

A journey to Earth Science Projects at Physics Department, the State University of Surabaya: progress in recent years

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A journey to Earth Science Projects at Physics Department, the State University of Surabaya: progress in recent years

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Abstract. Earth Science Projects are research topics conducted by some people working on subjects related to hazard mitigation study on the basis of all efforts in disaster risk reduction through maximizing awareness of science and minimizing all risks of earth-related disasters. These people have joined Center for Earth Science Studies at Physics Department since 2011 and performed computational work, focusing on tsunamis, earthquakes, and volcano eruptions for reliable early warning system development. Other work has in part examined applications of geophysical methods to localize hydrocarbon reservoirs using analysis of broadband-noise spectral amplitude and low-frequency spectrogram, and distinguish underground nuclear tests from natural earthquakes of seismic origin. The Projects may also be relevant to science and/or physics education students as final projects with earth-related disasters as the main themes using laboratory approaches. Several publications made by the group members and students in recent years are therefore discussed, emphasizing on seismic hazard assessment and analysis. Future direction of possible research collaboration between research groups in the department will also be discussed in terms of challenges and technical difficulties.

1. Introduction

Due to its unique geographical position and geological condition, Indonesian territory is vulnerable to geophysical hazards. These earth-related disasters include seismic catastrophes of either tectonic or volcanic origin and destructive tsunamigenic-earthquakes. Recent records from [1] have reported that the occurrence of these disasters across the country is not as frequent as hydro-meteorological hazards, but earthquakes, tsunamis, and volcanic eruptions are found to be the primary cause, in the first place among all disasters, for making up more than 50% of human casualties and property losses. Regarding science education at all levels and public awareness of earth science, which are the cornerstone of approaches aimed at reducing vulnerabilities to such disasters, human responses play a crucial role in the degree of vulnerability to catastrophes [2]. Within this context, there remains a room for promoting earth science to students in schools and universities thereby introducing ‘good culture’ of prevention. At this stage, it seems that misconception about disasters as ‘natural curses’ is a psychological barrier towards safety issues. Therefore, disaster education is expected to change people’s mindset and hence to promote disaster risk reduction program in a fashionable way during studying times in schools and universities and in turn to build, in a time sequence, a long-term, disaster-resilient community [3].

In response to the need for introducing disaster-related science and transforming science literacy in practice for university students, as suggested by [4], as well as considering the importance of this issue

as a complicated task requiring collaboration work from relevant parties [5], some co-working people at Physics Department, Faculty of Mathematics and Natural Sciences, the State University of Surabaya have then initiated a research group: Center for Earth Science Studies since 2011, focusing upon issues related to earth science. This research group has facilitated group members and students with projects on the applications of geophysical methods to develop early warning system for tsunamis [6,7,8,9] and earthquakes [10,11] and examine source parameters of eruption [12], as well as other possible uses, such as accurate identification of a potential hydrocarbon reserve [13] and an artificial explosion [14]. Either laboratory or computational work is utilized to examine the physics of tsunamis, earthquakes, and eruptions using particular softwares (for example, *Joko Tingkir* and MTINV) or freely accessible secondary data available from reliable global data sources (see, for example, National Oceanic and Atmospheric Administration (NOAA) Center for Tsunami Research at <https://nctr.pmel.noaa.gov> and National Geophysical Data Center (NGDC) at <http://www.ngdc.noaa>). These data sources include numerical datasets extracted from broadband seismic waveforms and tsunami magnetic signals [15] recorded by relevant stations around the globe. Since this review describes research progress made by the group members merely in a global sense, interested readers are advised to refer to corresponding papers in the reference list for a greater detail of description.

Although many studies have recently been performed for the development of hazard assessment and mitigation study in correspond to hazardous disasters that frequently occur throughout the country, the nature of the disasters remains poorly understood. Thus, we here provide a brief review of progress particularly in tsunami and earthquake sciences made by the group members since 2011 to date in accordance with relevant work of other authors, for example [3,16], in searching for the best solution to the country's problem. We then divide discussions on this review into three groups of publications: (1) papers directly related to devastating disasters (tsunamis, earthquakes, eruptions); (2) papers discussing about ways of detecting potential hydrocarbon reservoirs and methods of differentiating nuclear explosions from natural earthquakes; and (3) papers about science and/or physics education relevant to disasters. Discussions on the recent published papers by the group members, including submitted manuscripts for upcoming publications elsewhere are directed towards possible research and future work on the core themes.

2. Projects towards development of early warning system

Among all types of disasters, tsunamis, earthquakes, and volcanic eruptions are the most damaging natural events induced by sub-surface, seismic (either tectonic or magmatic) activities in Indonesia. These events pose threat to human lives and properties with increasing scales as population growth is continuously spread over time in potentially dangerous areas in the country, such as along active faults and close to shorelines in the subduction zones. In this section, we provide the saline points of papers published by the group members, working on this nation-wide issue to develop early warning system, hazard assessment and its corresponding analysis associated with these geological hazards.

The major, devastating 2004 Indian Ocean tsunami that hit many regions in the west-coast of Aceh has driven the Indonesian government through the Indonesian Agency for Geophysics, Climatology, and Meteorology (BMKG) to set up the so-called Indonesian Tsunami Early Warning System (Ina-TEWS) since 2008. Once an earthquake occurs with its hypocenter at a point deep below the surface, the Ina-TEWS automatically estimates common earthquake parameters, including origin time (OT), epicenter (latitude and longitude positions), hypocenter (depth), and magnitude in a local measure. When these parameters are identified as critical values for tsunami warning, BMKG officially notifies tsunami alert for public announcement. However, the applications of these source parameters for use in the Ina-TEWS have been in debate since many events were falsely issued as tsunamigenic potential during the initial years of implementation [10].

For comparison with respect to the advancement in the discipline, which is in line with the need for a reliable method of detecting tsunami generation in the open ocean, [17] introduced a new parameter, namely, earthquake rupture duration T_{dur} for effective tsunami warning, instead of source magnitude. Applying this method to local events with large scales in magnitude in regions of Indonesian territory, [6] found that the majority of the events corresponds to a critical value of source rupture duration, about 65 s in regard to 50-55 s for teleseismic earthquakes used by [17], above which a tsunami is

most likely generated, independent of source mechanisms. Along with the P -wave dominant period T_d , these two important parameters were, using a direct procedure developed by [18], rapidly computed for accurate analysis of tsunami potential for two occurrences in the west-coast of Sumatra in April and October 2010 [7].

In order to develop a more reliable method of detecting the presence of a tsunami wave in only several minutes after mainshock, [19] suggested a new technique of tsunami-discriminant calculations. This technique was adopted by [8] for cases in Indonesia, in addition to tsunami importance defined as the sum of descriptive indices discussed in [18], leading to a set of five criteria for tsunami assessment and hence tsunami early warning: $T_{dur} \geq 65$ s, $T_d \geq 10$ s, $T_{65ex} \geq 1$, $T_{dur} \times T_d \geq 650$ s² and $T_d \times T_{65ex} \geq 10$ s. If three, or more, of these five indicators are numerically satisfied then a tsunamigenic earthquake is possible to occur. For example, in the case of a relatively shallow, large earthquake with 7.8 in size that occurred off the west-coast of Sumatra on March 2, 2016, only T_{dur} was measured to be greater than a critical value and other parameters were less than critical values required for tsunami warning, leading to no tsunami generation [9]. Another example is provided here with a complete feature of tsunami assessment seen on figure 1, describing how these tsunami discriminants are rapidly analyzed and assessed using a validated *Joko Tingkir* programing package detailed in [8].

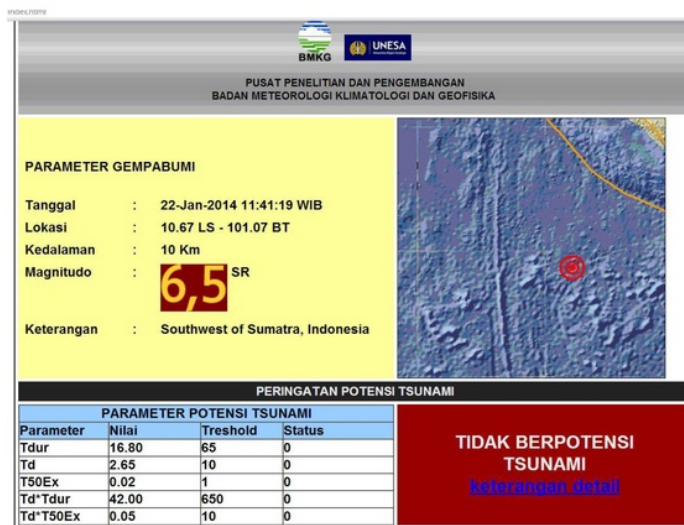


Figure 1. Tsunami assessment on the basis of tsunami discriminants for a shallow source of 10 km deep found with a local magnitude of 6.5 that occurred in southwest of Sumatra on January 22, 2014 (available from <http://inatews.bmkg.go.id> for academic purpose only).

Further development of tsunami early warning is performed by [20] with the inclusion of a filtering process, namely the M-filter application for T_d automatic computation to reduce noise effects, thereby improving the Ina-TEWS performance.

As widely accepted, earthquake of tectonic origin hypocentered below the ocean floor at depth is the major cause for damaging tsunamis in the worldwide. In the context of Indonesian archipelago, [21] addressed a likely positive trend in the eastern provinces, particularly in Sulawesi island, where locations of earthquake hypocenters were systematically shifted from underground on lands to oceans in the deep, and hence potential to tsunami generation. It follows that earthquake early warning is also of fundamental importance to develop for better prediction of seismo-tectonic hazards, which include tsunamis. The development mainly concerns with concept, method, and reliability, as claimed by [5]. Therefore, research on the nature of earthquake is generally linked to that of tsunami, bringing ideas to incorporate T_{dur} , T_d , and T_{65ex} used in [6,7,8,9] into earthquake parameters, such as the OT, depth, and

magnitude that are frequently inconsistent with values given by the centroid moment-tensor (CMT) catalogue as the global reference for assessing earthquakes [10]. Evaluation of earthquake parameters is expected to improve the Ina-TEWS performance and prevent society from 'false warnings', thereby reducing seismic hazard risks to a minimum level at a maximum effort.

As with the improved performance of the Ina-TEWS using routine monitoring of seismic signals by BMKG, alternative techniques designed for magnetic signal observations owing to tsunami passage are now in demanding suggestions. These have actually been in common for international community primarily due to physical grounds but are not yet applicable in Indonesia as magnetic measurements are rare compared to seismic surveys. Motivated by previous work on 'ocean dynamo effects' by [22], [15] considered tsunami-magnetic signal generation during a tsunami event as magnetic perturbations with respect to the ambient geomagnetic field. The secondary magnetic signals are possibly detected as 'local anomalies', attributable to sensitive instruments at various positions either on satellites [23], ground observatories (see International Real-Time Magnetic Observatory Network - INTERMAGNET accessed at <https://www.intermagnet.org> and Bureau Central de Magnetisme Terrestre - BCMT accessed at <https://www.bcmt.fr> as two global magnetic institutions), Deep-ocean Assessment Reports of Tsunamis (DART) buoys on the sea surface, freely available from <http://www.ngdc.noaa.gov>, or Ocean Bottom Electro-Magnetometer (OBEM) at the sea floor [24,25,26]. These magnetic anomalies were reported in [15] as the vertical b_z and horizontal b_H components of the tsunami-magnetic field for large occurrences in Chili (2010), Tohoku, Japan (2011), Mentawai (2010), and Aceh (2004), where the maximum amplitudes of b_z and b_H were determined using frozen-flux theory and magnetogram.

Using the global data for the ambient Earth's main field, ocean depth, and sea surface elevation, [12] examined the 2010 Chilean and 2011 Tohoku tsunamis in which two dynamic aspect ratios used: a depth ratio $h/L \geq 2.0$ adopted from [26] and a speed ratio $c/c_s \approx 1$ were satisfied, frozen-flux theory can be used to estimate accurately b_z and b_H , neglecting oceanic diffusion. For the 2010 Chilean case, b_z was estimated to be about 0.5 nT, in good agreement with [25] whereas for the 2011 Tohoku event, b_z was 15.5 nT, lying in the range between values reported by [24]. The results for these events are consistent with magnetogram given by either INTERMAGNET and/or BCMT. For the Mentawai case, b_z was no longer calculated using frozen-flux approximation since diffusion was considered important. However, the resulting calculations of $b_z \leq 2.2$ nT were consistent with the maximum amplitudes for b_z in regions near the equator including the 2004 Aceh tsunami, about 2.0 nT, as claimed by [22].

As widely known, linear shallow-water approximation is commonly used, to first order, to describe tsunami propagation. The wave height evolution during propagation in the open ocean to shorelines is here discussed. At its arrival on beaches, the wave brings enormous energy causing severe destruction on surrounding infrastructures, human injuries, and even deaths. In the light of tsunami hazard risk reduction, this issue is important as it gives rise to the importance of tsunami run-up prediction [27]. Using physics principles of conservation of energy density flux, [28] combined the basic Green's law, relying on external parameters of offshore and onshore depths, to include wave behavior in terms of effects of refraction when the wave approaches shorelines. This resulted in simple parameterization for run-up height, where 70% of cases reported were resolved in considerable accuracy.

As pointed out by [1], there has been increasingly active faults more than three times since 2010 to date found in the Indonesian territory, including regions of West Sulawesi and Central Sulawesi. With respect to the need for rapid and accurate magnitude determination for a number of moderate events recorded as shallow sources in majority by a network of seismic stations in the two regions of interest, [11] examined local earthquakes with secondary data available at <http://eida.gfz-potsdam.de/webdc3/> and <http://www.globalcmt.org/>. Using high-frequency broadband seismic waveforms from these sites, [11] then derived an empirical relation between the local size M_{pd} and the dominant period T_d extracted from P -waves using *Joko Tingkir*. For all events considered, the calculated values of M_{pd} are compared to the magnitude reference M_w^{CMT} given by the global CMT catalogue. The results for local magnitude estimates of M_{pd} for each province are found to be consistent with the reference values of M_w^{CMT} with a small uncertainty of approximately 0.2, suggesting that the proposed method by [11] is reliable to estimate local earthquake size of moderate scales. Figure 2 below describes insignificant differences in magnitude scales between M_{pd} and M_w^{CMT} for both provinces.

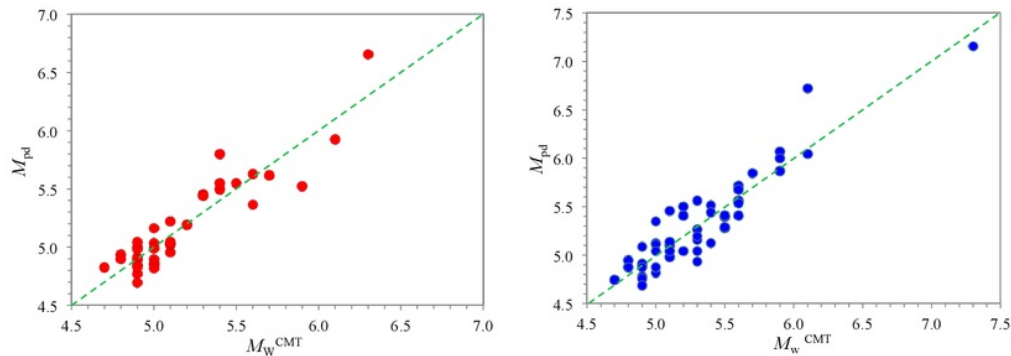


Figure 2. Distribution of all events considered for West Sulawesi (left) and Central Sulawesi (right) during 2008-2015 years, showing no significant differences in magnitude between M_{pd} and M_w^{CMT} for moderate scales, as illustrated in [11].

Further investigation into magnitude determination of the same range in size for local earthquakes in North Sulawesi, in addition to the two previous provinces, has been in progress [29]. In this study, local magnitudes M_{pd} are used to generate duration magnitudes M_{dur} using a reliable scaling relation between the two scales in magnitude, $M_{dur} = 1.05M_{pd} - 0.17$, as adopted from previous work of [30]. The results for this scaling successfully confirm that M_{dur} estimates are in good agreement with M_w^{CMT} as the global references to within ± 0.2 units [2]. These studies suggest that empirical formulas that relate M_{pd} to T_d in [11] and M_{dur} to M_{pd} in [29] are appropriate for accurate magnitude determination to improve rapid assessment of seismic hazards in the three provinces.

As early stated, owing to its uniquely geographic location surrounded by the Pacific ring of fire, Indonesia is home for active volcanoes along the Sunda arc hence vulnerable to volcanic eruption. Therefore, routinely monitoring of seismo-magmatic activities is of importance for the development of hazard mitigation study associated with catastrophic eruption [31]. Analysis of a volcanic earthquake allows us to examine magma dynamics and its complicated geophysical and geological processes inside a volcano. This is ultimately performed in the spirit of making the best efforts to better predict volcanic eruption to occur hence to estimate possible impacts on the surroundings.

In the case of eruptive moments driven by magmatic processes of Mount Agung, Bali that occurred on September 28, 2017, [12] investigated such an usual earthquake using a specific software, namely MTINV 3.05 developed by [32] for a seismic inversion method. This method simply separates source mechanisms of seismo-magmatic activities into isotropic (ISO) and deviatoric (DEV) components, where the DEV part is further decomposed into a vertical compensated-linear vector dipole (CLVD) component and a double-couple (DC) component. Using the full moment-tensor inversions, [12] found that this earthquake is rare in nature and frequently associated with an active volcano. Furthermore, using this seismic inversions [12] calculated for the 65% variance reduction corresponding to the event of $M_w = 3.64$ in size and the hypocenter of 9.7 km in depth, where the rare-quake was characterized by two comparable seismic moment-tensors: the 40% vertical CLVD and the 33% ISO, and the other, which is a relatively unimportant component in this case, the 27% DC. As widely believed by many, the DC part is the cause for earthquakes of tectonic origin and therefore the comparable calculations of both the CLVD and ISO components show that the volcanic earthquake is dominated by uplift motion of fluid flows from a magma chamber followed by a change in a magma volume inside the volcano. As these features are common for volcanic earthquakes before eruption to occur, [12] then concluded that the volcano was in its stages of eruption while remaining active. Detailed results of computation using the seismic inversion method are given in figure 3.

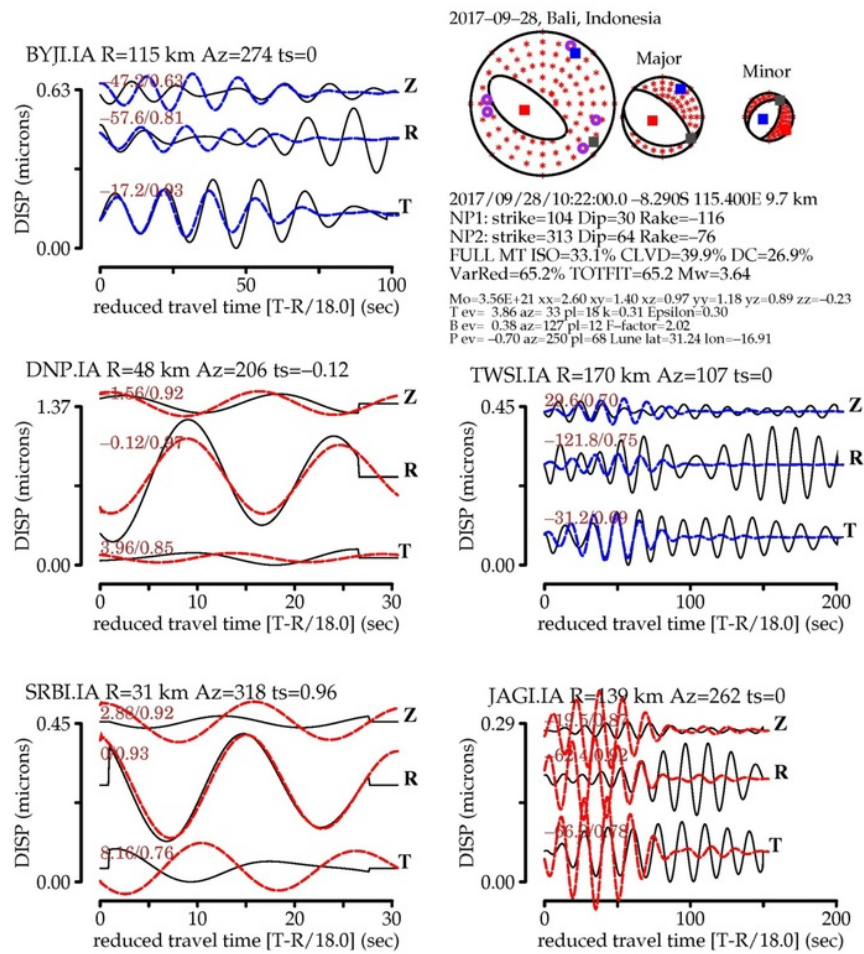


Figure 3. Broadband seismograms, showing fittings of observed and synthetic waveforms recorded by a network of five local stations for the case of an unusual volcanic earthquake on 28 September 2017, where the black colors are observed signals whereas the red and blue colors represent synthetic ones. These features of the full moment-tensor inversions, taken from [12], including the calculated results for source parameters and focal mechanisms are all here provided.

3. Other applications

Since oil and natural gases are vital resources for energy consumption in most Indonesian territories, the search for a potential reserve of hydrocarbons in some new oil fields is thus crucial. In this context, the application of geophysical methods can extend to determine potential hydrocarbon reservoirs using broadband-noise analysis of spectral amplitudes and frequency spectrograms. This analysis is based on the apparent behavior of hydrocarbon micro-tremor signals, which demonstrate amplitude anomalies in the frequency range between 2-4 Hz [33]. Using this technique, [13] found a potential hydrocarbon reservoir at some depth beneath the YOGI seismic station in the perimeter of a Yogyakarta basin. Shown in figure 4 below, the results are provided for the broadband-noise spectral amplitude analysis (left panel) and the corresponding spectrogram for frequency (right panel). The hydrocarbon signals in both peaked at a value of 2.9 Hz, consistent with previous work of [33].

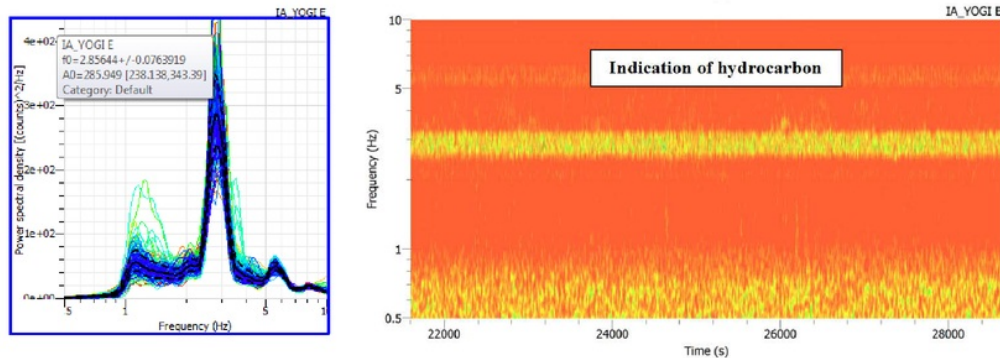


Figure 4. Left panel, showing analysis of spectral noise amplitudes extracted from the E component at low frequency ranges recorded by the YOGI station. The amplitude anomaly achieves its maximum at about 2.9 Hz (in the range of 2-4 Hz, as claimed by [33] for hydrocarbon micro-seismic tremors). Right panel, showing frequency spectrogram analysis extracted from the E component of the noises. Detected micro-tremor signals are, lying around 3 Hz, induced by the presence of a potential reserve of hydrocarbons beneath the YOGI station. These panels are hence, both originally taken from [13], in support of each other to detect the precise location of a potential hydrocarbon reservoir.

Another application of geophysical methods can also be found in seismic signal identification for detailed source mechanisms. Accurate identification of the signal whether it is generated by a natural earthquake of either tectonic or volcanic origin, or by a nuclear test is of fundamental importance for both safety and environmental issues. Using the Real Time Monitoring Nuclear Explosion (RTMNE) method that included determination of source location, direction of the first vertical displacement, and the relative dominance of the *P*-wave component with respect to the *S*-component, [14] successfully identified the recent blast on September 3, 2017 as a nuclear bomb, rather than an earthquake event. However, this method was somewhat uncompleted since it gave no information about source size and imprecise source depth determination.

In the light of searching for a more accurate identification, [34] used an alternative method, namely the full moment-tensor inversions (MTINV) for detailed analysis of broadband seismograms recorded by the 4 regional stations (IC.BJT, IC.MDJ, IU.INCN, IU.MAJO – seen on the left panel of figure 5, covering a perimeter of about 1,100 km away from the source). The origin time of the suspicious explosion on September 3, 2017 was estimated at 03:30:08 UTC with the epicenter were at 41.33° N and 129.03° E. The results using this method were accurate enough to locate the source depth at 1 km beneath the surface and determine the seismic moment of $M_0 = 6.25 \times 10^{24}$ dyne cm, corresponding to the magnitude of $M_w = 5.80$. Besides a relatively shallow source and strong magnitude of the event, other important features extracted from this seismic inversion included statistical analysis of variance reduction of almost 73% and the relative dominance of ISO component of 50% over DC component of only 6.8%. This relatively large ISO component over the others (CLVD and DC components) suggests that the event was believed to be underground nuclear test, instead of a volcanic or a tectonic activity.

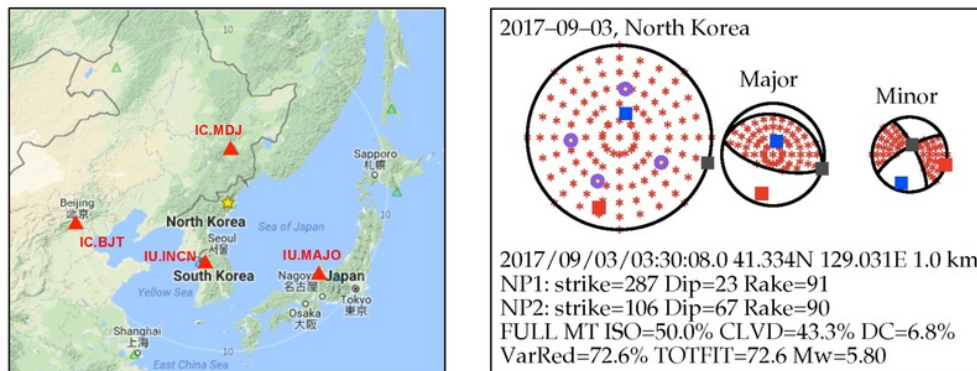


Figure 5. Left panel, showing the source location of the **b₃** event on September 3, 2017 (shown as yellow star) and **s** surrounding regional seismic stations from https://ds.iris.edu/wilber3/find_event. Right panel, the results of the full moment-tensor inversions (MTINV) for the broadband waveforms collected from the four stations (shown as red triangles on the left panel). While the left panel is taken from [34] for a full appearance of all regional stations used in the measurements, the right panel is partly taken from the MTINV method proposed in [34].

4. Projects towards science or physics education

As previously stated, good knowledge of science and/or physics education relevant to disasters is also important for school and university students. The science and/or physics of disasters can be introduced to the students via classroom activities in the schools or final projects in the universities. For example, [35] examined gravity current propagation in a long, horizontal tank in the laboratory to demonstrate uniform motion. Gravity current is here simply illustrated as the horizontal movement of two fluids with different densities in the opposite directions. Applying simple measurements of total water depth in the set up and the density difference between fluids of the dense current and the less dense current, [35] reported that frictionless density-driven currents propagate at constant speed. In the presence of small-scale turbulent mixing observed during runs, the current speed was found to be influenced by the density contrast between the fluids and water depth, consistent with previously reported work [36]. This remarkable result may bring some ideas to students in understanding propagating tsunami waves in the open ocean as the speed of horizontal gravity currents are, in principle, similar to the speed of non-dispersive tsunamis. The way in which tsunamis as long, surface gravity waves propagate helps the students understand the concepts of tsunami travel time and travel time delay between observed and simulated tsunami waves, particularly for trans-oceanic tsunamis, owing to speed reduction along great travel distances [37,38].

However, gravity current speed measurements did not reveal whether or not energy is conserved during the motion but corresponding current depth measurements did [35,36]. As it stands, mass is always conserved while energy could be, in some sense, lost during a physical process or transformed from one form into another. These basic physics principles hold for particular disasters, such as lava flows and tsunamis, two types of disaster that are possibly examined using laboratory gravity currents. Regarding mass and volume conservation for incompressible fluids constituting gravity currents, [39] reported that mass and volume are conserved to within a negligible, tiny fraction of losses in mass and volume but found that some amount of energy is dissipated by friction during propagation. This brings also some ideas about tsunami energy decay hence tsunami amplitude attenuation during propagation for distant tsunamis across the Pacific. Within this context, [40,41] claimed different mechanisms responsible for energy release in the zone of propagation. In short, conversion from the gravitational collapse of potential energy into kinetic energy in the initial stage of tsunami wave generation and propagation is present whereas conservation of total mechanical energy follows in the next stage.

5. Concluding remarks

Within the framework of hazard mitigation study and the importance of the science and/or physics of disaster, a comprehensive approach is likely to be the answer to the problem in question related to frequent disasters in the Indonesian territories. As tsunami waves are the most devastating catastrophe, much attention is then given to the further development of the Ina-TEWS operated by BMKG, using seismic signals monitoring, as is the case in the present method. For an alternative method, relying on monitoring of magnetic field anomaly owing to tsunami passage in the ocean could also be considered. Given that tsunami-magnetic signals are relatively weak compared to the main geomagnetic field, sensitive magnetic sensors are required to examine past tsunamis hence better predict future tsunamis. Meanwhile, in the perspective of end-user objectives, information regarding tsunami-magnetic signals could also be introduced to the students in school and university settings via curricula development. This requires an integrated approach that may combine theoretical analysis of case studies considered, field measurements, and numerical simulations for a more reliable, developed method. The final hope is that all efforts in the disaster risk reduction program can significantly contribute to preventing lives and properties from fatalities caused by any type of disaster.

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