Seismic monitoring for nuclear explosive testing: projects old (DPRK) and new (data rescue)

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Seismogram from China, of a Soviet underground nuclear test in 1989

Cartoons to explain the various waves we record
$Pn$ - wave path
(travels mostly in the mantle)

$Pg$ - paths, in the crust,
all with similar travel times
projects
old (DPRK) and new (data rescue)
Nuclear test explosions in North Korea:

2006 October 9
Nuclear test explosions in North Korea:

2006 October 9

2009 May 25
Nuclear test explosions in North Korea:

2006 October 9

2009 May 25

2013 February 12
Nuclear test explosions in North Korea:

2006 October 9

2009 May 25

2013 February 12

2016 January 6
Nuclear test explosions in North Korea:

2006 October 9

2009 May 25

2013 February 12

2016 January 6

2016 September 9
Nuclear test explosions in North Korea:

2006 October 9

2009 May 25

2013 February 12

2016 January 6

2016 September 9

??

**MDJ, BHZ**
- 371.5 km
- az = 6.1
- baz = 186.5
- 2006-10-09
- M4.3

**MDJ, HHZ**
- 370.8 km
- az = 6.9
- baz = 187.3
- 2009-05-25
- M4.7

**MDJ, BHZ**
- 371.0 km
- az = 6.5
- baz = 186.8
- 2013-02-12
- M5.1

**MDJ, HHZ**
- 368.8 km
- az = 7.2
- baz = 187.6
- 2016-01-06
- M5.1

**MDJ, HHZ**
- 371.9 km
- az = 7.1
- baz = 187.5
- 2016-09-09
- M5.3

- Surface wave

- Pn
- Pg
- Lg

(time (sec))
Evaluation of a seismic event, 12 May 2010, in North Korea
Won-Young Kim, Paul G. Richards, and David P. Schaff (Columbia University, New York); and Karl Koch (Federal Institute for Geosciences and Natural Resources, Hannover, Germany).
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Consortium for Verification Technology (CVT)

Claims of a small nuclear explosive test in North Korea, conducted in May 2010 and additional to those generally recognized, were first published by Lars-Erik De Geer in 2012, on the basis of radionuclide evidence. Several papers have supported his claim from this evidence. Additionally, in 2015, Zhang and Wen found seismological evidence that on May 12, 2010, a very small seismic event (magnitude ~1.5) occurred at the North Korea nuclear test site. They too claimed, unambiguously, that it was from a nuclear explosion. In this project, we have found and analyzed seismograms for the May 2010 event. We used an open station, MDJ, in China, and the temporary Dongbei network, shown here in maps on the left (above depicted waves).

We developed training seismograms of twelve earthquakes and twelve explosions, located in the map on the right, as recorded by station MDJ. We then developed an objective procedure to discriminate between these two types of seismic signal, using Dongbei data. We conclude that the seismic event of interest was a very small earthquake. Our work indicates that the North Korean nuclear test site can be monitored for explosions down to a few tons of explosive yield.

Earthquake and explosion seismograms—note the different P/S ratio for these two types of source; examples of our data in the present case, for known explosions of 2006 & 2009 and the problem event; and our first measurements of spectral ratios (made only on the vertical component).

Development of the Mahalanobis technique for this application.

Mahalanobis developed his methods principally in biology, e.g. to identify butterflies, but they have been applied more widely.

Objective results

The first Figure shows the score for training sets (12 eq, triangles; 12 ex, circles) using vertical data at MDJ. Squares are from Dongbei data; nuclear explosions of 2006-2005, and the problem event of 2010.

A final Figure, and concluding remarks.

An event suited to on-site inspection (CTBT, post ELF)?

Our final Figure is similar to the one immediately above it, but we have added several points. Those in yellow, are derived from the 2015 paper of Zhang and Wen, made at their best station (SMT, in a borehole at a distance of only 120 km from the North Korea test site—see the map, top right). These values are for three earthquakes, for two known nuclear explosions, and for the 12 May 2010 event, at the frequencies needed to evaluate the discriminant score we have used for vertical component data. The known earthquakes and explosions fall appropriately into their respective populations. The 12 May 2010 event falls among the earthquakes. Also shown is a green square for the problem event, derived from an additional station (NE3C) for the event of interest. It is an outlier among the earthquakes, but on the side away from being explosion-like.

At magnitude around 1.5, the 2010 event has signals about 300 times smaller than those of the (small) nuclear test of 2006. A paper giving further details is now in press with the Bulletin of the Seismological Society of America (first issue for 2017). A preprint is available via https://doi.dropboxusercontent.com/u/32478215/BSBA-D-16-00111_accepted.pdf

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Accurate Relative Location Estimates for the North Korean Nuclear Tests Using Empirical Slowness Corrections

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SUMMARY

Declared North Korean nuclear tests in 2006, 2009, 2013, and 2016 were observed seismically at regional and teleseismic distances. Waveform similarity allows the events to be located relatively with far greater accuracy than the absolute locations can be determined from seismic data alone. There is now significant redundancy in the data given the large number of regional and teleseismic stations that have recorded multiple events, and relative location estimates can be confirmed independently by performing calculations on many mutually exclusive sets of measurements. Using a 1-dimensional global velocity model, the distances between the events estimated using teleseismic P phases are found to be approximately 25% shorter than the distances between events estimated using regional Pn phases. The 2009, 2013, and 2016 events all take place within 1 km of each other and the discrepancy between the regional and teleseismic relative location estimates is no more than about 150 m. The discrepancy is much more significant when estimating the location of the more distant 2006 event relative to the later explosions with regional and teleseismic estimates varying by many hundreds of meters. The relative location of the 2006
Figure 10. Commercial satellite image (from 18 September 2014) of the Punggye-ri test-site region near Mt. Mantap (as viewed on Google Earth), with a possible anchoring of the relative location estimates taking into consideration the ground infrastructure and assuming that maximizing the available overburdens was a test engineering priority. The coordinates of the proposed 2006 test hypothesis are 41.2904°N, 129.1039°E (elevation 1920 meters) and the corresponding coordinates for the January 2016 event are 41.2964°N, 129.0793°E (elevation 2189 meters). Any small lateral translation of this template (within a few hundred meters) is consistent with the seismic data presented in this study. A translation to the South would reduce the lengths of the necessary tunnels but also reduce the overburden.
projects
old (DPRK) and new (data rescue)
Seismology as an observational science is based upon studies of ground motion from earthquakes and explosions that were successfully documented by analog recording methods for about eighty years, prior to the emergence of digital recording in the 1960s and 1970s.
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We ask: how can archives of analog seismograms be turned into a usable resource in the digital era, which today permits sophisticated methods of analysis that cannot directly be applied to the earlier types of recording?
Seismology is an observational science, continually surprising us with features in seismograms that are not fully explained by current theories of wave propagation applied to current models of earthquake and explosion sources, and models of Earth structure.

Since the early 1980s, seismic ground motion has been documented via digital recordings that for many stations are commonly made easily available to the research community. There are questions about access to digital data from stations not easily available in this way, but this presentation asks “what to do with the information acquired earlier, during decades of analog recording, when most nuclear test explosions occurred?” There is more than 25 years of experience in Europe and in Asia addressing the question of how to rescue earthquake seismograms recorded in the analog era, and a somewhat different history of data rescue efforts in the United States, where on the order of ten institutions, holding millions of analog seismograms, are beginning to ask how long to maintain such archives. Horror stories abound, of major archives discarded without enough thought, and of losses to flood and decay.

The main graphic here, shows timelines: for nuclear testing, for different types of data acquisition; and for careers of old and young. Opportunities for interaction between those familiar with analog seismograms, and modern analysts, will not last indefinitely. Data rescue entails: event selection; searches for records; scanning; digitizing; and setting up systems for distribution with metadata. We have done this work for nuclear test explosions in Eurasia. The effort to do this for nuclear test explosions in the continental U.S. (including Alaska) and in the Pacific is a management problem, costing far less than acquisition of new data from chemical explosions.
- Vast archives of analog seismograms exist in many different countries, that have developed different practices on how such archives should be treated.

- Specific efforts at scanning and digitizing key datasets have been successful, and such efforts at data rescue need to be communicated to institutions responsible for unused archives.

- Basic documentation on what data exist in the United States, and what can be accessed, is hard to find.

- Very few seismologists who received their training since the 1980s have practical experience of working with analog seismograms. Seismologists who were trained in the 1970s or earlier and are still active, face a daunting task in developing ways to bring out the relevant information recorded in the past, for study using the methods that future generations of seismologists will surely develop.

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- Can we develop consensus on what subsets of analog data should be saved, if such data cannot all be kept indefinitely?
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These are all management problems, and we can solve them.
270 Seismographic Stations Used in the Digitized Analog Seismogram Archive
Potential Projects:

excitation efficiency of chemical explosions vs nuclear explosions

studies of cratering and associated excitation efficiency (of seismic waves)

comparisons of teleseismic and regional interpretations of the same event

studies of the effects of depth of burial (PNEs),
    and of surface topography (Degelen), on regional wave excitation

studies of the effects of near-source rock damage, on excitation efficiency (Degelen)

at Balapan (Shagan River):
    for the largest UNEs, comparisons of $m_b(P)$ and $m_b(Lg)$

for atmospheric nuclear explosions, effects of HOB and Y on seismic excitation

checking/validation, of 3D models of Earth structure in Eurasia
    (and associated travel times)

evaluation of variability of spectral ratios and coda properties,
    in the context of source identification
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Seismology is an Observational Science

More discussion of analog seismograms & data rescue issues, is given in poster #29