DEPTHS OF DPRK UNDERGROUND NUCLEAR EXPLOSIONS:

Making predictions using Monte Carlo simulations with Bayesian data synthesis

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Introduction

The Democratic People's Republic of Korea (DPRK) conducted six nuclear tests at the Punggye-ri nuclear test site. These tests were conducted in 2006, 2009, 2013, two in 2016, and one in 2017.[1] These tests will be referred to as tests 1-6 chronologically. Information surrounding these tests is limited due to the denied access of the Punggye-ri nuclear test site and the DPRK's lack of reporting. Previous work has reported absolute yield estimations for these tests via extensive seismological data collection and analysis.[2] In this work, "absolute" refers to a non-probabilistic result such as an exact explosive yield or precise location and depth of burst. Similarly, absolute locations of test epicenters have been determined by combining remote sensing techniques such as Interferometric Synthetic aperture radar (InSAR) with precise relative locations (+/- 100 meters) determined by differential seismic arrival time analysis.[3] This estimate was conducted a year after the final test and took a large collective effort to obtain all seismic and InSAR data.

All DPRK tests have been subterranean. The underground test facilitates uncertainty from the international community to determine aspects of the DPRK nuclear weapon technology. The international community has difficulty estimating yield, location, and depth of burst rapidly because of the nature of remote sensing and a lack of a centralized seismic database.[4,5,6] Depth of burst estimations have generally been conducted using analysis of the prior reported absolute locations in tandem with seismic data.[7]

This paper will use methodologies refined by Duncan in his 2021 article, "Predicting depths of burst at denied access sites using Bayesian data synthesis," to determine probabilistic estimates for yield and location utilizing Monte Carlo simulations and seismic data for the DPRK sites located in Waveforms From Nuclear Explosions (WFNE). Bayesian data synthesis will be conducted to improve the precision of the depth of burst estimation for each test utilizing terrain analysis and yield.

Methods

The first step in our methods is to gather seismic data, this is done through access to the WFNE dataset. Users must create an account for the WFNE repository, and then search for the desired test. From the WFNE dataset, you can download the seismic information from each test and sort the body wave magnitude, wave type, and arrival times. From this seismic data, we use the wave data to generate yield and location estimations through Monte Carlo simulations and Bayesian analysis. A Monte Carlo simulation is a method to predict a set of outcomes using a range of possible values for the input parameters. In this work, we use known ranges of values for the geological input variables to predict the what the equations for yield and depth of burst would yield if the DPRK specific constants were known.

Using topographical analysis of the location and depth of burst estimation derived from yield, we can combine our results through Bayes' theorem to arrive at a final depth of burst probability density estimate.[8] Test 1's data from WFNE was not available for analysis. Figure 1 demonstrates a general flow of our methods to arrive at a final analysis of depth of burst.

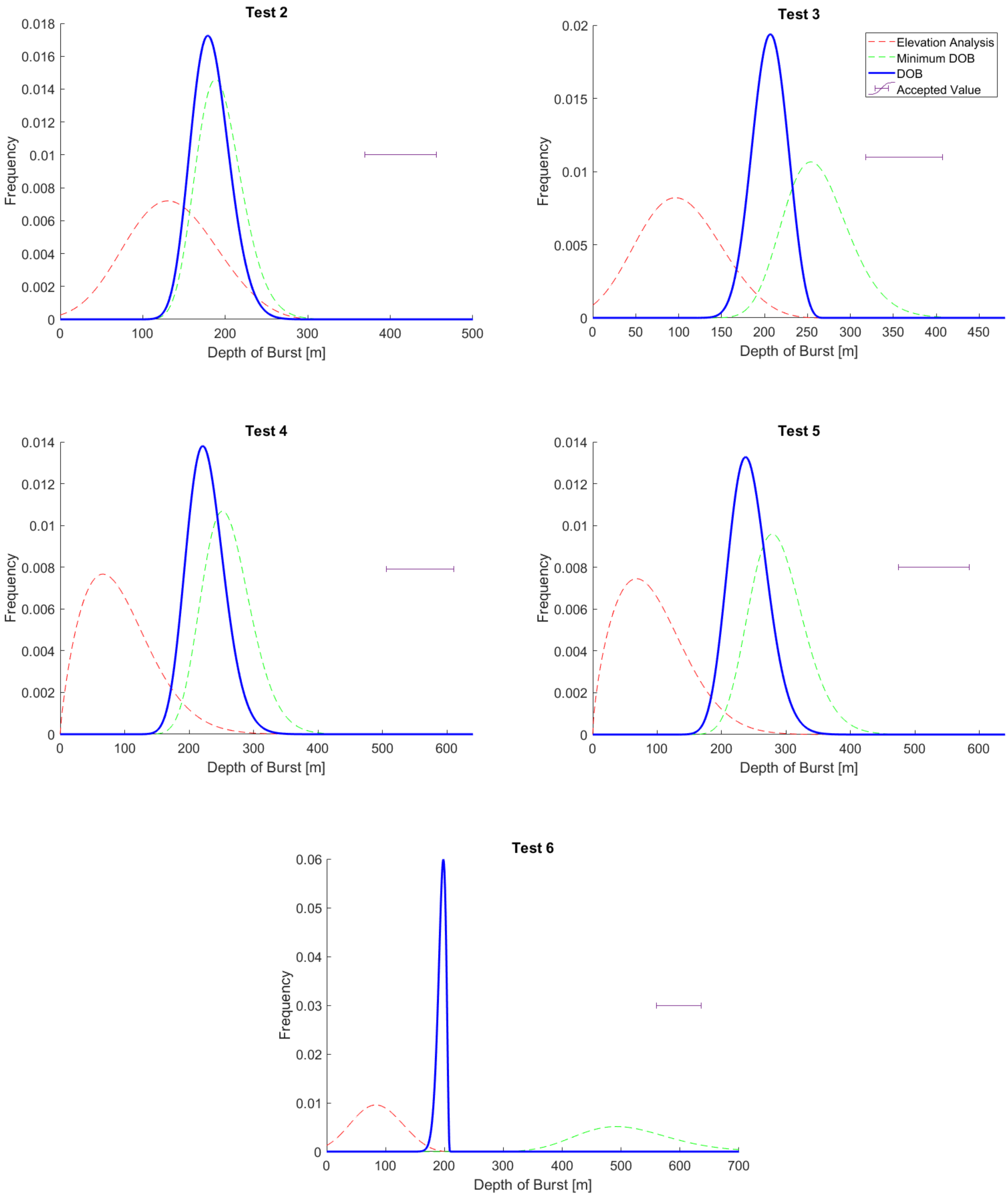

FIGURE 1. The process to estimate yield, location, and depth of burst of an underground explosion (Author Produced Figure).

Yield estimation

From WFNE, we obtain the seismic data for the DPRK tests. The seismic data includes arrival time, amplitude, and wave type from each station. Utilizing the body wave magnitude, of an explosion's seismic data, the yield can be estimated via Equation 1.[9, 10, 11, 12] Where A and B are both geological constants specific to the testing and seismic station sites.

$$Y = 10^{\frac{M_b - A}{B}} \quad (1)$$

Each seismic sensor will generate slightly different values for the body wave magnitude. Using a Monte Carlo simulation, we estimate yield using Equation 1 where we randomly select a body wave magnitude from the WFNE dataset.

The denied access to the DPRK test site results in an inability to provide accurate geological constants, A and B from Equation 1. For the Monte Carlo simulation, we utilize a uniform probability distribution for constants A and B. For both constants, the range used was based on the geological constants for the Nevada Test Site of the United States and the Semipalatinsk test site of the Soviet Union.[13, 14, 15]

100,000 iterations of the Monte Carlo simulation were run utilizing the programing language MATLAB to estimate yield according to Equation 1 to ensure proper randomization. Each iteration of the yield estimate was fit to a histogram of 100 bins. The best-fit curve was selected from MATLAB's 17 native distributions via the akaike information criteria (AIC) in combination with MATLAB's maximum likelihood estimation function using fitmethis version 1.6.1.[16] MATLAB's maximum likelihood estimation function determines the parameters for a probability density function (PDF) that fits the yield histogram. Once this is done for 17 different distribution types, we select the PDF that fits the histogram the best according to the AIC. We utilized MATLAB, but this methodology can be recreated using the Python package SciPy's "norm" function, without requiring proprietary software.

To determine the minimum depth of burst at which a device could be detonated and remain contained, an equation was developed by the Joint Soviet-American Experiment on Verification program (Equation 2).[17, 18]

$$Minimum\ Depth\ of\ Burst\ [m] = C * Y^{\frac{1}{\alpha}} \quad (2)$$

Where Y is the explosive yield in kilotons, C is a proportionality constant, and α is a scaling parameter.

Similar to yield estimations, we used a Monte Carlo simulation using MATLAB to generate a probabilistic distribution for the minimum depth of burst utilizing Equation 2. The simulation was run for 100,000 iterations and used the probabilistic results generated from the Monte Carlo simulation for yield to estimate the minimum depth of burst. Constant C is dependent on the geology of the test site and again due to the lack of site access, must be estimated. For C, the estimate was based on values given in the case of a deep blast with no visible surface deformation generated for the Nevada Test Site and the Semipalatinsk Test Site.[19]

The United States defined the scaling parameter α as 3, and the Soviet Union defined the parameter as 3.4 based on different containment objectives.[20,21,22] No other constraints or assumptions were integrated into the simulation.

Location estimation

Shown in Figure 1, we use the seismic arrival times from the WFNE repository to estimate an underground explosion's location. Within the WFNE dataset, we extract the wave type, wave arrival time, and station location and use this data as input for Bayesian Seismic Locator (Bayesloc). This program utilizes Markov Chain Monte Carlo (MCMC) simulations with travel time corrections to generate a location distribution as an output. This output is a point location with standard deviations in the cardinal directions.[23]

Elevation depth of burst estimation

As shown in Figure 1, we leverage the location estimation to generate a range of possible depth of bursts through topographical analysis of each test region. Utilizing the latitude and longitude generated from Bayesloc, we define a rectangular box whose center coincides with the center of the predicted test locations and whose height and width are taken to be 2.5 standard deviations away from the origin.[24] Elevation data with 30 m spatial resolution within the boxed test location was obtained from the United States Geological Survey (USGS).[25, 26, 27]

We define a 2-D matrix containing the possible depths for each longitude and latitude as:

$$PD(x, y) = Surface\ Elevation(x, y) - Minimum\ Elevation \quad (3)$$

Where x and y represent the longitude and latitude of the predicted region, *Surface Elevation* is a similar 2-D matrix generated from the USGS data, *Minimum*

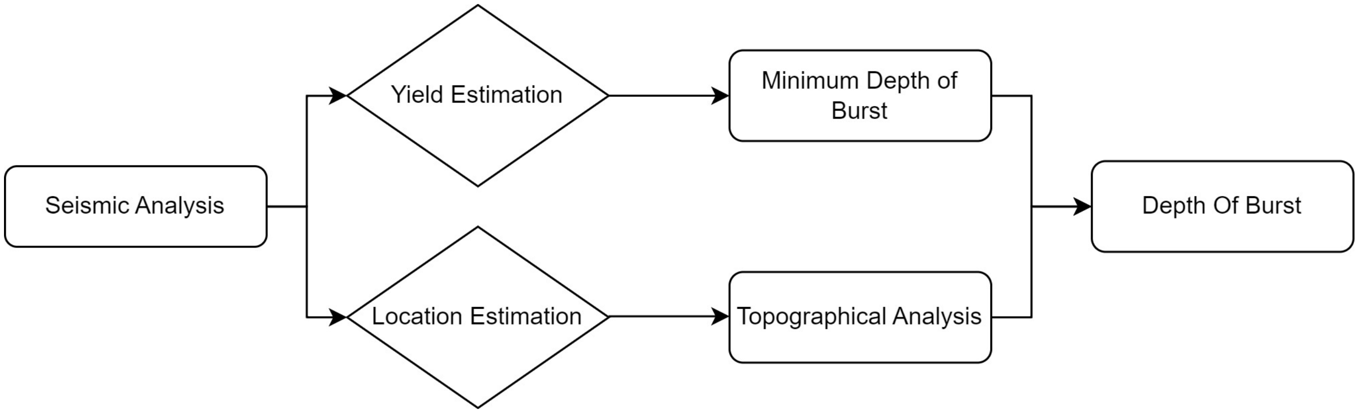

FIGURE 2. Bayesian synthesis for depth of burst for tests 2-6 with accepted depth of burst estimations (Author Produced).

Elevation is the lowest depth of each boxed region,[28] and PD (Equation 3) is a matrix of possible depths at which the explosion could have taken place.

Equation 3 assumes that within each bounded region, the minimum elevation is roughly in line with the water table of that region. For this reason, it is assumed that the test would not be conducted below the water table due to the difficulties in tunnel construction and nuclear explosion testing environment. WFNE and these simple estimation methods can provide accurate, rapid, location estimations for underground explosions within a reasonable error.

Results

Depth of burst

Figure 2 shows the results of the final depth of burst estimations using Bayesian analysis with elevation and the minimum depth of burst. The improved depths of burst are shown with the solid blue line. The current values estimated for these tests are shown by the horizontal bar. Compared to other methodologies for depth of burst which generate uniform distributions, our methodology generates probabilistic distributions.[29]

The similar depths and yields for tests 2-5 were very consistent in both their depths of burst as well as their yields. Test 6 is unique in that the elevation of its placement follows the same range as the previous 4 tests, but the yield is substantially larger. The estimates for depth are all more shallow than previous estimates, which were determined by estimating the overburden necessary to generate the surface deformations recorded by InSAR.[30] For this reason, it appears that test 6 was placed similarly to the previous tests through a horizontal tunnel,[31] but the yield was larger than the DPRK may have expected.

The sudden jump in explosive yield raises concerns over the potential successful detonation of a two-stage thermonuclear device by the DPRK. It is possible that the previous tests were attempts at a two-stage detonation, but without successful fission stages. Test 6, having been emplaced similarly to previous tests and with a drastically enhanced yield, may have been a successful fission explosion generated by a two-stage device.

Conclusions

Using methodologies validated against the United States and Soviet Nuclear Test programs.[32] We were able to determine the possible depth of bursts for the DPRK nuclear tests. This methodology used in combination with WFNE seismic data was able to generate similar signatures for DPRK tests 2-5, indicating likely successful contained fission explosions. However, test 6 has an unusual yield when compared to the previous tests, nearly an order of 10 larger, while still being placed in a similar location and depth. This can be explained by a possible successful two-stage nuclear explosion design. ■

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Notes

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APPENDIX A

Data and Software Availability

Source data

Source data used in this study is taken from the Waveforms From Nuclear Explosions website available at https://www.wfne.info/. The data taken from here was from the region of Korea, DPRK with the date range of 2006-2017. All the data available via WFNE are from open and publicly released sources. All the IMS data contained in this version of the WFNE are from open IMS stations and can be freely accessed and processed by approved users.

A range of options are provided for accessing/downloading these data resources including menu-based and map-based alternatives. For a complete description of the WFNE data resources and access tools, the WFNE User Manual provides an orientation and guide including a summary of what data are available, functionality of various web-based access and display options, and step-by-step examples for several typical WFNE data queries.

Some features of the WFNE website are still being developed or supplemented.

Data information

The WFNE database provides seismic data from the six DPRK nuclear test events. WNFE provides four main components in its data for each event, the descriptions for each of the calculated data files, the calculated data files themselves, the raw waveforms in SAC file format, and the instrument response functions for each station. In this work only the calculated data files were used. These files were generated by WFNE conducting their own analysis on the raw waveforms as well as pulling results from already existing sources. For each test, our methods used to determine the depth of burst were identical, however the number of stations used for WFNEs calculations were variable.

Test 2 used data from 37 stations, Test 3 used 84 stations, Test 4 used 80 stations, Test 5 used 90 stations, and Test 6 used 126 stations.

Software

Archived source code at time of publication:
https://zenodo.org/record/8321978