oriard (1972) were then used to calculate likely bounds on ground velocities at these structures, and an appropriate charge size was selected to keep the predicted velocity of these structures below 2 inches per second (5 cm/sec), the threshold for cosmetic damage recognized in the United States (Nicholls et al., 1972). The recognized threshold for structural damage is 20 inches/sec (50 cm/sec). Our study tests whether the Oriard formula was an appropriate predictor of ground velocity and thus acceptable shot size. The Oriard maximum and minimum formulae are:

$$\text{Oriard minimum predicted velocity: } V_{min}(\text{cm/sec}) = 20*[(\text{offset/m})/\sqrt{(\text{charge-weight/kg})}]^{-1.54}$$

$$\text{Oriard maximum predicted velocity: } V_{max}(\text{cm/sec}) = 184*[(\text{offset/m})/\sqrt{(\text{charge-weight/kg})}]^{-1.54}$$

In addition to the literature based on mining and engineering blasts (e.g. Hendron & Oriard, 1972; Nicholls et al., 1972; Army Corps of Engineers, 1989) there have been studies using recordings from refraction surveys (e.g. Kohler & Fuis, 1992; Fuis et al., 2001). However, in all crustal-scale refraction surveys few seismographs are placed at the short offsets where there is a risk of structural damage, so the resultant formulae are often weighted towards measurements at long offsets. Although we recorded data at offsets up to 400 km from our shots, in this study we only analyzed recordings at less than 10 km distance from each shot. No damage, cosmetic or structural, was reported from any of the 20 shots fired during the EAGLE project.

Data Reduction and Verification

To obtain true vertical ground velocities from our recordings, our high-frequency data (recorded with 4.5 Hz geophones) were deconvolved with the geophone response curve. This process recovers the amplitude of low-frequency waves that are of particular interest because they cause the most damage to buildings. After applying these corrections, the high-frequency vertical data were then compared with broadband vertical and horizontal data to confirm that the deconvolution worked well and to confirm that the vertical velocities were not systematically lower than horizontal velocities (figure 1), thereby justifying the use of high-frequency data for which many more values are available. We also compared our data set with the much larger LARSE II data-set collected in southern California (Fuis et al. 2001) to confirm that the Ethiopian data were not systematically biased from previous results (figure 2). Because EAGLE used larger shots we have proportionally more data at shorter scaled distances.

Data Description

We follow Kohler & Fuis (1992) in grouping our results by environment; and we present our results compared to the Hendron & Oriard (1972) predictions (figures 3-6). The Oriard formula predicts maximum ground velocities well for a wet solid rock environment (figure 3). Rock types included basalt, rhyolite, and pumice. However, the Oriard formula overpredicts maximum ground velocities for shots in wet unconsolidated material (figure 4) and in dry solid rock (figure 5). Unconsolidated material included sand, silty clay, and gravel, and dry solid rock included pumice, ignimbrite, and basalt. The Oriard formula underpredicts velocities for lake shots (figure 6). However, since buildings are rarely located in close proximity to lake shots, this is of less concern.

All the EAGLE data exhibited a concave-down trend in log-velocity/log-scaled distance plots. Partly due to this concave-down trend, the Oriard formula overpredicts velocities for all shot environments at scaled distances less than .003 km/kg$^{1/2}$. The maximum ground-velocities discussed in this paper are due to surface waves, not body waves. We theorize that the concave-down trend at offsets comparable to or less than the source depth (<50m) is due to weak excitation of surface waves. The Oriard formulae were derived using near-surface charges designed to displace rock; in contrast seismic sources are intended to be confined at depth.

Conclusions

We recommend use of the maximum Oriard formula to calculate shot size for wet solid rock, wet unconsolidated material, and lake shots. For dry solid rock the charge size calculated from the Oriard formula could be doubled without compromising the safety of nearby structures. Both the EAGLE and LARSE II data sets show a similar concave-down trend at short offsets. In the future we aim to construct an empirical formula based on the compilation of these and other data sets that will better predict velocities at smaller scaled distances. This, in turn, would permit the use of larger shot sizes without endangering nearby buildings.

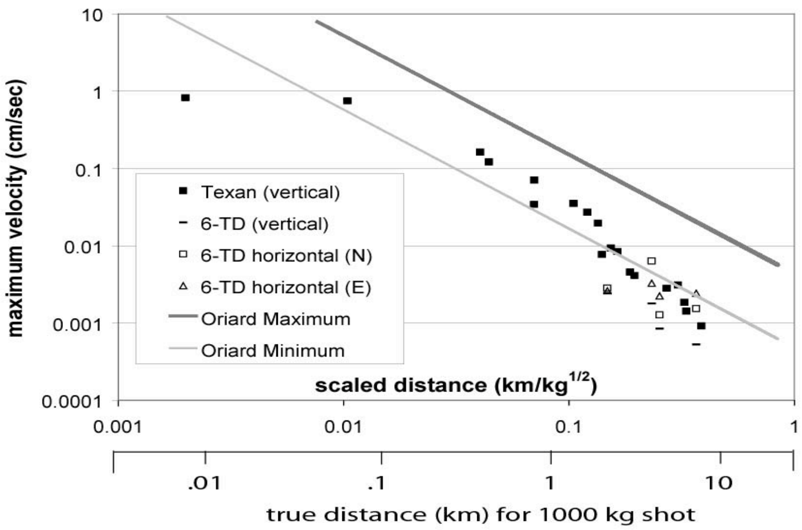

Figure 1. Maximum ground velocities from short-period and broadband three-component sensors for a single shot.

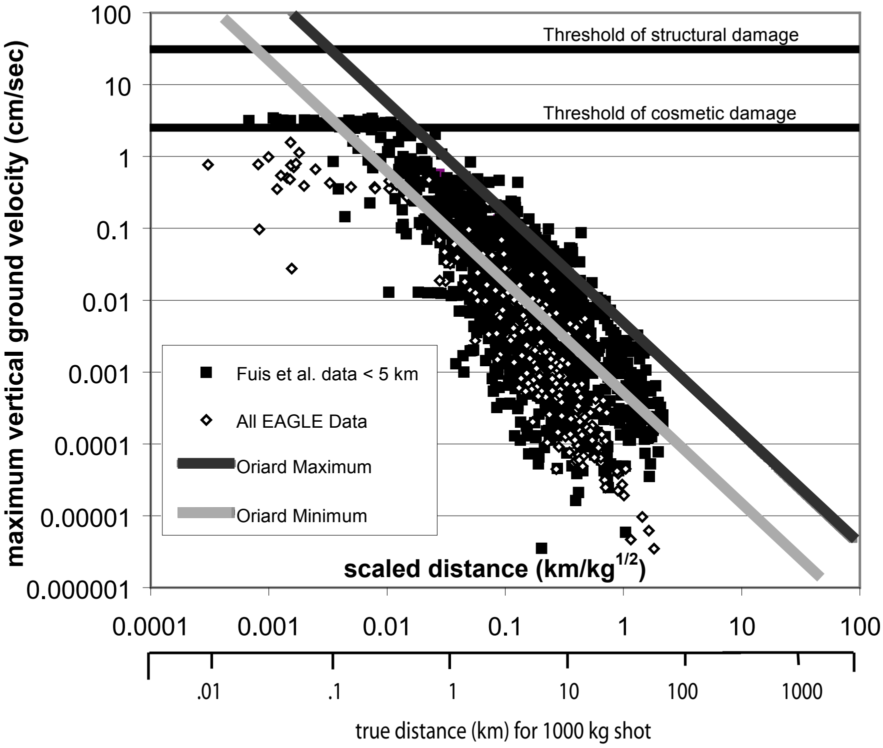

Figure 2. Maximum vertical ground velocity from short-offset LARSE II and EAGLE data. Threshold for cosmetic and structural damage from Nicholls et al. (1972).

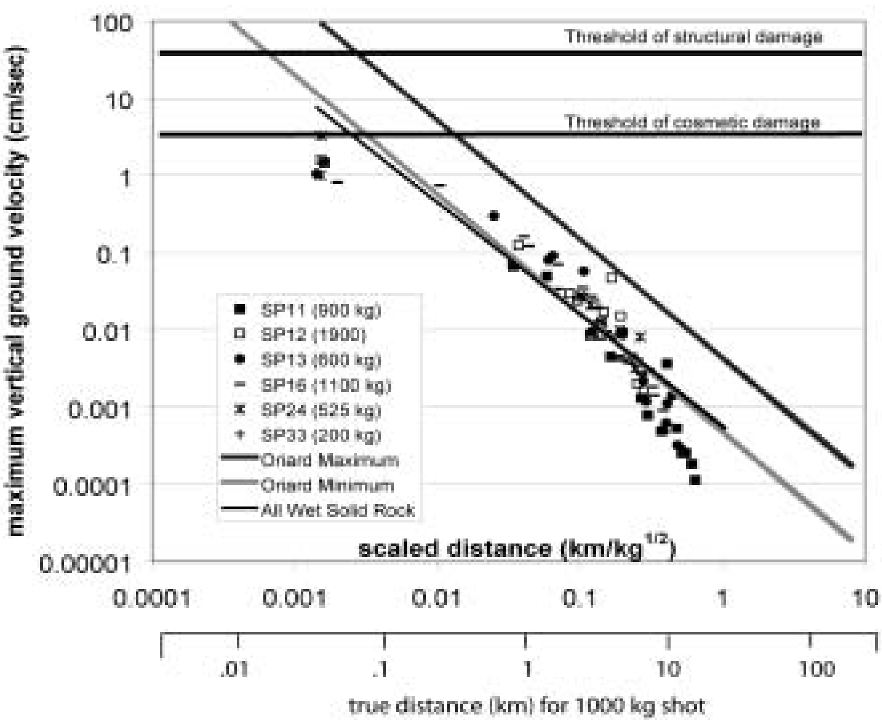

Figure 3. Maximum vertical ground velocities for borehole shots in wet solid rock.
The 'All wet solid rock' trendline shows the best-fit curve of the Oriard form to our EAGLE data.

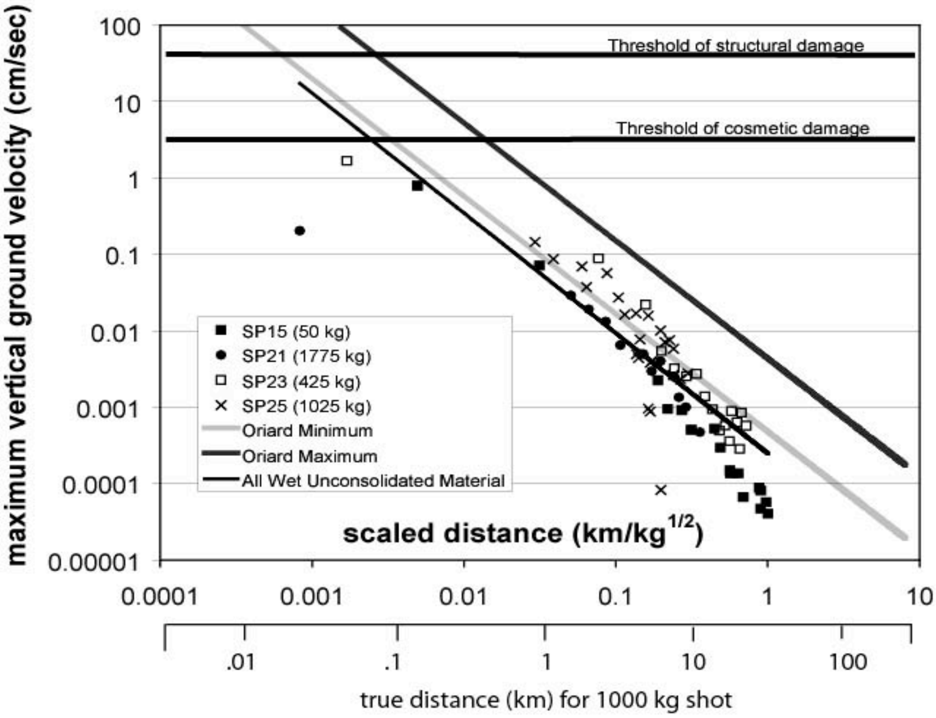

Figure 4. Maximum vertical ground velocities for borehole shots in wet unconsolidated material. The 'All wet unconsolidated material' trendline shows the best-fit curve of the Oriard form to our EAGLE data.

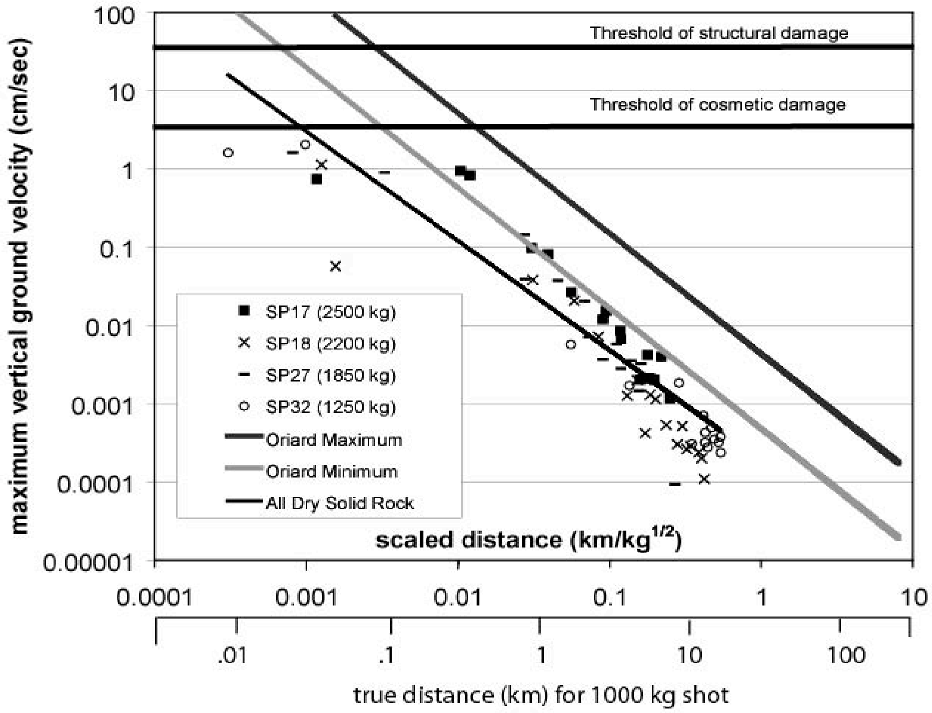

Figure 5. Maximum vertical ground velocities for borehole shots in dry solid rock.
The 'All dry solid rock' trendline shows the best-fit curve of the Oriard form to our EAGLE data.

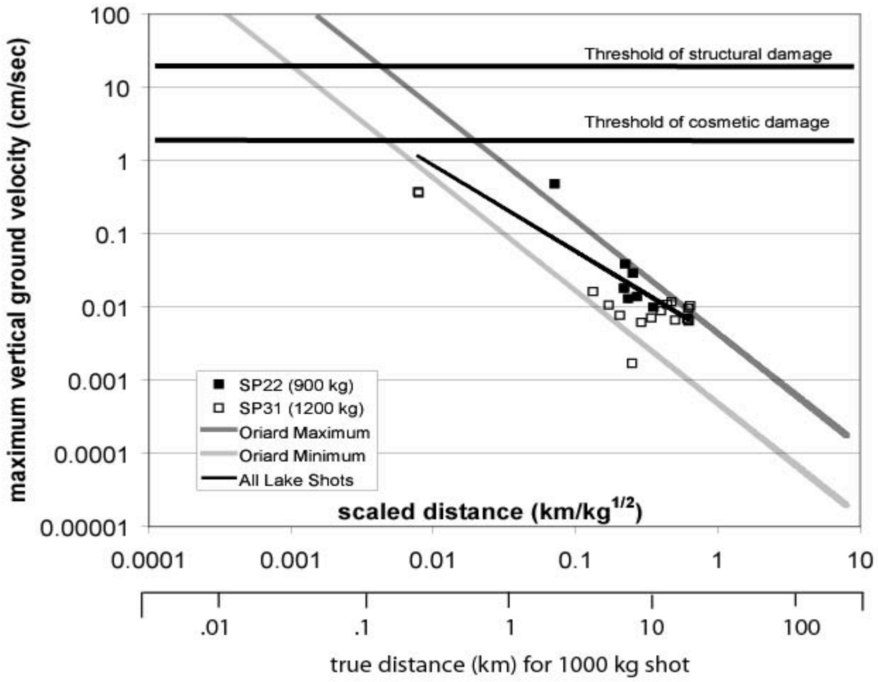

Figure 6. Maximum vertical ground velocities for lake shots. SP 22 was fully confined and fired at the optimum depth of 87m in Lake Shala. SP 31 was only partially confined (it produced water boils) - it was fired in a shallower lake (Arenguade) on the lake bed at 31 m. The 'All lake shots' trendline shows the best-fit curve of the Oriard form to our EAGLE data.

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