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Submission date: 19-Feb-2020 02:34PM (UTC+0700)

Submission ID: 1260062242

File name: Prastowo_2019_J._Phys.___Conf._Ser._1417_012003.pdf (1.59M)

Word count: 3536

Character count: 18593

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To cite this article: T Prastowo *et al* 2019 *J. Phys.: Conf. Ser.* **1417** 012003

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Discriminating a Nuclear Blast from A Natural Seismic Event Using A Full Moment-Tensor Inversion Method

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Abstract. Identification of seismic signals if they are generated by tectonic or volcanic origin or underground nuclear tests is of primary importance for impacts on environmental issues. The recent blast on September 3, 2017 has been in question due to its potential destruction on the global environment. Here, we applied a method of full moment-tensor inversions to analyse broadband waveforms generated by such an explosion. The signals were recorded by a network of 4 regional seismic stations (MAJO, INCN, MDJ, BJT), situated between 360 and 1,100 km away from the explosion epicenter. The results showed that a variance reduction of 72.6%, providing high confidence for all values obtained from the method used: a seismic moment of $M_0 = 6.25 \cdot 10^{24}$ dyne cm, corresponding to a moment magnitude of $M_w = 5.8$, with a dominant volumetric component (ISO) of 50% relatively compared to a 6.8% double-couple (DC) part and a 43.2% compensated linear vector dipole (CLVD) part, and a centroid-depth of 1.0 km. The relative dominance of the ISO seismic component over the other two components, along with the shallow source extracted from the cross-correlation and source mechanism analysis, suggests that the September 3, 2017 explosion was induced by a suspected nuclear test.

1. Introduction

Routine monitoring and accurate identification of seismic signals generated by natural earthquakes or underground nuclear detonations have long been performed for reasons associated with safety issues. Detection of nuclear explosions using a combined model of source mechanisms was proposed by [1] in response to inconsistencies of each particular model with field data obtained from the explosions. Discriminants of artificial explosions from natural events are important and can possibly be obtained from analysis of broadband seismic waveforms recorded by regional stations [2, 3] or observed as teleseismic sources [4]. Relevant work on direct comparisons between human-induced explosions, including a nuclear test, and earthquakes of either tectonic or volcanic origin was explored by [5] using both numerical modelling and surface wave data analysis.

As detonations produce seismic signals propagating beneath the surface to a large area of coverage, experts could then examine propagating waves back in time to the exact source location and determine the corresponding source mechanism. In regard to the analysis of surface waves, a common method, the so-called *P/S* ratio, describing comparison between *P*- and *S*-wave amplitudes hence their energies, was explored by [6] to separate artificial signals from those of earthquakes. Using this direct method, the *P/S* ratio from nuclear explosions is found to be larger than that from naturally occurring events, suggesting the clear dominance of *P*-wave energy over energies from other seismic wave components. In contrast, seismic energy induced by earthquakes is distributed over both body and surface waves, and in some cases most of the energy is taken away from the source by *S*-wave. However, [7] showed



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the P/S discriminant dependence on frequency, making it applicable with caution as the generation of S -disturbances in underground blasts, such as a nuclear test, may be possible, leading to a failure in using the discriminant [8].

As a nuclear weapon brings potential destruction on its surroundings, a watch for the development of nuclear weapons testing around the globe is in demand. The North Korean government is suspected to perform nuclear tests in a series of years since 2006 to date with increasing magnitudes measured. These were the single-blast explosion detected on October 9, 2006 with $M = 4.3$ [9], the second test observed on May 25, 2009 with $M = 4.7$ [10], the third test on February 12, 2013 with $M = 5.1$ [11], the fourth on January 6, 2016 with $M = 5.1$ [12]. All of these previous studies clearly distinguished underground explosions from natural earthquakes recorded by surrounding regional observatories (complete information can be found at <https://ds.iris.edu/ds/nodes/dms/specialevents/>).

In this study, we extend the methodology of discriminating explosions from earthquakes based on real-time monitoring of a nuclear explosion, including travel time inversion for depth estimates [13] to a full moment-tensor inversion method using broadband waveforms acquired from regional stations. We examine and analysis the North Korean's nuclear blast on September 3, 2017 at 03:30:08 UTC with a magnitude of $M = 6.3$ by GEOFON-GFZ at <http://geofon.gfz-potsdam.de/eqinfo/special/korea>. We then use the recent blast as a case study and compare it to earlier tests by the same government. The main aim of the present case is thus to determine whether the latest detonation is a nuclear bomb. In addition, the method developed for this case is proposed with an expected accuracy in prediction of explosion-earthquake discriminant better than that of relevant work, as discussed in [13].

2. Method

The case considered in this study is the latest explosion in North Korea with a measured magnitude of $M = 6.3$ on September 3, 2017 at 03:30:08 UTC. The epicenter of the explosion is located at 41.33° N and 129.03° E. Datasets in the form of broadband seismic digital data were obtained from a network of regional stations managed by The International Federation of Digital Seismograph Networks (FDSN), routinely supervising IU: Global Seismograph Network (GSN-IRIS/USGS), which is freely accessible at <http://www.fdsn.org/networks/detail/IU/> and another IC: New China Digital Seismograph Network (NCDSN) available at <http://www.fdsn.org/networks/detail/IC/>. These provided 4 regional stations used in the current study, namely IU.MAJO, IU.INCN, IC.MDJ, and IC.BJT, where the corresponding locations relative to the source location are listed in table 1. For comparison, all the datasets used were also collected from https://ds.iris.edu/wilber3/find_event.

Table 1. Regional stations used in this study with the corresponding epicentral distances.

FDSN code	Station	Latitude	Longitude	Epicentral Distance	
				in degree	in km
IU	MAJO	36.55° N	138.20° E	8.67°	954
	INCN	37.48° N	126.62° E	4.33°	476
IC	MDJ	44.62° N	129.59° E	3.35°	368
	BJT	40.02° N	116.17° E	9.94°	1093

Figure 1 provides a geographical map of the September 3, 2017 explosion, including all stations used for characterizing the explosion. The yellow star indicates the epicenter whereas the red triangles represent the 4 stations listed in table 1; each station is positioned within a radius of 10° (one degree is about 110 km) away from the epicenter. Green-triangle stations are not used for nuclear test detection as some of them are located outside the radius of 10° permitted or positioned at the perimeter but giving unclear waveforms.

The method of full moment-tensor seismic inversions used in the present work was detailed in [14]. We here provide the saline points of the method using broadband seismograms of seismic signals filtered at low frequency ranges. A full moment-tensor is usually decomposed into two components, that is, an isotropic (ISO) component and a deviatoric tensor. The latter is then further transformed

into a double-couple (DC) part, commonly believed to be responsible for most of tectonic earthquakes, and a compensated-linear vector dipole (CLVD) part, normally associated with volcanic activities. For determination of source mechanisms exploded on September 3, 2017, we have used a MTINV 3.05 software (with permission from Dr. Ichinose). Analysis of broadband data was performed by inverting 3 local seismic waveforms (abbreviated as **Z** = vertical, **R** = radial, and **T** = tangential components) directly obtained from a network of the 4 regional stations in table 1 to extract the source parameters and their corresponding source mechanisms.



Figure 1. The source location and regional stations from https://ds.iris.edu/wilber3/find_event

3. Results and Discussions

Following the methodology in [14], we have performed the full moment-tensor inversion method to analyse broadband seismic waveform signals recorded from the recent blast on September 3, 2017 initiated by the North Korean government, as investigated by [13] but with different techniques and procedures, in order to determine source parameters and mechanisms of the detonation. The results are given in two correlated Figures (Figure 2 and Figure 3), from which relevant discussions are provided. Note that these Figures contain all about seismic information required for characterizing the explosion. The following paragraphs will provide such information concerning with the source parameters and their corresponding source mechanisms.

Figure 2 describes waveform fittings from field observations and numerical simulations completed with all 3 local components of seismic waveforms for recorded micro-displacements (symbolized here as **Z** = vertical, **R** = radial, and **T** = tangential components, respectively). Different from teleseismic observational datasets used by [4], for the datasets in all the 4 regional stations used in the present case (the detailed stations are provided in table 1), black-colored signals represent waveforms from surveys and corresponding red-colored ones show synthetic waveforms. The results of the full moment-tensor seismic inversions for all broadband seismograms recorded by the 4 stations can be seen in Figure 2. Numerical values characterizing the blast-event are featured, including the origin time of the explosion at 03:30:08 UTC, the source epicenter measured in longitude and latitude degrees (41.33° N and 129.03° E, respectively), the source centroid-depth at 1 km below the ground, the station geographical locations in radial distances and azimuthal positions with respect to the source epicenter (see table 1 for complete information), nodal planes (NP1 and NP2) quantifying types of strike, dip, and rake for each nodal plane, the event seismic moment of $M_0 = 6.25 \cdot 10^{24}$ dyne cm, which directly corresponds to the moment magnitude of $M_w = 5.80$, as well as 6 major elements of the fully decomposed moment-tensors ($M_{xx} = 1.84$, $M_{xy} = 0.07$, $M_{xz} = 1.87$, $M_{yy} = 1.58$, $M_{yz} = 0.51$, $M_{zz} = 5.95$) and the following sets of paired moment-tensors $M_{yx} = M_{xy}$, $M_{zx} = M_{xz}$, and $M_{zy} = M_{yz}$ as they are symmetric tensors.

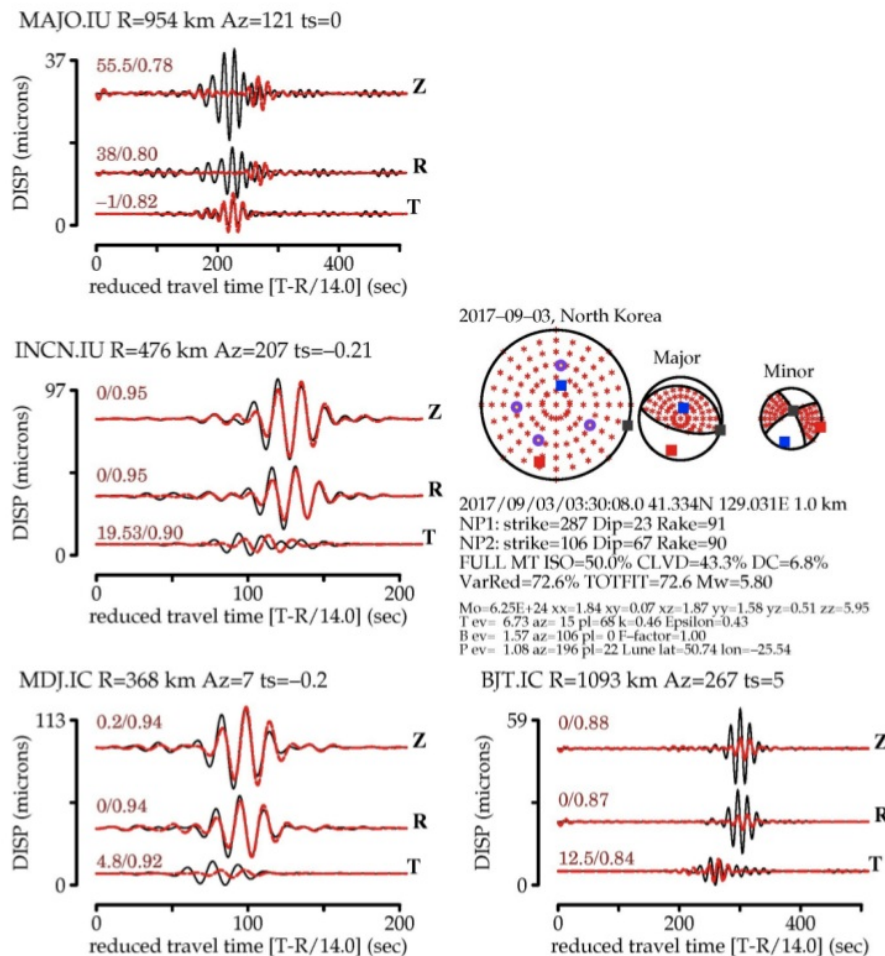


Figure 2. Broadband data with local **Z**, **R**, and **T** waveforms from the September 3, 2017 blast-event, showing fittings of observed (black) and simulated (red) waveforms from the 4 regional stations used (MAJO and INCN provided by IU network, MDJ and BJT provided by IC network).

From a statistical analysis perspective, the resulting seismic inversions give a value of 72.6% for the variance reduction, providing a high level of confidence for all values of the parameters examined. From a physical ground, the seismic inversion method is different from the *P/S* ratio analysis in that this method does not rely on direct comparison between the surface wave amplitudes or energies [6]. Instead, the full moment-tensors are decomposed into two parts, isotropic and deviatoric components. The volumetric (ISO) part of 50.0% was found to be dominant, indicating that the case considered in this study is likely to distribute its energy radially outward. This type of radiant energy distribution in nature is similar to properties of a compressional-longitudinal wave [7]. This is a supporting evidence for the explosion in question, prompting that it was detonated by a nuclear weapon test.

Following standardized decomposition for the full seismic moment-tensors, as discussed in [3, 5], the deviatoric component is further decomposed into the double-couple (DC) and compensated linear vector dipole (CLVD) tensors. Here, the DC mechanism was measured as a relatively small proportion of only 6.8%, suggesting that the source mechanism is unlikely due to shear-dislocation movement of

combined compressional and extensional waves, usually found for seismic activities of tectonic origin. The 43.2% CLVD component completed the full moment-tensor decomposition, for which the energy is rapidly released from the source location via vertically spatial energy distribution through soil layers beneath the surface reaching up to a remarkable distance of tens of kilometers above the zero point. Along with the depth reported, these findings resolve the September 3, 2017 blast as a nuclear bomb, similar to those from earlier nuclear tests previously claimed by [9, 10, 11, 12].

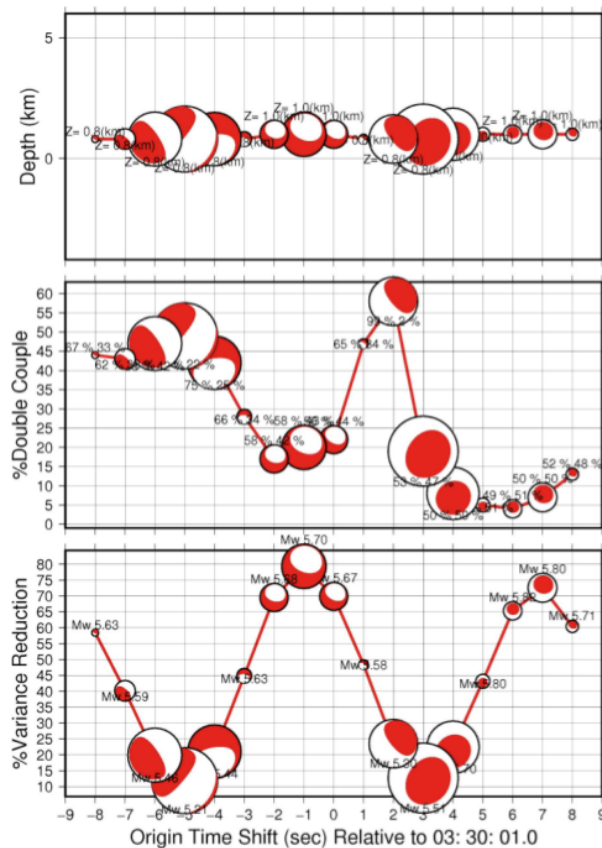


Figure 3. Graphics, showing the cross-correlation of the variance reduction, DC part, and the centroid-depth with respect to time taken for the moment-tensor inversions as the horizontal axis. The variance reduction achieves its peak at 73% corresponding to a seismic moment of $M_w = 5.8$ (bottom panel), which correlates to about 7% DC component (middle panel) and a 1.0 km centroid-depth (top panel).

Plotted in Figure 3, graphics as a result of the full moment-tensor inversions for the case examined. Three plots show a cross-correlation of variance reduction, the DC and its counterpart, the ISO (both in per cent), and the centroid-depth (given in km). With respect to the time shift estimated for the first explosion at 03:30:08 UTC, the September 3, 2017 blast rapidly released its huge amount of energy only within seconds. The energy, measured here as seismic moment, matches with an observed peak of approximately 73% statistical variance reduction, corresponding to a measured moment magnitude of $M_w = 5.8$, followed by earthquakes with a relatively small portion of about 7% for a DC mechanism at the moment the ground explosion was detected at 03:30:08 UTC to only a maximum value of 15% several seconds later. These support for a claim that the energy is not associated with tectonic release. The dominance of the ISO component over the other, particularly the DC, can thus be a good indicator

for explosion-earthquake discriminant [3, 14], in addition to other seismic discriminants, for example, the ratio of body to surface wave amplitudes or energies in [4], the P/S ratio analysis in [6, 7, 8], and the direction of the first vertical micro-displacement in [13].

Regarding all the above findings, from this stage we can make a definitive statement that owing to the full moment-tensor inversions developed by [14], the event in question had a significant isotropic component of 50% compared to only a 7% double-couple with an adequately high level of confidence. This, as in most similar cases, places the relative proportion of the ISO component in a major role in monitoring of broadband seismic signals generated by nuclear tests. Together with the results derived from the full moment-tensor inversions detailed in Figure 2, these parameters of the cross-correlation in Figure 3 yield the same centroid-depth of the source, estimated to be only 1 km below the surface. This finding of the source centroid-depth is in good agreement with that reported by GEOFON-GFZ, which released the depth to be 1 km (accessed at <http://geofon.gfz-potsdam.de/eqinfo/special/korea>). But using the Real Time Monitoring Nuclear Explosion (RTMNE) method that included determination of the source location or hypocenter, [13] reported a depth of up to 2 km deep beneath the ground. However, this method gave no clue about source magnitude and arguably provided imprecise source depth determination, as claimed by [15]. In regard to the difference in source depth estimates, we here to some degree believe that the calculated results from the current method, including the source depth, are obtained with a better resolution and hence a sufficiently high level of accuracy.

In addition, characterization of seismic signals requires a common measurement of energy release, which is, for practical purpose, best represented by a magnitude scale of the signal. Regarding this, GEOFON-GFZ reported a magnitude of $m_b = 6.3$ for the September 3, 2017 suspected event based on measurements of body seismic waves whereas this work measures the magnitude of $M_w = 5.8$ based on the centroid full moment-tensors. In part, the main reason for this magnitude difference is that most of the seismic energy release is taken away by the propagation of surface waves rather than body waves. However, within uncertainties in magnitude measurements both scales arguably have no influence on the determination of whether the blast was underground nuclear detonation or generated by a common natural earthquake. Another method of magnitude determination of a particular seismic signal using earthquake rupture duration as a local parameter recorded by a local network of seismic stations was discussed by [16] in terms of 'duration magnitude' but the methodology presented is not relevant to the present study. Considering possibly increasing scales of any artificial explosions in coming years, it seems that the source depth is likely to be more important for the explosion-earthquake discriminant than the magnitude. While the hypocentre of natural events is usually found from tens of kilometres to a greater depth in some cases, the common source depth of underground nuclear detonation is found to be relatively shallow to only within 1-2 km deep for technical reasons.

4. Conclusions

We have utilized the full moment-tensor inversions to distinguish signals generated by a nuclear test, blasted on September 3, 2017 by the North Korean government from those induced by a natural event. The signals were recorded by a network of 4 regional stations, namely MAJO and INCN (IU network) and MDJ and BJT (IC network), in which these stations were within a radius of 1,100 km away from the epicenter. The results give a value of 72.6% for the variance reduction, providing a high level of confidence for all calculations, including a seismic moment of $6.25 \cdot 10^{24}$ dyne cm, corresponding to a moment magnitude of M_w 5.8, with the dominant ISO component of 50%, and the less important parts of the 6.8% DC and the 43.2% CLVD parts, and the centroid-depth of only 1 km. The clear dominance of the ISO component over the DC part, along with the relatively shallow source depth extracted from careful analysis of the cross-correlation and source mechanisms, suggests that the explosion in quest was generated by a nuclear weapon test. This finding is in good agreement with the results officially announced by some institutions around the world, suggesting that the methodology in the present work is therefore reliable and sensible for monitoring of broadband seismic signals with a better resolution in discriminating nuclear blasts from natural events.

Acknowledgments

The authors personally acknowledge Dr. Gene A. Ichinose for firmly allowing us to use MTINV 3.05, a programming package for seismic data inversions as well as The Incorporated Research Institute for Seismology (IRIS) network and The International Federation of Digital Seismograph Networks (FDSN) for the data available for use in this work.

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