Challenges and Achievements of Monitoring for Nuclear Test Explosions in the Context of the CTBT

Paul G. Richards

IO1–722

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Columbia University | Earth Institute
Atmospheric and Underground Nuclear Testing
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<td>to June 18, 2021</td>
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Numbers in red: these explosions took place in the era of analog recording

almost all nuclear testing in the atmosphere took place in the analog era

Numbers in green: these explosions took place in the era of digital recording
SEISMIC VERIFICATION of Nuclear Testing Treaties

2002

TECHNICAL ISSUES RELATED TO THE COMPREHENSIVE NUCLEAR TEST BAN TREATY

1988

THE COMPREHENSIVE NUCLEAR TEST BAN TREATY
TECHNICAL ISSUES FOR THE UNITED STATES

2012
Regional waves ($Pn$)

Teleseismic waves ($P$)

Amplitude

Distance

1000 km

2000 km

Crust

Mantle

Source

Pn

P

Speed

Depth
Six different steps in nuclear explosion monitoring:

Detection
(did a particular station detect a useful signal?)

Association
(can we gather all the different signals from the same “event”?)

Location
(where was it?)

Identification
(was it an earthquake, a mining blast, a nuclear weapon test?)

Attribution
(if it was a nuclear test, what country carried it out?)

Yield estimation
(how big was it?)
Detection
(did a particular station detect a useful signal?)

Association
(can we gather all the different signals from the same “event”?)

Location
(where was it?)

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(was it an earthquake, a mining blast, a nuclear test?)

Attribution
(if it was a nuclear test, what country carried it out?)

Yield estimation
(how big was it?)

Assessment: How well can we carry out these steps, 
(1) for nuclear tests carried out “in the usual way” (like 2040 past tests) 
(2) for nuclear tests carried out “evasively”? 
Detection
(did a particular station detect a useful signal?)

Association
(can we gather all the different signals from the same “event”?)

Location
(where was it?)

Identification
(was it an earthquake, a mining blast, a nuclear test?)

Attribution
(if it was a nuclear test, what country carried it out?)

Yield estimation
(how big was it? A major issue, 1976 – 1990, for TTBT.)

Assessment: How well can we carry out these steps,
(1) for nuclear tests carried out “in the usual way”
(2) for nuclear tests carried out “evasively”?

Who decides?
INSTRUCTOR ANSWER SHEET:

QUESTIONS

7. Q: Describe what you learned from your data alone.

A: The student learned the distance from the epicenter to the seismic station.

10. Q: Describe step by step how using more data narrowed down the possible epicenter locations.

A: With one data set, the epicenter could be anywhere on the circle, two data sets narrow the possible locations to two (where the circles intersect), and three or more data sets pinpoint the location of the epicenter being where all of the circles intersect.

11. Q: Locate the epicenter on a map showing Earth's tectonic plates. Based on the map, would you expect an earthquake in this area to be fairly common or rare? Explain your answer fully.

A: It depends on the event. Most likely the event is located in close proximity to a plate boundary. Earthquakes are common near most plate boundaries due to the motions of one plate with respect to the adjacent plate.
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Solution for triangulating the student's 3 seismic stations as derived from IRIS's online app “Triangulation”.

P (red), S (blue) and Surface (Yellow) wave picks for the three stations in the student worksheets.
HOW DO WE KNOW WHERE AN EARTHQUAKE ORIGINATED?

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The method of using measured arrival times (at different stations) to locate seismic events is more than a hundred years old.

It is a good way to get an approximate location, but it suffers from three fundamental flaws:

• it uses a small fraction of the information in seismograms;

• it is based on information taken from where the signal is small;

• it requires a method to convert the measurement (time, or $\Delta T$) to a distance (for example the radius of the circle) – and the conversion factor is different for different regions.

ISC, PDE, REB, LEB, ... all use measured arrival times.

Source-Specific Station Corrections, and other methods, help to address the last bullet (enabling use of better regional travel-times).
An Overview of
Seismological Capabilities to Monitor Nuclear Testing in DPRK
Summary statement:

There are many seismic monitoring assets in this part of the world. They are operated by

- Regional organizations in China, Japan, South Korea;
- International organizations for global research + CTBT IMS and IDC; and
- Useful temporary stations.

We can detect underground explosions down to a few tons of TNT equivalent.
Figure 1. A map showing the location of North Korean nuclear tests (open stars), earthquakes (open circles), single-hole explosions and large industrial explosions (inverted triangles), seismographic stations (triangles), in the northeastern Korean peninsula and in northeast China. Dotted circles concentric with the North Korean test site have radii 100, 200, and 300 km.
Figure 7. A map showing locations for: the summit of Mount Mantap (black triangle); the first of North Korea’s UNEs (small star), to the east and south of this summit; five subsequent UNEs conducted within the mountain (larger stars) including the large test explosion of September 3, 2017; and a series of small aftershocks aligned over several hundred metres, about eight km to the north of Mount Mantap (red circles). Adapted from Kim et al. (2018).
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The $Lg$-wave is transverse-wave ($S$-wave) energy, trapped in the crust, having amplitudes that decay exponentially with depth below the crust-mantle interface (the “Moho”).

The crust thus becomes an efficient waveguide (just like the way an optical fiber carries light efficiently). But $Lg$ is blocked if the crust becomes thin (just as an optical fiber fails, if the fiber thins).
Can High-Precision Methods of Seismic Monitoring for Earthquakes and Explosions find Application for Broad Areas?

Paul G. Richards and David P. Schaff
Lamont-Doherty Earth Observatory of Columbia University

SnT2019 Conference, Vienna, Austria
26 June 2019
ONE CENTURY OF SEISMICITY IN MONGOLIA (1900 - 2000)

Authors: Datsy M., Ankhtoerv D., Batsaikhan T., Batz T., Baruva C., Batjargal Ch., Erdenechuluun L., Erdenechuluu D., Munkhsaikhan A., Mansan T., Narambazarg Ch., Sylenge L., Tsogtbaatar B., Tsangkhala M., and in collaboration with BASE since 1996 and its scientific (BASE/ILIG) and technical (BASE/UMG) teams.
Regional waveform-correlation detection for seismic events in and near Mongolia

David P. Schaff, Paul G. Richards

Presentation No: 03.5-398

Lamont-Doherty Earth Observatory
Columbia University | Earth Institute
To apply modern methods of event location in a particular region of space and time, six separate steps can be identified:

1. identify seismic events likely to be well recorded, using, for example, a regional bulletin or detailed global bulletin;
2. pull out their waveforms (our work to date has identified a few tens of seconds of the $L_g$ wave, usable as templates);
3. cross correlate the template for each channel against the continuous archive for that channel, and note detections (e.g., via CC values greater than a value identified via a predetermined false alarm rate, as discussed in Slinkard et al., 2014, using an idea developed by David Schaff);
4. validate such detections (via an association approach or against a local bulletin); after a review of the quality of the detections,
5. measure the relative arrival times (via cross correlation) of pairs of events that were not far apart from each other and were recorded at common stations (with sub-sample precision);
6. and then relocate as many events as possible using double-difference methods.
See a paper at this SnT2021 (03.5–398, by Schaff and Richards). •  The work can be computationally challenging.

• It’s not like Artificial Intelligence or Machine Learning methods because the work is done on the basis of choices made by experienced analysts (filter bands, time windows; and choices of phase, of S/N levels, and false alarm rates).

• Our work on this at Lamont-Doherty Earth Observatory has proceeded steadily over the last ten years (Schaff, Waldhauser, Kim, and recently Ekström and Lopez) with much assistance from Megan Slinkard and Amy Sundermeier (Sandia National Laboratories)
Regional waveform-correlation detection for seismic events in and near Mongolia

David P. Schaff, Paul G. Richards, dschaff@LDEO.columbia.edu

- About 1000 master templates from LEB at two or more stations
- Continuous data for five years from 2012 – 2016 on sparse network of IMS arrays and 3 component stations
- About 33,000 events detected by master templates (33x as many) and located in cluster locations
PASSCAL deployment 2012 – 2016
by Lehigh University

WMQ
Regional waveform-correlation detection for seismic events in and near Mongolia

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- Time-of-Day and Day-of-Week shows these 12 largest clusters with about 800 to 6000 events are man-made

- 10 clusters have 97% or more of events from working hours from 9 am through 5 pm (green lines)

- Sunday is first day of week
- Saturday is seventh day of week
- 8 clusters have 30% or less events on weekends

- The fifth cluster with 1275 events has 1018 events occurring at 12 noon and 233 occurring at 6 pm and 24 events occurring at other times.
Regional waveform-correlation detection for seismic events in and near Mongolia

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Next 12 largest clusters also man-made except for one with more random origin times like earthquake cluster
Regional waveform-correlation detection for seismic events in and near Mongolia

David P. Schaff, Paul G. Richards, dschaff@LDEO.columbia.edu

- Blue circles: clusters with 4 or more events in cluster and 75% or more from 9 am thru 5 pm
- Cyan circles: clusters with 3 or less events in cluster or less than 75% from 9 am thru 5 pm
- Red stars: clusters with 30 or more events in cluster and 75% or more from 9 am thru 5 pm
Regional waveform-correlation detection for seismic events in and near Mongolia

David P. Schaff, Paul G. Richards, dschaff@LDEO.columbia.edu

- Absolute locations in LEB (top)
- Relative Lg correlation locations (bottom)
- Map axes same scale in km
- Mislocations about 15 km
- 95% confidence relative location errors less than 1 km

- Two of largest clusters (right and left)
Regional waveform-correlation detection for seismic events in and near Mongolia

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- Green vegetation
- Brown surface mines spanning several km
- Mean cluster absolute location plots on top of mine
Regional waveform-correlation detection for seismic events in and near Mongolia

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- Green vegetation
- Brown surface mines spanning several km
- Mean cluster absolute location within 1 km of mine
Regional waveform-correlation detection for seismic events in and near Mongolia

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- Lighter areas surface mines spanning several km with roads
- Mean cluster absolute location plots within 2 km of mine
Regional waveform-correlation detection for seismic events in and near Mongolia

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Regional waveform-correlation detection for seismic events in and near Mongolia

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- Lighter areas surface mines spanning several km with roads
- Four clusters match four smaller mine clusters separated by a couple km
- Means of four cluster absolute locations plot within 15 km of mine
Close acquaintance with details of the CTBTO’s International Monitoring System and the International Data Centre can tempt a keynote speaker to present the work as highly complicated, with success coming only via enormous effort. But stepping back from details such as the very size of datastreams received by headquarters in Vienna, and of datasets accumulated after nearly 25 years of operations, it is more important to note the main achievement of the IMS and IDC — namely that the CTBTO draws appropriate attention to events which member States can choose to study in greater or lesser detail.

Intense efforts can then be brought to bear on events of particular interest, as deemed necessary.
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Intense efforts can then be brought to bear on events of particular interest, as deemed necessary. **Many assets can be used for this purpose!**
Estimates of the Yield of a Nuclear Explosion are of many types.
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Although “Yield” is not directly a technical issue in the CTT context, it is still of some interest – for example, it is useful to be able to say that a particular method of monitoring (in application to signals from a particular region), enables effective verification down to some particular Yield level.

For example, an original goal for the IMS was that it would enable monitoring down to “one kiloton, not evasively tested.”
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Methods for Yield estimation include:
Measurement of radionuclides; and
Seismic methods,
   based on teleseismic primary waves or surface waves;
   or based on regional waves, or coda...

But seismic methods must all deal with a fundamental issue; what fraction of the Yield goes into seismic energy?
В.В. Адушкин А.А. Спивак

ПОДЗЕМНЫЕ ВЗРЫВЫ

НАУКА
Figure 1.14 Results of the seismic imaging of the rock massif conducted after 12.5 kt explosion: 1 – cavity and chimney, 2 – crush zone, 3 – zone of inelastic deformations, 4 – zone of localized inelastic deformations. Seismic velocities are also shown in the cross-section.

A zone of inelastic deformations extends up to 120–130 m/kt$^{1/3}$; however it can reach 150 m/kt$^{1/3}$ in some directions. In this distance range new fractures are rarely created, but are sometimes observed. The fracture openings are 2–10 mm on average, while in weaker areas they can reach 10-50 mm. The rock fragments have natural color and physical properties similar to the intact rocks. $P$-velocities are reduced by 5 – 10 %. Permeability is close to that of the intact rocks. Drilling in this zone is similar to the drilling into the intact massif. Significant block movement and opening of the existing fractures is observed, as well as the signs of the “hidden fractures” and changes in elastic properties of the massif due to joint and fracture opening. A sub-zone of renewed fractures is observed within the zone of inelastic deformations up to distances of 50-60 m/kt$^{1/3}$.

A zone of local inelastic deformations is observed up to distances 200 – 220 m/kt$^{1/3}$. Within this zone inelastic deformations along structural discontinuities can be detected instrumentally. These post-explosion changes can be manifested as rocks fallen from the tunnel ceilings, typically in the areas of tectonic deformations. In some cases pre-existing tectonic deformations may become “renewed” allowing gas formed by the explosion to seep from the cavity.

Results of field studies suggest that the mechanical effects of an explosion on rock massif are determined by its pre-existing structure. For example, presence of a tectonic discontinuity (of IV – V order)$^{11}$ near the working point determines the asymmetry of the explosion cavity. Moving away from the epicenter, structural discontinuities play even more important role in the changes to the mechanical properties of rocks. In addition, the nature of damage strongly depends on the local pre-existing geological conditions.

$^{11}$ There are different orders of tectonic faults/deformations in Russian literature
ENHANCED COUPLING AND DECOUPLING
OF UNDERGROUND NUCLEAR EXPLOSIONS

R. W. Trehune
C. M. Snell
H. C. Rodean

September 4, 1979

doi
10.2172/6047353

Work performed under the auspices of the U.S. Department of
Energy by the UCRL under contract number W-7405-ENG-48

LAWRENCE LIVERMORE
LABORATORY
Lawrence Livermore National Laboratory
1. Almost all UNEs were fully tamped.
2. Seismic wave strength increases slightly as cavity radius is increased.
3. For a 1 kt UNE, the cavity radius must be bigger than 6 m to reduce seismic signals more than 50%.