

3-D Characterization of Seismic Properties at the Smart Weapons Test Range, YPG

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Summary

The Smart Weapons Test Range (SWTR) is a new facility constructed specifically for the development and testing of futuristic intelligent battlefield sensor networks within the Yuma Proving Ground (YPG), Arizona. In this paper, results are presented for an extensive high-resolution geophysical characterization study at the SWTR site along with validation using 3-D modeling. In this study, several shallow seismic methods and processing techniques were used to generate a 3-D grid of earth seismic properties, including compressional (P) and shear (S) body-wave speeds (V_p and V_s), and their associated body-wave attenuation parameters (Q_p and Q_s). These experiments covered a volume of earth measuring 1500 m \times 300 m \times 25 m deep (11 million cubic meters), centered on the vehicle test track at the SWTR site. The study has resulted in detailed characterizations of key geophysical properties. To our knowledge, results of this kind have not been previously achieved, nor have the methods developed for this effort been reported elsewhere. In addition to supporting materiel developers with important geophysical information at this test range, the data from this study will be used to validate sophisticated 3-D seismic signature models for moving vehicles.

Introduction

Development of battlefield sensor networks intended to classify, track, and monitor ground vehicle traffic in forward operation areas will become increasingly critical to the modern Army's intelligence mission. It is expected that these networks will rely heavily on seismic sensing capabilities and must function with a high degree of reliability across a wide range of geologic settings. Discriminating and classifying various types of surface vehicles based on their unique seismic characteristics or signature requires *a priori* knowledge of each target vehicle's characteristics and information about the local near-surface earth properties that influence the propagation of the seismic wavefield.

Resolution requirements of seismic wavefield propagation models and real earth properties dictate the size and orientation of each grid cell within the specified earth volume. Characteristics of this volume determine the propagation of the modeled seismic wavefield used for quantitative comparisons with field-measured vehicle signature data. Designing the distribution of cells in the model, interpolating between sample points, and constructing confidence levels for geophysical

properties in the 3-D volume is best done using geostatistical procedures.

Key seismic propagation parameters, including seismic body-wave velocities (V_p , V_s) and estimates of seismic energy loss in terms of Q_p and Q_s , must be determined for each cell. In addition to these key properties, earth models must also preserve local topographic variation, layer positioning, and thicknesses to be realistic. Evaluations of propagation patterns and the imaging potential of different seismic methods focused on P- and S- body waves (reflected, direct, and refracted) as well as multi-modal surface waves (inversion of dispersive attributes). Estimates of these seismic properties throughout the 3-D earth model can effectively be bounded by geostatistical analyses. Optimal, and preferably redundant, independent estimates of V_p , V_s , Q_p , and Q_s are necessary for each sub-surface cell.

Geologic Setting

YPG is in the Sonoran Desert of the Basin and Range Province in southwestern Arizona (Millet and Barnett, 1970). The ground surface at the SWTR site slopes gently southward with distinct 1 to 2 m high ridges that meander generally north to south across the northern half of the site. Sediment particles within the 0.5 km² test area vary in size from gravel to clay, with locations in the site where sorting into distinct surface patches is evident. Geological logs from borings near the center of the SWTR site suggest that the first 100 m of sediment are composed predominantly of silt, gravel, and sand. From 0 to 7 m depth, the materials are silt with sand and minor amounts of gravel. Between 7 and 28 m depth, the sediments are mostly gravel with some suggestions of boulders. From 28 to over 65 m depth, the sediments are predominantly silts and sands with minor amounts of gravel.

Testing Various Seismic Methods

Establishing feasibility and appropriate acquisition design specifications for quantifying the 3-D seismic properties of the test area mandated a unique combination of seismic walkaway testing with geostatistical analyses. A set of test data were acquired using a 2½-D radial-fan spread configuration, which from a geostatistical perspective best provided estimates of geophysical directionality in the test area (Figure 1). Data acquired along each of three radial profiles were used to estimate the orientation and extent of spatial continuity of geo-

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physical properties. These walkaway noise tests were the basis for determining the accuracy and effectiveness of each seismic method, as well as estimating the optimal orientation and spacing of the seismic array.

Geostatistical Analysis and Grid Design

A major objective of the walkaway test was to determine if there were significant anisotropies in geophysical properties at the test site, possibly as a result of local trends in the geology. The radial design of the seismic lines provided measurements of geophysical properties along three different orientations. By computing the semivariance along these three lines, a directional estimate of the range of a geophysical property such as V_p could be made.

The sampling plan used at the SWTR site consists of parallel lines oriented in the direction of most rapid change in geophysical properties. Observations collected along these lines have the greatest sampling density (1.2 m) in the direction of most rapid change in seismic properties. The spacing between lines (50 m) is much greater, but seismic properties are more persistent in this direction.

Acquisition of 2½-D Grid

After geostatistical analysis of the radial test data, a 2½-D grid with the long axis oriented parallel to the test track was determined to be optimum for local geologic conditions (Figure 1). Inline spacing of geophones was 1.2 m with short axis lines 300 m long and separated by 50 m. Tie lines were separated by 100 m, parallel to the test track, and 50 m offset from the center of the 300 m spreads and test track. This 40-spread configuration resulted in a uniform 2½-D grid within the 1.5 km × 300 m study area.

To ensure that sufficient offsets were recorded for refraction tomography and that close trace spacing was maintained for MASW analysis, a fixed spread of 240 receiver stations spaced at 1.2 m was deployed for each 300 m profile. A 240-channel Geometrics StrataView seismograph was used to record these fixed-spread data using a source spacing of 4.8 m inline and 1.2 m offline. Each source location was conditioned with an initial unrecorded impact to seat the plate, followed by three recorded impacts. Since the optimum offset window for surface wave sampling of the upper 30 m at this site is between 2 and 25 m, the 240-channel spread can easily be split into appropriate uniform gathers.

Processing of 2½-D Grid

The optimum 60 traces were retained to create consistent offset-distribution shot gathers necessary for best results during MASW processing. These 60-trace gathers were analyzed with SurfSeis (a proprietary software package from the Kansas Geological Survey facilitating use of MASW for continuous profiling). Each shot gather generated one dispersion curve and 1-D V_s profile, which was assigned a surface location corresponding to the middle point of the spread being analyzed (Figure 2). Joint analysis of surface waves and refractions (JASR) was used to generate a V_p cross-section (Ivanov et al., 2000).

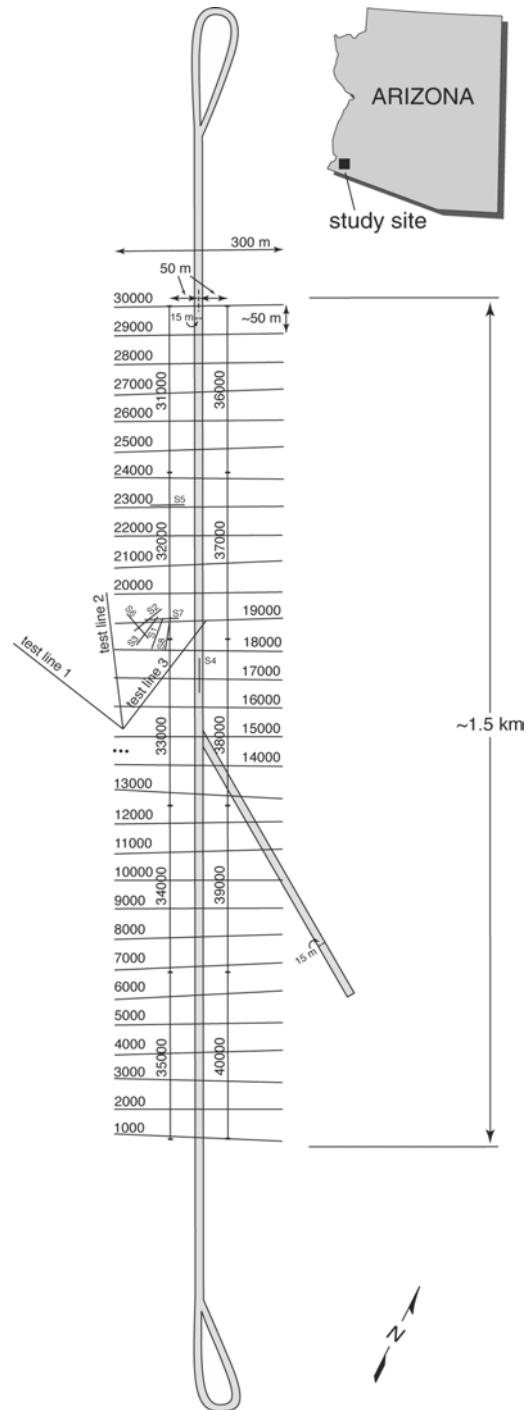


Figure 1. SWTR site relative to the state of Arizona. Profile lines as defined by the high-resolution GPS survey. Relative grid orientations, testing areas, and well locations are identified.

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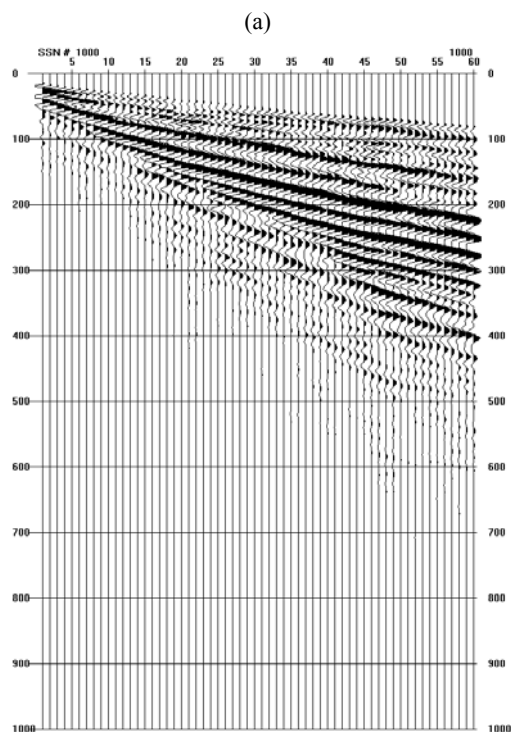
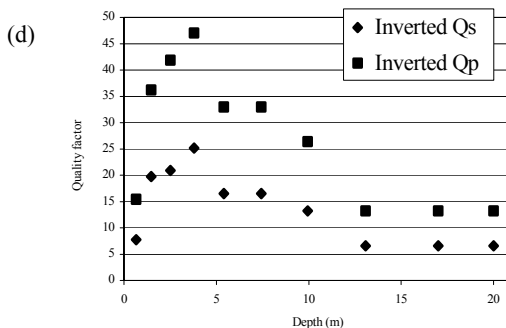
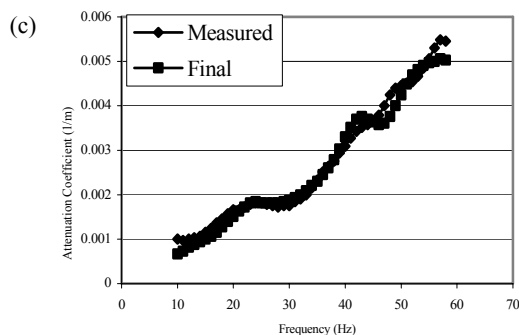
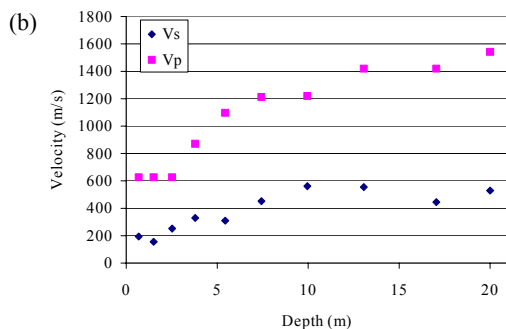


Figure 2. Data example from key output portions of the acquisition and processing flow. a) Raw shot gather edited for only appropriate trace offsets and propagation directions, b) velocity model derived from MASW and JASR methods, c) Rayleigh wave attenuation coefficient as a function of frequency for these data, and d) Q_p and Q_s inverted from attenuation, frequency, and velocity information.



Estimates of Q presented in this paper are enhanced developments based on initial work described by Xia et al. (2002). Consistent with other estimations of Q in the shallow subsurface, Q decreased with depth. Intuitively, increasing depth should increase the quality factor which then relates to decreases in attenuation.

Geostatistical Processing of V_p , V_s , Q_p , and Q_s

Conventional statistics assumes that observations used in estimation are independent; that is, the value of one observation has no influence on the value of a subsequent observation. This assumption is not valid for many natural phenomena such as geophysical properties, because a value at one location obviously is related to values at nearby locations and less closely related to values at more distant locations. Although the geo-

statistical literature is vast, there have been relatively few applications in geophysics. To produce the earth model of a geophysical property such as V_s (Figure 3), we first compute directional semivariograms and examine them for non-stationarity.

Simulations Using 3-D Volumes of V_p , V_s , Q_p , and Q_s

Simulations of wave propagation through the Yuma earth model defined here were performed using a 3-D 8th order finite difference staggered grid scheme (Ptop) and directly compared to field data. The combined variations in geophysical parameters and topography in three dimensions make seismic wave propagation a highly complex phenomenon. Successful synthetic comparisons with field data give both validation of the Ptop code and demonstrate the consistency of

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geologic characterization. Time domain plots of the normalized velocity amplitudes for the anelastic case and field data are shown in Figure 4. The synthetics predict accurate arrival times for both the P and surface waves out to 100 meters. The parameters provided by the real geophysical data from YPG were V_s , V_p , Q_s , Q_p , ρ , and elevation. A 3-dimensional view of V_s is plotted in Figure 5.

Conclusions

Synthetics from the Yuma model with Q predict the amplitude, dispersion and distribution of energy in

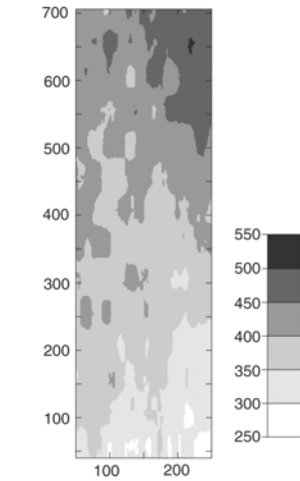


Figure 3. Shaded contour map of V_s at 5 m depth, SWTR site, YPG. Map coordinates are in meters from an origin at the southwest corner; contour interval is 50 m/sec.

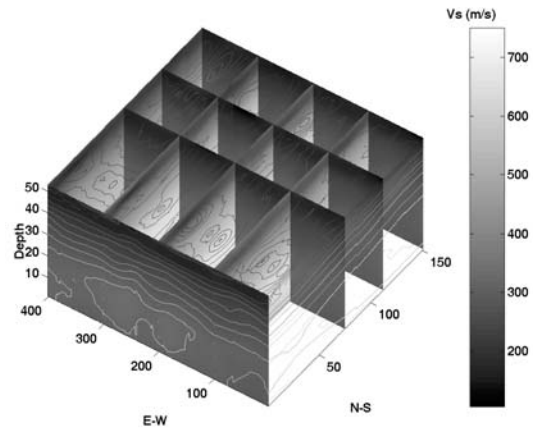


Figure 5. 3-D S-wave velocity used in finite difference calculations.

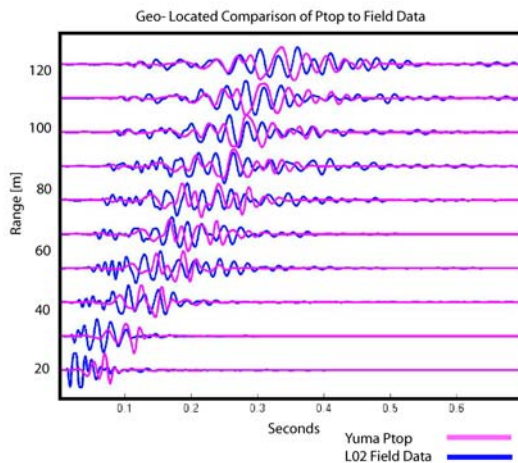


Figure 4. Record section of Ptop synthetics (violet) vs. field data (blue). The fundamental features of P-wave and surface wave arrival times and relative amplitude agree well.

the frequency domain observed in field data. The agreement is a preliminary validation of finite difference code developed at ERDC-CRREL. The good correlation of Ptop synthetics with field data using simple sources bodes well for future applications where more complex sources are to be used. The ability to predict accurate seismic velocity field displacement is key to relying on synthetic data for sensor system development and optimization. Reliable synthetic data will dramatically reduce system development time and cost.

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