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2-D Seismic Reflection Method for Identifying Caverns Generated by Underground Nuclear Explosions in Synthetic Data

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INTRODUCTION AND MAIN RESULTS

Detection of explosion-induced underground cavities is a major challenge for the Comprehensive Nuclear-Test-Ban Treaty (CTBT) verification. Using Spectral Element Method simulations and 2D seismic reflection, we show that cavities generate distinct seismic anomalies that can be identified through conventional processing techniques such as trace stacking.

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Introduction

The detection of underground cavities generated by nuclear explosions represents a significant technical challenge in the context of verifying the Comprehensive Nuclear-Test-Ban Treaty (CTBT).

This work explores the use of 2D seismic reflection data and processing techniques, such as seismic trace stacking, to identify anomalies associated with this type of structure.

By solving the elastic wave equation with the spectral element method (SEM), results have been obtained for caverns generated by explosions of 1, 20 and 150 kilotons and models with one layer and two layers, obtaining seismic traces in which we can observe the effects of the structure.

Applying seismic exploration techniques, it is concluded that caverns created by a nuclear detonation can be detected in seismic data. These findings provide a reference framework of seismic responses, supporting rapid identification of explosion-induced cavities in future surveys.

Methodology

The steps followed during this research work go as follows:

1. Identify the lithology present in the areas where nuclear tests were conducted.
2. Create finite element meshes with the appropriate properties according to the lithologies present at different sites.
3. Use the Spectral Element Method (SEM) to perform wave propagation simulations.
4. Obtain synthetic seismograms from the wave propagation simulations.
5. Stack the traces obtained from the synthetic seismograms.

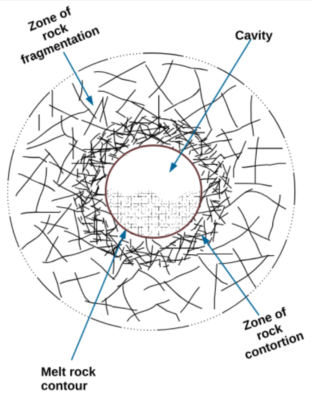
There are two main software used in this work:

1. SWP (Seismic Wave Propagation software), developed by De Basabe (2009). This is a software that can solve the elastic wave equation and at the same time set a seismic survey design, getting two products in one go: seismic wave propagation snapshots (vertical and horizontal components of displacement) and seismic traces of each source for the seismic processing.
2. Seismic Unix developed by Center for Wave Phenomena (CWP). Used for usual seismic processing.

Cavern generated by a UNE

An Underground Nuclear Explosion (UNE) creates a structure like the one proposed by Adushkin et.al (2004) in the image bellow (modified by Ortiz-Aguilar (2020)): Cavity, Melt rock contour, Zone of rock contortion and Zone of rock fragmentation.
The models proposed in this work have the following configurations:

Model	Medium	Vp (m/s)	Vs (m/s)	Density (g/cm³)
One-layer	Granite	5520	3380	2.67
One-layer	F. Granite	2400	1500	2.54
2-Layer	Shale	2800	1600	2.20
2-Layer	Granite	5520	3380	2.67
2-Layer	F. Granite	2400	1500	2.54



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DISCLAIMER: Results are preliminary and intended for scientific discussion.

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Numerical experiments

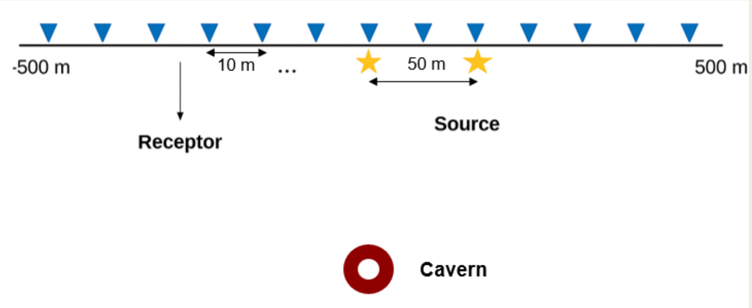
Numerical experiments require a series of parameters to be calculated:

- Properties of the medium.
- Finite element mesh (made with Coreform Cubit).
- Seismic survey design.
- Spectral element method software.

The following table shows the size of each zone considered in the simulations:

Yield (kt)	Cavity (m)	Crushed rock (m)	Fractured rock (m)
1	10	4	25
20	27	11	68
150	53	21	133

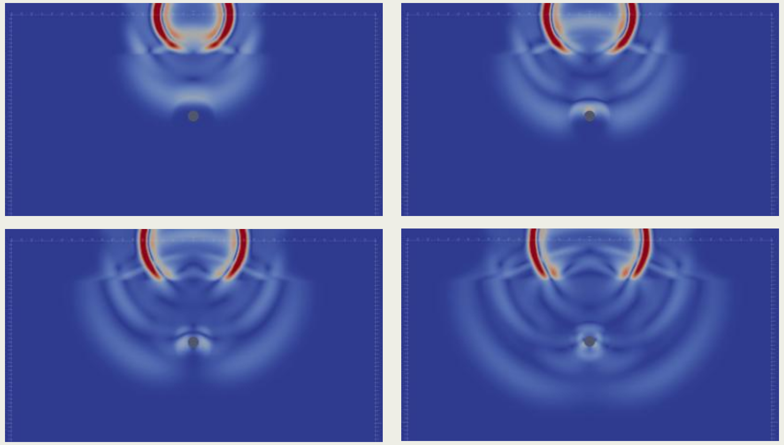
And the seismic survey design has the following set up:



The design has a total of 101 receivers separated by 10 m each and 21 sources separated by 50 m.

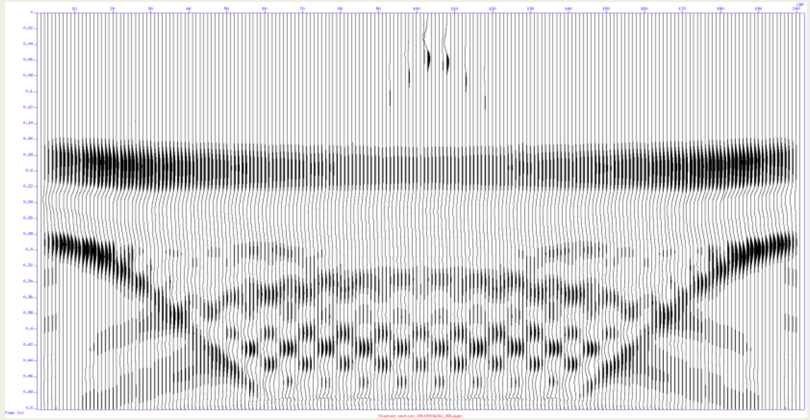
Results

The depth of the cavity varies with the explosion, with the damage zone at 300m bellow the surface for the 1 kt explosion, 500m for the 20 kt explosion and 600m for the 150 kt explosion. The results shown in this section belong to the 20 kt case with a two-layer configuration. Results (animations of the simulations and stacked sections) from the other five cases can be found in the QR code:



The snapshots represent the normal displacement of the wave field at times of simulation: 147ms, 168ms, 189ms and 210ms. These snapshots help with the interpretation of the seismic traces since we can monitor the times at which the waves reached the receivers.

Results/Conclusions



From the stacked section above, we can identify two things: the interface between the two layers and two hyperbolic signals, the first from the waves reflected in the damage zone and the second from the waves reflected in the cavity.

Processed and stacked seismic data reveal reflections associates with both the cavity and surrounding damage zone. These anomalies, expressed as concentric diffracting bodies, show that in simplified synthetic models, the damaged zone enhances the detectability of underground cavities.