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THE POTENTIAL OF AN EARTHQUAKE EARLY WARNING SYSTEM FOR INTERMEDIATE-DEPTH EARTHQUAKES IN GREECE

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ABSTRACT

We investigate the potential of operating an Earthquake Early Warning (EEW) system for intermediate-depth earthquakes along the Hellenic arc, using past data recorded by the Hellenic Unified Seismological Network (HUSN). We specifically test PRESTo (PRobabilistic and Evolutionary early warning SysTem) software for EEW to playback data from past moderate-magnitude, intermediate-depth earthquakes that occurred on the Aegean subduction zone aiming to assess a) the applicability of the underlying method to detect intra- and inter-slab earthquakes b) the appropriateness of existing empirical relations to sufficiently quantify the magnitude of these events, as well as the amplitudes of shear-waves (S-waves) at remote, densely populated areas such as the largest cities on the Island of Crete and c) to estimate the order of magnitude of the reaction time that future warnings may provide. Our results suggest that the installation of a denser sensor array could reduce the area of the blind zone and increase reaction times. Also, they show that although continuous calibration of the EEW system would be required, especially due to the sparsity of intermediate-depth events, the large depth of the examined events allows the issuing of prompt warnings, usually >10s before the arrival of S-waves. A real-time application of the tested software could provide more realistic assessments of the actual reaction times, as hardware and data transmission delays need to be quantified and taken into account, as well. In any case, warnings can be prompt enough for automatic protection reactions or even manual risk mitigation procedures if combined with appropriate training.

Keywords: earthquake early warning system, Aegean, intermediate-depth earthquakes, PRESTo

INTRODUCTION

Over the past years, the emergence of earthquake early warning (EEW) systems has proven to be a useful tool to sustain possible losses from the occurrence of a strong earthquake. A seismic damage mitigation could be achieved not only by the continuous seismic hazard assessment and earthquake monitoring, but also by an EEW system that can prepare citizens for an upcoming seismic event. Public transportation, industrial plants and machineries could stop from operating if the earthquake warning is transmitted in a timely manner. As

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current knowledge is growing, new advances make the application of EEW systems feasible in cases thought to be incapable of providing alerts.

The EEW systems seek to provide alerts after the appropriate estimation of the earthquake origin time, hypocenter, magnitude and the realistic assessment of the intensity of the imminent ground motion that is expected within a target area. In order to achieve an effective alert, EEW systems need to balance the trade-off between operational speed and accuracy in estimating these parameters (*Kamigaichi et al., 2009*). Therefore, seismological network operational latencies (signal transmission, digitizer errors etc.) should be reduced and computational speed should increase. Another aim of EEW systems is to provide fast warnings and reduce the extend of the blind zone, i.e., the area that has been already struck by the earthquake by the time the event has been detected and an alert has been transmitted.

Despite the operational latencies and the computational speed, there are plenty other factors affecting the accuracy of an EEW system. High seismicity regions (such as Greece) with many seismogenic sources need a dense seismological network in order to record an event shortly after its origin time. To operate an EEW system in Greece is challenging due to the complex geotectonic setting of the area, the abundant seismogenic sources, the lack of monitoring stations in the sea area and the current network operational latencies. However, recent studies (e.g. *Thelen et al., 2016*) have shown that the blind zone for intermediate-depth earthquakes has significantly smaller spatial extent compared to shallow depth earthquakes for the same region. Therefore, our study aims to test the potential for the operation of an EEW system in Greece for intermediate-depth earthquakes.

DATA USED AND METHODOLOGY

The spatial distribution of the M > 5.8 intermediate and shallow depth earthquakes which were recorded in the Greek region for the period 2002-2017 is shown in Figure 1. Most of the recorded events have occurred along the Hellenic arc and near large urban areas, such as Ionian Islands, Crete, Karpathos, Rhodes. The southern Aegean volcanic area is characterized by high attenuation of the amplitudes of the recorded waves (mainly S waves), which are different for intra- and inter-slab earthquakes due to their different paths of propagation (*Skarlatoudis et al., 2009*). The anelastic attenuation is stronger for ray-paths crossing the mantle wedge, which generated the Hellenic volcanic arc (comprising of volcanoes such as Nisyros, Milos, Santorini and more). Hence, it is challenging to test the applicability of methods to detect intra- and inter-slab earthquakes. To determine whether an EEW system could issue alerts for the urban areas such as those aforementioned and to examine the possible effect of the strongly attenuating southern Aegean structure, we chose to test earthquakes with epicenters near Crete.

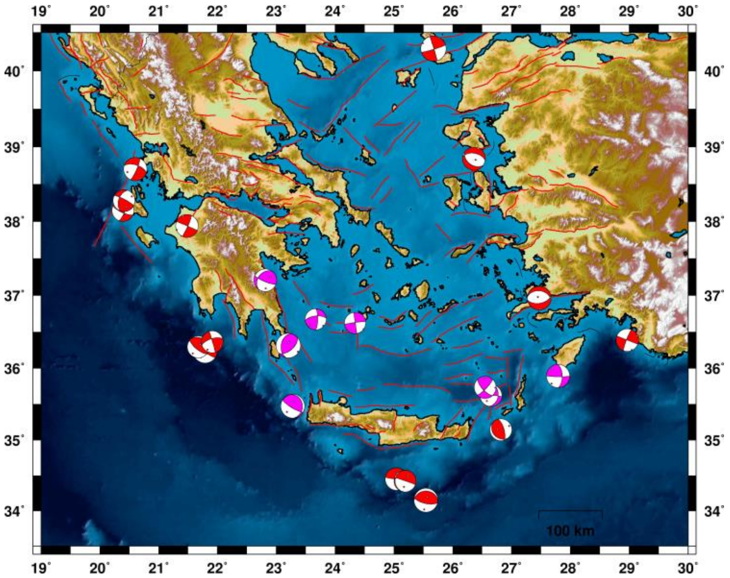

Figure 1. Epicenters of intermediate-depth (magenta beach-balls) and shallow (red) earthquakes (Mw > 5.8) for the period 2002 – 2017.

We used recordings from 40 stations operated by the Institute of Geodynamics of the National Observatory of Athens (NOA), which is part of the Hellenic Unified Seismologic Network (H.U.S.N.). The locations of the stations used in this study are shown in Figure 2 as red triangles and most of them are installed in the southern Aegean region. Prior to using the recorded data for back-testing, we removed the instrument response from each recording.

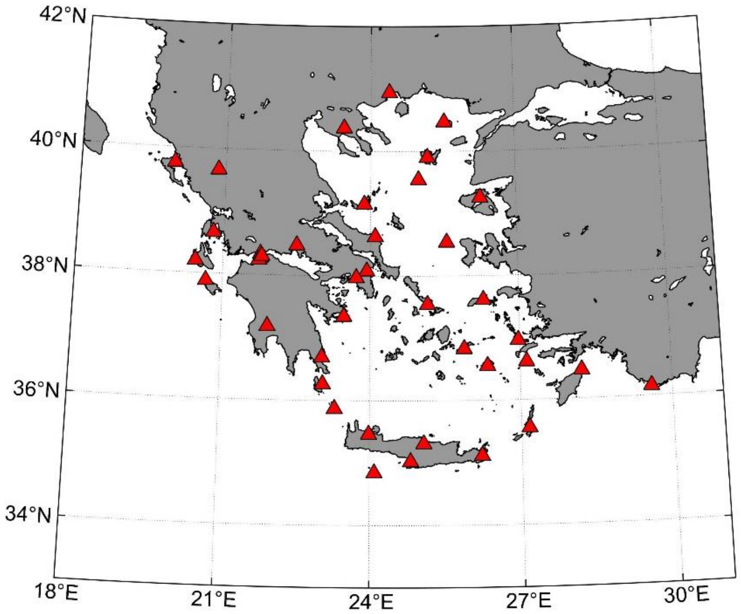

Figure 2. Spatial distribution of NOA (H.U.S.N.) stations that were used in this study.

Initially, in order to have a rough estimate of the radius of the blind zone, we computed the minimum hypocentral distance needed for an event to reach at least three (Fig. 3-left) or four (Fig. 3-right) neighboring stations. This number is considered to be the minimum required to trigger an EEW system, which is based on regional network data. The histograms shown in Figure 3 roughly depict the radius of the blind zone (since more computational time is needed to transmit an alert) which is at least 50 km for our dataset and stations configuration. The mean distance value for an event to reach the minimum requirement of 3 and 4 stations is ~125 km and ~150 km, respectively. Thus, near-source recordings are either limited or absent and alert issuing is expected to apply mostly to areas at distances where strong motion has been significantly attenuated with respect to its amplitude within the blind zone.

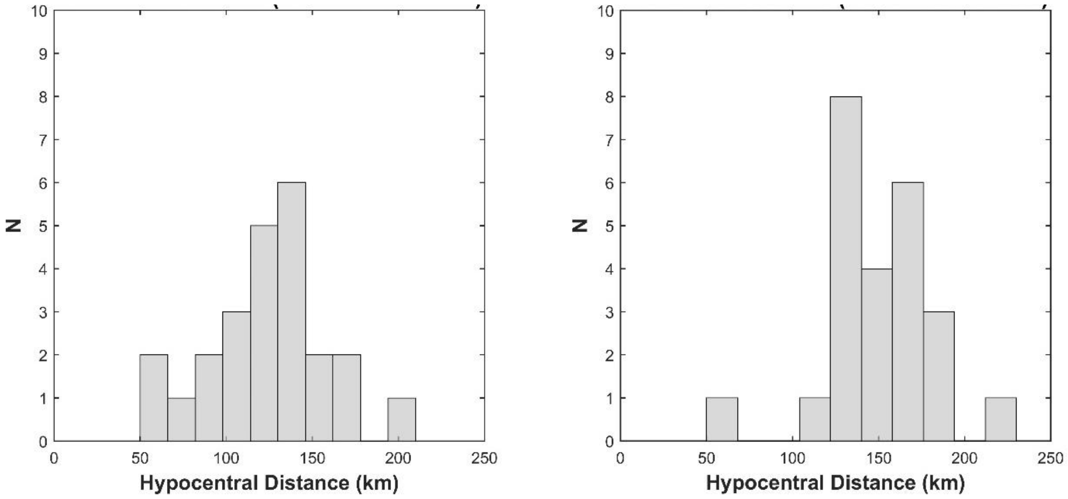

Figure 3. Histograms of the minimum hypocentral distance required for an event of the present study dataset to be recorded in three stations (left) and in four stations (right).

To examine the feasibility of an EEW system for intermediate-depth earthquakes, we used PRESTo (PRobabilistic and Evolutionary early warning SysTem) (*Satriano et al., 2011*), an open-source software which can be used for both real-time and back-playing of earthquake data. The way that PRESTo operates and he implemented algorithms are also discussed in detail by *Festa et al., (2018)* and *Carranza et al., (2017),* providing examples from the successful application of the software. The first P-wave arrivals are detected and picked by the Filter Picker algorithm (*Lomax et al., 2012*). In our back-testing, we allowed a significantly large time window for triggering coincidence and association (15 sec) from at least three stations in order to detect an event. This choice was, in fact, forced by the sparsity of permanent seismological stations in the southern Aegean area. After the P-wave arrival picking from the Filter Picker algorithm in at least three stations, the RTLoc algorithm (*Satriano et al., 2008*) exploits pre-computed travel-time grids to provide a probabilistic event location using triggered and non-triggered stations. Then, the RTMag algorithm (*Lancieri and Zollo, 2008*) is used for magnitude estimation, based on a Bayesian approach using the peak displacements (by processing 2 and 3 secs of P-waves or 2P, 3P and 2 secs of S-waves or 2S). The RTMag algorithm uses empirical relations between the peak displacement, Pd, observed within the 2P, 3P and 2S time windows, the magnitude, M, and the station hypocentral distance, R, which have the form of Equation 1:

$$\mathrm{Log(Pd)} = A + B\mathrm{M} + \mathrm{CLog(R/10)} \tag{1}$$

where A, B and C are coefficients which depend on the phase and the duration of the time window. Alerts for imminent ground shaking are transmitted to areas of interest (targets), while empirical Ground Motion Prediction Equations (GMPEs) are used to estimate the expected PGA and/or PGV values. In our tests, we used the GMPE proposed by *Akkar and Bommer (2007),* which has the form of Equation 2:

$$\mathrm{Log(PGA)} = a_1 + a_2\mathrm{Mag} + a_3\mathrm{M}^2 + (a_4 + a_5\mathrm{M})\ \mathrm{Log}\left((\mathrm{R}^2 + a_6^{2})^{(1/2)}\right) \tag{2}$$

where a_1, a_2, a_3, a_4, a_5, a_6, are coefficients. Travel-time grids were generated using the NonLinLoc software (*Lomax et al., 2009*) for all stations and targets of the study area (grid dimensions: 10 km × 10 km × 10 km). To generate the travel-times, we used the 1-D velocity model of *Panagiotopoulos & Papazachos (1985),* which comprises three layers and we superimposed a layer for shallow/elevated formations with lower velocity (Table 1). All model layers have a fixed density value (ρ = 2.7 kgr/m^3). The acquired travel-time grids are implemented by the RTLoc algorithm in order to be used on the location of events and the computation of body wave arrival times and alert times for target areas.

Table 1. 1-D velocity model used in this study (from *Panagiotopoulos & Papazachos, 1985*)

	Depth (km)	**Vp (km/sec)**	**Vs (km/sec)**
Layer 1	-2	5.8	3.2
Layer 2	0	6.0	3.3
Layer 3	19	6.6	3.7
Layer 4	31	7.9	4.4

As seen in Figure 3, the expected alert times and PGA values for the present study correspond mostly to distant sites, since the network is rather sparse. The implementation of a denser network would significantly reduce the extent of the blind zone. The accuracy of the resulting warning depends greatly on the accuracy in the estimation of the event location, since uncertainties and errors in location propagate and affect the computation of alert times and expected PGA values at the target sites (computed by Equation 2).

RESULTS

We back-tested several of the events shown in Figure 1 and we observed that PRESTo, with its built-in empirical relations, could not detect many of them. We attribute this incapability to the fact that PRESTo is calibrated for strong motion data (sensitive to different frequency band) and built-in relations result in problematic picking on the long period body wave phases of the velocity records from the Aegean stations.

This leads to unrealistic results. This is combined with the strong anelastic attenuation that seismic rays undergo as they propagate through the Aegean magmatic chambers, which diminishes the amplitudes of the S-waves. Therefore, the tested software with its built-in relations does not seem to be able to be used as is in the Aegean area. Algorithms and relations should be thoroughly revised to meet the specific needs of the Aegean seismotectonic environment. An example of an unsuccessful back-testing is shown in Figure 4, where the Filter Picker algorithm does not identify any S-wave arrival. Additionally, the picked P-wave arrival on station YDRA is far off the actual P-wave onset.

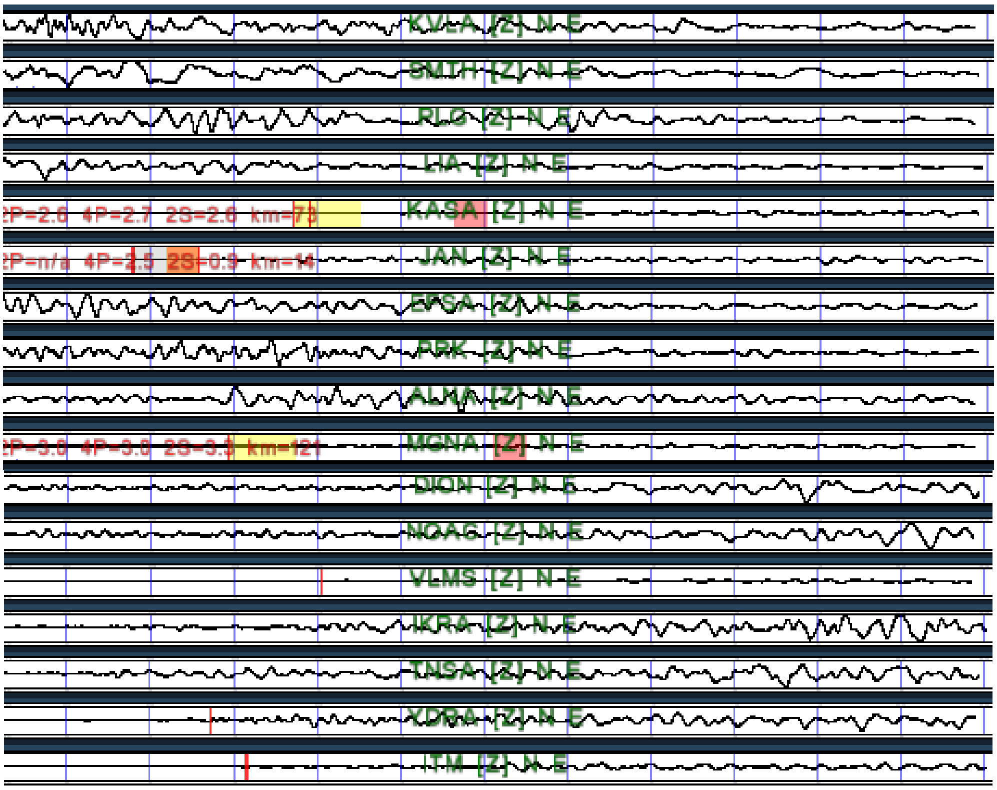

Figure 4. Snapshot of part of PRESTo graphical interface that show an example of problematic S-wave phase picking during the back-testing.

Back-testing results were not disappointing for all events. For a number of tested earthquakes, the S-waves were detected and successfully picked by the Filter Picker algorithm, as for example the M 6.5 10/12/2013 earthquake (Fig. 5), with its epicenter located close to the western coast of Crete, and focal depth at 46 km. Although several arrivals were incorrectly picked (e.g. station IACM P-wave arrival), many were accurately detected (e.g. ANKY) and a realistic solution was derived. The comparison between the real and the estimated earthquake parameters is shown in Table 2. The estimated origin time is ~ 8 s later than the original, creating a significant latency in the estimated alert times (Fig. 6). The longitude and latitude errors are smaller, indicating a good location of the event epicenter. In contrast, PRESTo depth is ~29 km shallower than the original and this affects the estimated PGA values included in the alert. PRESTo magnitude, on the other hand, matches the real magnitude exactly.

Table 2. Comparison between real and PRESTo parameters for the M 6.5 10/12/2013 earthquake

	Real	**Estimated**
Origin Time	13:11:54.7	13:12:02.7
Longitude (deg)	23.280	23.3396
Latitude (deg)	35.470	35.7889
Depth (km)	46	29.4
Magnitude	6.5	6.5

The spatial variation of P (yellow) and S (red) wave arrival times for the examined earthquake is shown in Figure 6, which was taken from the output animation generated by PRESTo at the initial alert (after the initial alert, the software continuous to improve the solution for a time pre-set by the user). The innermost circle indicates the blind zone for this earthquake. The arrival times of S-waves for urban areas like Rethymno and Chania are ~9 sec later than the initial warning time. In contrast, the neighboring to the event city of Chania fall almost inside the blind zone and there is not sufficient reaction time. Time after the initial warning for islands like Santorini, Karpathos and Kasos are >30 sec, which is significantly large, although predicted PGA values were not important, at least for the particular event examined.

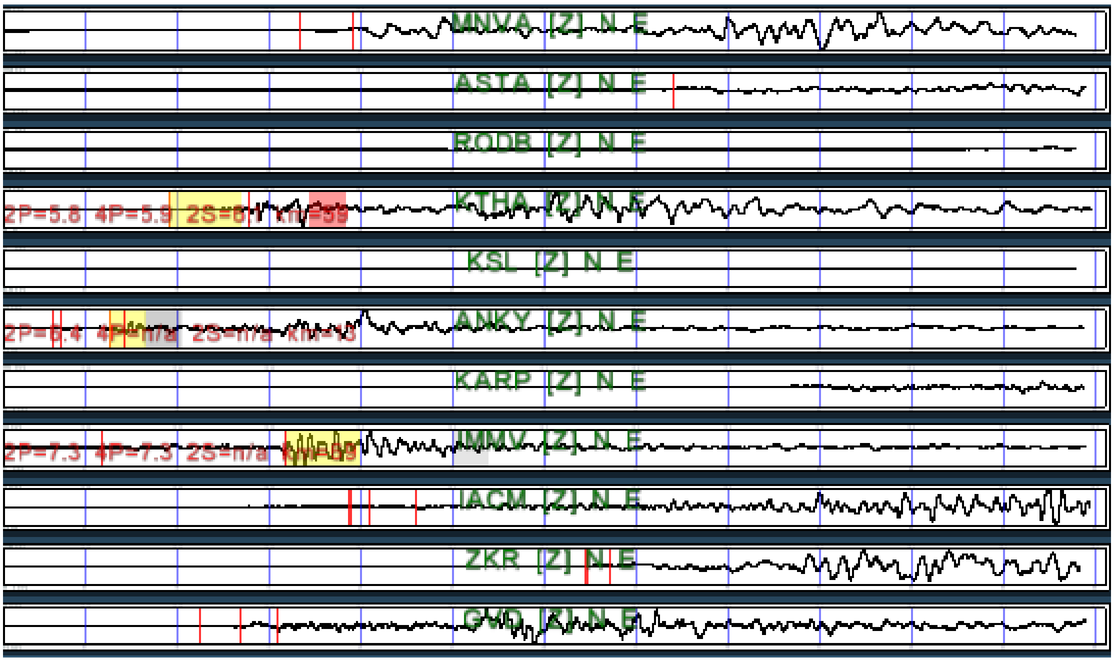

Figure 5. Example of a successful S-wave phase picking during the back-testing.

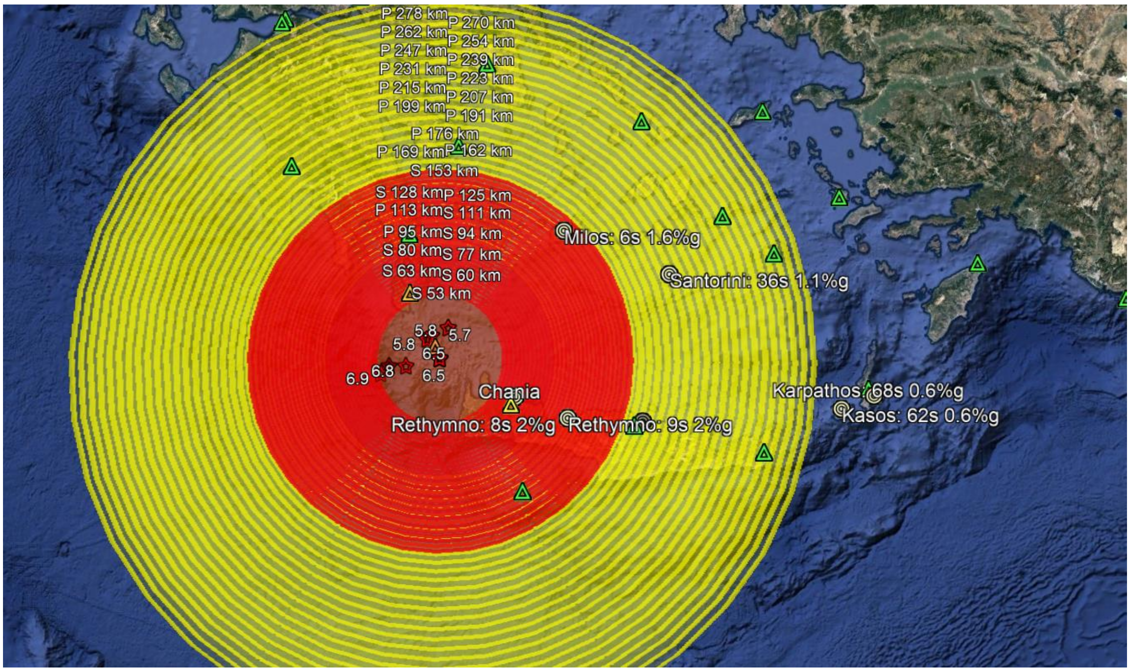

Figure 6. Screenshot of PRESTo output animation at the moment of first alert issuing. Red circles are the isochrones of S-wave arrival times and yellow circles the isochrones of P-waves. Remaining time until the arrival of S-waves (usually the most destructive waves) and predicted PGA levels are shown for selected target sites.

CONCLUSIONS

We examined the applicability of an EEW system operation in Greece for intermediate-depth earthquakes which occurred along the Hellenic Subduction Zone. We used recordings from the Greek broadband seismological network stations and the EEW software PRESTo in playback mode. The network configuration examined is such that seismic waves usually have to travel at hypocentral distances of the order of 150 km and more before being recorded by three or four stations. These numbers are the minimum required for the triggering of an EEW system such as the one tested in this study. The result of the sparsity of the Hellenic monitoring network is that blind zones (i.e., the regions where S-waves arrive before the first alert is issued) have important spatial extent. This means that in these zones lead time is practically zero and no safety actions can be taken before the strong ground shaking of a disastrous event. Apart from this difficulty that stems from the configuration of the existing permanent network, in several of the intermediate-event cases we tested, body wave arrivals could not be properly picked. This may be due to the fact that we used broadband waveforms whereas PRESTo is calibrated for strong motion recordings. The successful performance of PRESTo in the case of a strong event near Crete suggests that, if properly calibrated, the software could issue alerts for densely populated areas along the Hellenic arc, with lead time more than 10 sec. The closest sites, to the future epicenters, will probably fall within the blind zone of the EEW system. However, we must stress here, that earthquake damage mitigation actions seem feasible at more distant sites, which could be significantly damaged in the case of an earthquake of magnitude as large as the large historical events that are known to have occurred along the Hellenic arc. From this preliminary analysis it is obvious that future work should include the integration of the strong motion networks operating in Greece, combined with the seismic stations.

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