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RESEARCH ARTICLES

EARTHQUAKE ALERTS

Global earthquake detection and warning using Android phones

Richard M. Allen^{1,2*}, Alexei Barski¹, Micah Berman¹, Robert Bosch¹, Youngmin Cho¹, Xia Summer Jiang¹, Yun-Ling Lee¹, Steve Malkos¹, S. Mostafa Mousavi^{1,3}, Patrick Robertson⁴, Boone Spooner¹, Marc Stogaitis¹, Nivetha Thiruverahan¹, Greg Wimpey¹

Earthquake early-warning systems are increasingly being deployed as a strategy to reduce losses in earthquakes, but the regional seismic networks they require do not exist in many earthquake-prone countries. We use the global Android smartphone network to develop an earthquake detection capability, an alert delivery system, and a user feedback framework. Over 3 years of operation, the system detected an average of 312 earthquakes per month with magnitudes from M 1.9 to M 7.8 in Türkiye. Alerts were delivered in 98 countries for earthquakes with $M \geq 4.5$, corresponding to ~60 events and 18 million alerts per month. User feedback shows that 85% of people receiving an alert felt shaking, and 36, 28, and 23% received the alert before, during, and after shaking, respectively. We show how smartphone-based earthquake detection algorithms can be implemented at scale and improved through postevent analysis.

Earthquakes remain a constant challenge for many communities around the world. Our global understanding of where seismic events will occur is excellent (1), and we know how to engineer structures that can withstand shaking. However, we still face catastrophic earthquakes. Some kill and injure thousands of people such as in Türkiye and Morocco in 2023; many more injure hundreds, thereby disrupting many lives. Access to the knowledge and necessary resources to construct safe buildings remains a limiting factor in many parts of the world. Even with the resources, it would still take many decades to replace vulnerable buildings. Once earthquake-resilient buildings are in place, there remain hazards from falling objects inside buildings that can cause many injuries and some fatalities. We must therefore continue to look for additional strategies to reduce the impact of future earthquakes globally. Earthquake early-warning (EEW) alerts are one such strategy.

The global adoption of smartphone technology places sophisticated sensing and alerting capabilities in people's hands, in both the wealthy and less-wealthy portions of the planet. Although the accelerometers in these phones are less sensitive than the permanent instrumentation used in traditional seismic networks, they can still detect the ground motions and building response in hazardous earthquakes (2–9). Traditional seismic networks have been used to develop EEW systems that rapidly detect an earthquake close to the epicenter and issue a warning across the affected region (10). EEW was first implemented in Mexico and Japan. The success of these systems led to implementation in Taiwan, South Korea, the United States, Israel, Costa Rica, and Canada (11–17). All these systems use permanent seismic stations deployed as part of regional or national seismic networks.

We present the methodology and performance of an algorithm that uses the existing network of Android smartphones to detect earthquakes

globally and deliver early-warning alerts to smartphone owners ahead of hazardous shaking. The goal of the system is to deliver useful and timely alerts in as many earthquake-prone regions around the globe as possible. The system is supplementary to any existing national warning systems and includes the collection of uniform user feedback. We compare the accuracy of our early warnings against the global catalog of postshaking evaluations, and we also measured the utility of the alerts using surveys completed by more than a million alert recipients. We discuss the successes and challenges of this global sensing and alerting network called Android Earthquake Alerts (AEA) system.

Earthquake detection with smartphones

AEA uses the same principles of seismic wave propagation as traditional earthquake detection systems. When an Android smartphone is stationary, it uses the output of its accelerometer to detect a sudden increase in acceleration as would be generated by P and S waves in an earthquake. When an individual phone triggers, it sends a message to Google servers with acceleration information and an approximate location (location coarsened to preserve privacy). The servers then search for candidate seismic sources that are consistent with the time-space trigger distribution. When a candidate earthquake source satisfies the observed data with a high enough confidence, an earthquake is declared and its magnitude, hypocenter, and origin time (OT) are estimated on the basis of the arrival time and amplitude of the P and S waves. This detection capability is deployed as part of Google Play Services core system software, meaning it is on by default for most Android smartphones. As Android phones represent an estimated 70% of all smartphones globally (18), this system largely provides an earthquake detection capability wherever there are people, in both wealthy and less-wealthy nations.

From 1 April 2021 to 31 March 2024, AEA detected a total of 11,231 earthquakes (Fig. 1, fig. S1, and movie S1). Of these, 85% match an earthquake listed in a traditional earthquake catalog that our system was able to automatically ingest for detection validation (materials and methods). All nonmatching events were reviewed to verify whether they were earthquakes or not on the basis of user survey feedback, felt-shaking reports collected through Google Search (19), manual review of additional earthquake catalogs, and review of waveforms and triggers. For matching events, the traditional network magnitude estimates range from M 1.9 to M 7.8 (corresponding to an event in Japan and Türkiye, respectively). The ability of the system to detect earthquakes depends on the distribution of phones and other sources of cultural noise at the time of the earthquake. AEA does not detect earthquakes on most mid-ocean ridges but does detect subduction zone events that are tens to hundreds of kilometers offshore. Global Android detections and alerts are shown in Fig. 1 and fig. S1.

Figures S2 and S3 show waveform envelope record sections for two M 5.0 earthquakes illustrating P -wave sensitivity out to 100 to 200 km and S waves out beyond 350 km. To understand the detection sensitivity as a function of the distance of the earthquake from phones, we considered all detected earthquakes that were offshore and calculate the distance of the epicenter from the nearest coastline. Figure S4 shows that M 4.5 earthquakes were detected up to ~100 km offshore. A review of all AEA detections shows that the system has detected earthquakes within 30 km of 40% of all major onshore faults (fig. S5). The magnitude of completeness (M_c) is a standard measure of network detection sensitivity characterizing the minimum magnitude above which we are reliably detecting earthquakes. Using the maximum curvature method to determine M_c (20), we found a global M_c of 4.9 (fig. S6). In North America, M_c is 4.1; in South America, 4.9; and in Europe, 4.6.

The most challenging earthquake source parameter for EEW is rapid determination of the magnitude. Any delay in estimating the magnitude is also a delay in the warning provided to users. Figure 2 shows the improvement in the accuracy of the magnitude estimates generated by

¹Google LLC, Mountain View, CA, USA. ²Seismological Laboratory, University of California, Berkeley, Berkeley, CA, USA. ³Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA. ⁴Google Germany GmbH, Munich, Germany. *Corresponding author. Email: rallen@berkeley.edu

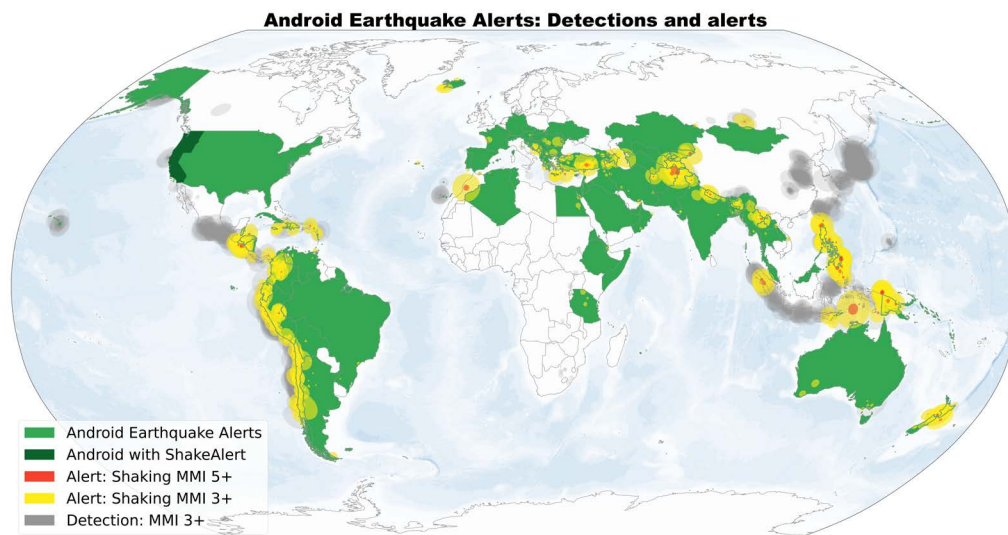


Fig. 1. Global distribution of earthquakes detected and alerted. Light-green areas show the countries where AEA is currently detecting and delivering alerts. Android also delivers alerts generated by ShakeAlert in California, Oregon, and Washington (dark green). Yellow and red circles show the areas alerted on the basis of Android detections (data S1), and gray circles indicate other detections in regions where alerts were not issued. The size of the circles indicates the approximate estimated shaking region with MMI 3+ (yellow and gray) or MMI 5+ (red).

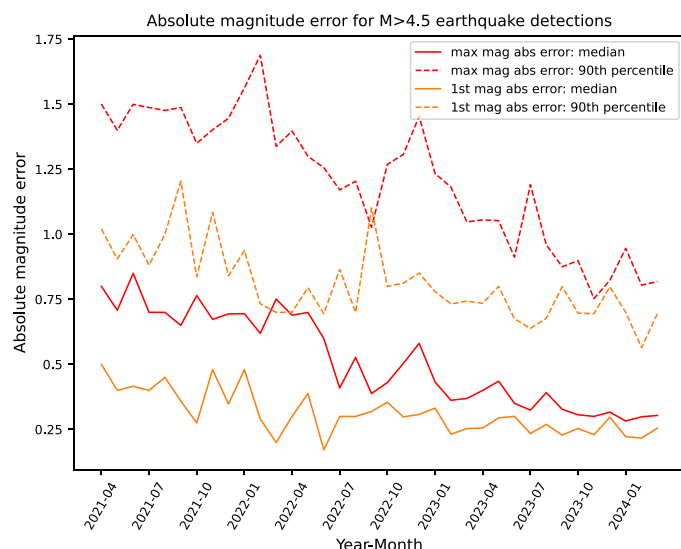


Fig. 2. Evolution of AEA earthquake magnitude error over the past 3 years (data S2). Plotted are the median and 90th percentile absolute magnitude errors for detected earthquakes each month with $M \geq 4.5$. We plot the error of the first magnitude estimate and the maximum magnitude estimate. Both magnitude metrics have improved over the 3 years of development of AEA. The median absolute magnitude errors of the first alert and the maximum magnitude are currently 0.25 and 0.30 magnitude units, respectively.

AEA over the past 3 years as the detection system has been improved. During an earthquake, source parameters are updated approximately every second as ground shaking evolves and more phone-based observations become available to centralized detection servers.

Figure 2 shows the accuracy of the first magnitude estimate and the maximum magnitude over the 3-year period. The first estimate is important because it provides the maximum warning time, whereas the maximum magnitude estimate generates an alert for the largest area. Over the past 3 years, the median absolute error of the first magnitude

estimate has improved from 0.50 to 0.25, and the 90th percentile has dropped from 1.02 to 0.70. The most important source of long-term improvement has been the development of regional detection models. These models account for the different tectonic settings and attenuation characteristics as well as differences in how varying models of phones sample ground motion because of regional variations in building type. They provide a data-driven regional scaling between parameters such as the number of phones triggering and the estimated magnitude. The result is an effective correction to the magnitude estimate, which ranges from +0.6 to −1.4 magnitude units (fig. S7).

Alert performance

As of May 2024, AEA delivered alerts to Android phones in 98 countries. In most countries, the alerts were generated from Android event detections (light green in Fig. 1). In

the United States, AEA also delivered alerts generated by ShakeAlert, which is the national EEW system using traditional regional seismic networks (17, 21). The priority of AEA, as with other EEW systems, is moderate- to large-magnitude earthquakes that represent a hazard to people living in the region. Alerts were therefore issued for earthquakes with an estimated $M \geq 4.5$ and delivered to the region expected to experience shaking of Modified Mercalli intensity (MMI) 3 or larger. Although an earthquake has a single magnitude estimate, the shaking intensity (MMI) varies as a function of distance from the earthquake fault rupture. The expected distance to which MMI 3+ occurs increases with increasing magnitude. Figure 1 shows the estimated MMI 3 regions for all Android-detected earthquakes with estimated $M \geq 4.5$. Events for which Android alerts were issued are shown in yellow or red; detections in countries where alerting was not activated are shown in gray.

The rollout of AEA started with the delivery of alerts generated by ShakeAlert in California on 11 August 2020. Alerts generated by Android detections started 28 April 2021 in New Zealand and Greece and then expanded to Türkiye, the Philippines, and central Asia on 15 June 21. In 2022, the system was rolled out to remaining high-hazard countries where alerting is allowed; AEA was delivering alerts in 93 countries by the end of 2022 and 98 countries by the end of 2023 (see data S1).

Figure 3 shows the number of people with access to EEW alerts globally from all sources. Alerting started in 1991 in Mexico City and then Japan in 2007. With the addition of Taiwan, South Korea, and the United States, 250 million people had access to EEW in 2019. Today, with the addition of AEA, 2.5 billion people have access to alerts. The EQN smartphone EEW system also provides alerts to an estimated 2 million users globally (22).

AEA has issued alerts to Android phones for a total of 1279 events detected by the Android phone network [as of 31 March 2024 (data S1)]. Of these, three were false alerts. Two were due to thunderstorms. The system detects many non-earthquake seismic events every day owing to various sources of acceleration detected by the phones. Most thunderstorms are correctly identified as such, but these two instances were outside the classifier range. Learning from these events, we expanded the range of parameters for a sonic source and increased the confidence required before an alert is used (materials and methods). Replays showed that these two events would no longer produce

an alert. The third false alert was due to a mass notification event vibrating many phones. In this case, improvements to the detection algorithm’s recognition of other events causing phone vibrations were made, and similar mass notifications have not triggered an alert since.

The alert region for each earthquake was determined by the rapid magnitude estimate. We compared the accuracy of the AEA magnitudes with those of EEW systems using traditional seismic networks. Table 1 compares the mean, median, and 90th percentile absolute error in the magnitude estimates for AEA, the US ShakeAlert, and the Japanese JMA EEW systems. We calculated the error in both the first magnitude estimate and the maximum magnitude estimate compared with final catalog magnitude determined after the event using traditional seismic networks. The errors are very similar for the three systems. AEA and ShakeAlert use the same M 4.5 threshold for alerts and have lower errors. JMA errors are slightly higher, but they also only issue alerts for larger earthquakes. AEA has the lowest errors and issues an order of magnitude more alerts than the other two systems (Table 1).

Two types of alert messages are delivered by AEA. When the estimated magnitude is ≥ 4.5 , a “TakeAction” alert is delivered to the region expected to experience $\text{MMI} \geq 5$, and a “BeAware” alert is delivered to the region expected to experience MMI 3 or 4. The alerts are delivered to octagonal regions centered on the estimated epicentral location to approximate the expected circular shape of the shaking region. The distance of the octagon vertices from the epicenter is determined on the basis of the estimated magnitude and the depth of the event. AEA currently uses the same alert distance contours as ShakeAlert (23, 24), but with a correction for event depth. For an event with an

estimated magnitude of 5.5 and depth of 20 km, the TakeAction alert would extend to 8 km, and the BeAware alert to 197 km. For a M 6.5, the alert regions extend to 78 and 442 km for TakeAction and BeAware, respectively. The same alert distance contours are currently used for all regions. Alerting performance can be improved in the future by accounting for regional seismic attenuation differences.

The TakeAction and BeAware alerts (fig. S8 and audios S1 and S2) were designed on the basis of best practices for alerts (25–28) and through focus groups. The goal is to deliver on the user’s desire for alerts whenever they feel shaking while also indicating urgency when stronger shaking is expected. The TakeAction alert breaks through all do-not-disturb settings, takes over the whole screen, and plays a loud and characteristic sound. It is designed to immediately draw the user’s attention and prompt them to take the recommended protective action, which in most countries is “Drop, cover and hold on” (DCHO) (fig. S8). In countries where this is not the recommended action, the screen displays “Protect yourself.” The BeAware alert appears on the phone in a similar way to other standard Android notifications but has a characteristic sound. It does not break through do-not-disturb settings. If an alert reaches a phone after the expected period of shaking, then an “earthquake occurred at...” notification is shown (fig. S8). Tapping on any of the alerts takes the user to an earthquake safety page with tips for what to do after the earthquake, more information about the quake provided by Google Search, and a link to a user survey that collects information about the user’s experience with the alert and shaking.

We illustrate typical AEA system behavior and warning times with two example earthquakes. The first is the 17 November 2023 earthquake in the Philippines with a magnitude of 6.7 and a hypocenter 40 km off-shore at a depth of 52 km according to the US Geological Survey (USGS) global catalog. It took about 12 s for the P wave to reach the closest cluster of phones, and the first alert was generated 18.3 s after the OT with an estimated magnitude of 5.5. The magnitude estimate grew over time to a maximum of 6.5, 28.6 s after OT (table S1). Figure 4A shows the warning time for users receiving a BeAware alert that ranged from a few seconds for those closest to the epicenter experiencing the strongest shaking, up to ~90 s for those at 400 km experiencing light shaking. Warning times for the strongest shaking (MMI 7 or 8, very strong to severe) ranged up to ~15 s. For the moderate shaking, which also causes damage (MMI 5 or 6, moderate to strong), warning times ranged from seconds up to a minute (Fig. 4A). Almost 2.5 million phones were alerted for this event, and more than 100,000 received TakeAction alerts. The TakeAction alerts (Fig. 4B) arrived at most phones a few seconds before the S -wave arrival and ~2 to 8 s before peak shaking of MMI 6, 7, and 8.

The second example is the 3 November 2023 shallow crustal earthquake in Nepal with a USGS catalog magnitude of 5.7 and a depth of 12 km. The first AEA alert was 15.6 s after the USGS OT with an estimated magnitude of 5.5. This was updated to 5.7 and then 5.9 at 28.2 s (table S2). The population was sparse near the epicenter, which delayed the detection and meant there was no warning time within ~50 km of the epicenter and no TakeAction alerts ahead of ground shaking. The BeAware alert extended beyond 300 km from where the intensity reported to USGS Did You Feel It (DYFI) ranged from 2 to 6 (weak to strong). Similar to the Philippines example, the large number of people experiencing MMI 5 and 6 received from a 10- to 60-s warning. More than 10 million BeAware alerts were delivered in this earthquake.

The most challenging events for all EEW systems are the largest ones, $M > 7.5$ (29, 30). The most impactful earthquakes since AEA became operational were the 6 February 2023 M 7.8 Pazarcık and M 7.5 Elbistan earthquakes in Türkiye. AEA was operational at the time

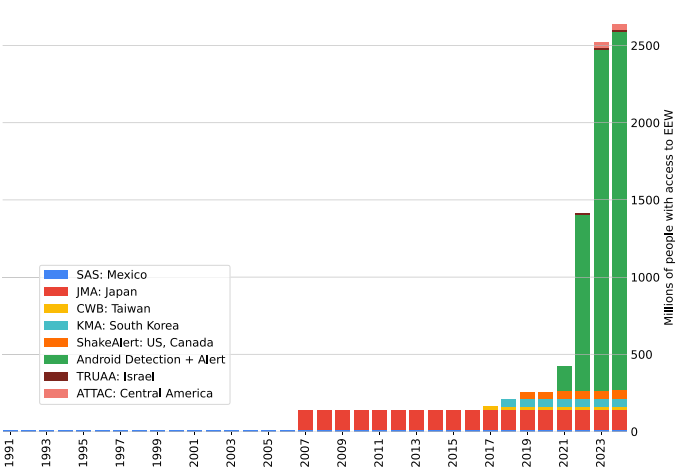


Fig. 3. Growth in the number of people with access to EEW alerts globally. The number of people with access to EEW alerts is estimated for each system on the basis of the delivery mechanism, smartphone penetration, and types (data S3).

Table 1. Comparison of magnitude errors for alerts issued by various EEW systems. Bold numbers indicate the lowest errors in each column.

EEW system	Number of events	1st magnitude absolute error median	1st magnitude absolute error 90th percentile	1st magnitude absolute error mean	Max magnitude absolute error median	Max magnitude absolute error 90th percentile	Max magnitude absolute error mean
Android*	1005 [†]	0.3	0.8	0.39	0.3	0.8	0.38
ShakeAlert [‡]	107	0.4	0.9	0.45	0.3	0.9	0.47
JMA [§]	102	0.4	1.1	0.54	0.40	1.0	0.47

*All public alerts through March 2024 (estimated magnitude ≥ 4.5 , 18 September 2020 to 31 March 2024). [†]Of the 1279 alert events, 1005 have matching events in the traditional network ground truth catalogs for error estimation (materials and methods). [‡]All public alerts through March 2024 (estimated magnitude ≥ 4.5 , 17 October 2019 to 31 March 2024). [§]All public alerts 1 January 2018 through 31 March 2024.

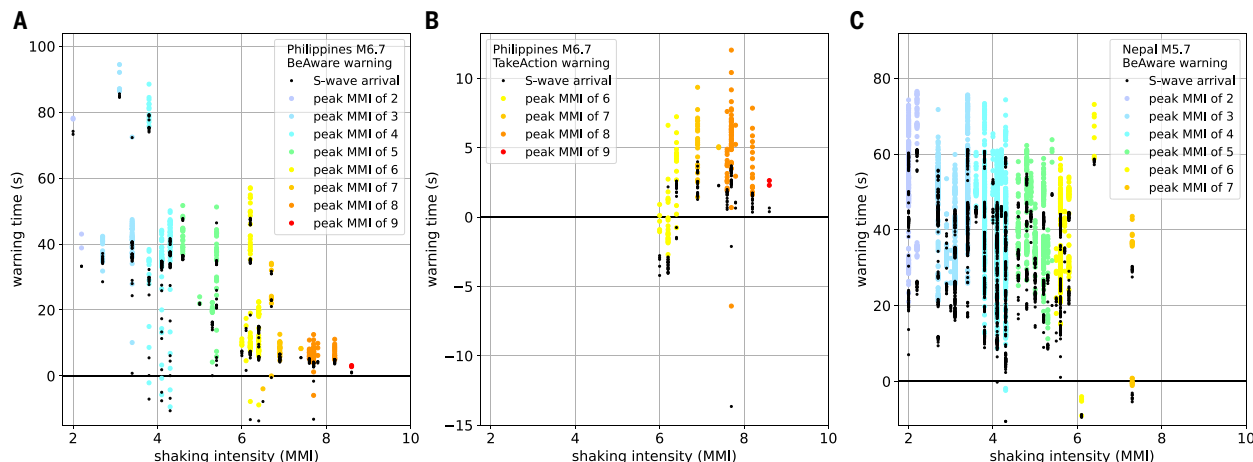


Fig. 4. Warning time versus shaking intensity. (A) BeAware alert warning times for the *M* 6.7, 17 November 2023 earthquake in the Philippines. (B) TakeAction alert warning times for the same Philippines event. (C) BeAware alert warning times for the *M* 5.7, 3 November 2023 earthquake in Nepal. In all three panels, the warning time is plotted as a function of the observed shaking intensity. The shaking intensity comes from the nearest USGS DYFI report of MMI shaking (within 5 km). Two warning times are plotted. Black dots show the time from alert delivery on a phone until the S-wave arrival. Colored dots show the time until peak shaking observed on the phone and are colored on the basis of shaking intensity (ShakeMap color scale). As peak shaking typically follows S-wave onset, warning times until peak shaking are a few seconds longer. Figure S9 shows the same data plotted versus epicentral distance. See data S4.

in Türkiye and detected both events. For the first event, the initial magnitude estimate was 4.5 at 7.1 s after OT, and the maximum magnitude estimate was 4.9 at 18.7 s. A total of 512,411 BeAware alerts were issued out to a distance of 64 km. In the second event ~9 hours later, the initial magnitude estimate was 6.1, at 24.4 s after OT, which increased to magnitude 6.3 5.2 s later. A BeAware alert was delivered to 3,944,909 phones in this event, with warning times ranging from a few seconds to more than a minute.

In addition to AEA, the EQN app-based warning system was also operational in the region at the time. They report detecting the *M* 7.8 Pazarcik event 12.1 s after OT and delivering alerts to 63,539 users, with 62,419 of those users receiving mild shaking alerts out to a distance of 3506 km. EQN did not detect the *M* 7.5 Elbistan quake (22).

Postevent analysis revealed several limitations to the detection algorithms that have since been improved. First, the duration of monitoring has increased. At the time of the event, the algorithm only allowed updates to earthquake parameters for 10 s after first detection. The number of allowed updates was limited because there was a trade-off between more updates providing additional information for larger earthquakes and more updates introducing outlying single-epic data causing a large overalert. We now allow updates for 30 s and use other checks on the rate of variation in earthquake parameters before updating an alert. Second, there were a large number of noisy phones in the monitoring pool at the time of the Türkiye earthquakes. These high-noise phones triggered late, particularly after the *P* wave for the *M* 7.8 event, which had a slow start and complex rupture (31–34). The AEA system is now more selective about which phones are included in the monitoring pool. Individual phones determine their noise level when they become available for monitoring, and this noise level is factored into the detection algorithm. Third, many phones were receiving a BeAware alert and vibrating, which prevented them from triggering on the earthquake ground motion. The alerts now issued by Android EEW no longer cause phones that are detecting to vibrate.

Using our evaluation system, we ran the new algorithms on the data collected for the Türkiye earthquakes in simulated real time. The algorithm in production today generated an initial magnitude of 4.6, 6.3 s after OT. The magnitude then climbed to a maximum magnitude of 7.4 over a period of 24 s. This generated TakeAction alerts out to 158 km that would have been received by 10 million Android phones, providing up

to a 35-s warning, and BeAware alerts to a distance of 604 km that would have been received by 67 million users, providing a 2.5-min warning before the first *S* wave (figs. S13 and S14). For context, the “heavy” MMI 8 shaking in places such as Antakya, Türkiye, did not occur until more than a minute after OT (32) (for more detail on both events, see materials and methods and figs. S10 to S14). Work continues to improve the algorithm for large ruptures, when the finite fault effect becomes important.

User response to alerts

The purpose of AEA is to deliver useful and actionable alerts to people. We therefore request information and feedback from users to determine their opinions of the alerts that they receive and actions that they take after the alerts. We accomplish this using Google’s standard in-product user surveys (35). When a user clicks on any AEA alert, they are presented with a page of additional information including safety tips and information about the earthquake. At the bottom of this page is another link inviting them to take a user feedback survey after an informed consent message (figs. S15 and S16). The survey consists of six questions as detailed in the materials and methods section and is currently delivered in 24 languages. This is not a randomized sample; rather, users choose to complete the survey. As far as we are aware, this is true of all surveys about EEW to date [e.g., (36–39)].

How helpful was the alert?

Over the period 5 February 2023 to 30 April 2024, $N = 1,555,006$ people responded to the survey after having received alerts generated from an Android detection—i.e., alerts in all countries except the US. Over the same period and region, 412 million alerts were delivered, giving a response rate of 0.38%. Of those responding, 3900 received TakeAction alerts, and the rest received BeAware alerts. The first question asked was “How helpful or unhelpful was the earthquake alert?” The users selected a score from 1 (“Not helpful at all”) to 5 (“Very helpful”). The average score was 4.7 with 85% of respondents reporting it was “very helpful” (Fig. 5). If we consider just those receiving TakeAction alerts, the average score was also 4.7. This positive response to EEW alerts (for both BeAware and TakeAction) is consistent with previous studies that ask whether an EEW alert is useful or not. For example, in the United States (one earthquake, $N = 2490$, 36) and Japan (two earthquakes, $N = 449$, 37), recent studies found that 67

and 75%, respectively, of people surveyed found the alerts useful. In an independent study of AEA alerts for two earthquakes ($N = 3150$) in New Zealand, 84 and 83% of respondents reported the alerts were useful (38). These studies were also based on responses to surveys.

Did you feel shaking?

Of the respondents (all of whom received alerts), 85% felt shaking, with 53% classifying it as “strong” and 32% as “weak.” Of the users reporting they felt “strong” and “weak” shaking, 87 and 85%, respectively, rated the alert as “very helpful” (Fig. 5). Of those reporting no shaking, still 79% rated the alert as very helpful. The fact that people are positive about receiving the alert, despite not feeling shaking, is likely due to one of several factors: (i) The alert plays a key educational role making the user aware of the system and demonstrating that it is functional (36, 38). (ii) There is a strong desire for immediate information after an earthquake (40), and the alert provides some of that information along with links to more. (iii) In almost every case there was an earthquake, and friends and neighbors likely felt it. Therefore, it is considered an effective alert and keeps people aware of what is happening in their community.

How strong was the shaking?

We separated responses according to whether they received BeAware or TakeAction alerts. As expected, a larger percentage of those receiving TakeAction alerts ($N = 2219$) classified the shaking as “strong” (92%), compared with 53% of those receiving BeAware alerts ($N = 1,116,395$; Fig. 5). There were very few users who received a TakeAction alert and then reported not feeling shaking (2%), compared with 14% of people receiving a BeAware. The very low fraction of people receiving the more intrusive and disruptive TakeAction alert who then did not feel shaking likely contributed to the overall forgiving response of users who do not feel shaking.

When did you receive the alert?

Of all the respondents ($N = 1,487,182$; the number of responses drops with each successive question), 36% said they received the alert before shaking, 28% during, 23% after, and 13% did not know (Fig. 5). BeAware alerts always extend farther from the epicenter than the TakeAction alerts, leading to longer BeAware warning times. This resulted in a larger fraction of BeAware alerts ($N = 1,082,495$) being received before shaking (44%) than TakeAction (14%, $N = 2136$; Fig. 5). There was a positive correlation between when the alert arrived and helpfulness score. Of those receiving the alert before, during, and after shaking, 93, 86, and 75%, respectively, rated the alert as “very helpful” (Fig. 5).

What action did you take?

Recommended actions when receiving an alert (or experiencing shaking) are mostly DCHO or flee and evacuate outside (41). Previous studies of what people actually do have found that the most common responses to receiving an EEW alert are to mentally prepare, tell others, look for more information, stop and wait, or do nothing (36–39). We confirm these conclusions, finding that 30% of all respondents shared the alert with others, 25% waited to see whether shaking started, 20% searched for more information online, and 19% did nothing.

The recommended protective action when feeling shaking or getting an alert in most countries is DCHO (41). This is the fifth most common response of our users receiving a BeAware alert, with 14% reporting taking DCHO action. Encouragingly, for users receiving a TakeAction alert, the most common response was DCHO with 28% of users reporting taking that action, whereas fewer shared the alert or waited (Fig. 5).

Will you trust future alerts?

For AEA to continue to be effective, and to be more effective in the future, users should trust the system and the alerts. The final

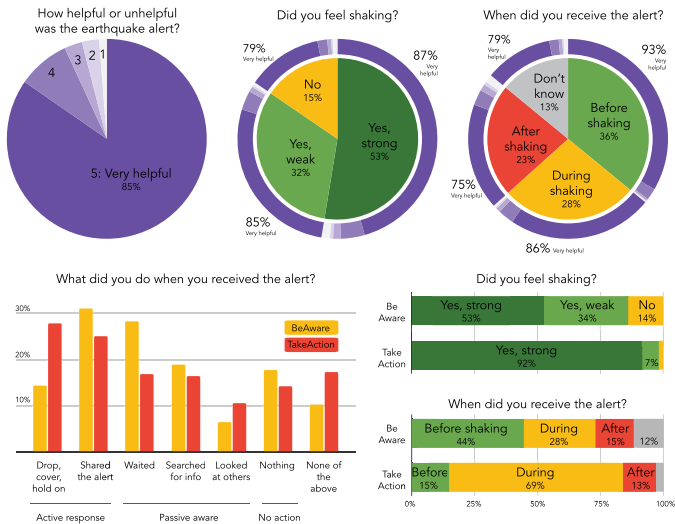


Fig. 5. Feedback from users who received an alert. A total of 1,555,006 responses to the user survey were collected over the period from 5 February 2023 to 30 April 2024. During this time, alerts were issued for 1042 earthquakes detected by AEA. Response data are included in tables S3 to S11.

question asked users about their trust in the system given their experience with the alert they just received. Of those responding, 84% said they would trust the system more next time, 13% said it did not affect their trust, and 3% said they will trust it less in future (fig. S10). Users also have the option to opt out of the system if they do not want future alerts. Three years into operation, only 0.1% of users have disabled alerts.

Implications for EEW systems

The proliferation of low-cost sensors in consumer products provides opportunities for new observations of our physical environment that are both dense and global in scale (42). AEA makes it possible to make global observations of earthquakes through smartphones by turning that information into useful alerts. Maximizing the effectiveness of EEW systems, including AEA, requires synergizing (i) our understanding of earthquake physics, (ii) the technical limitations of sensor networks and alert delivery, and (iii) user-informed social science about alert delivery. The physics of the earthquake process limit prediction of strong ($\text{MMI} > 5$) shaking to a few seconds ahead of onset (43). The TakeAction alerts were designed to prompt users to take protective actions, but by delivering them only when we have predicted strong shaking, we are only able to provide a few seconds' warning. The BeAware alerts are less intrusive and more informational and often delivered with a warning of many tens of seconds.

Most recipients of both alert types do respond. Goltz and colleagues (36) categorized user responses to EEW as “active,” “passive aware,” and “no action.” Although an active response such as DCHO is preferable, the more common passive aware responses will also likely reduce the number of injuries. Having been alerted to the pending hazard, and assuming the user has some basic knowledge of how to protect themselves, they are less likely to be injured when the shaking starts.

The BeAware alerts provide some of this education to users. Most users will receive a BeAware alert before they receive a TakeAction alert. This makes them aware of the system, provides simple information about what to do when they receive an alert, and has a very high helpfulness rating (86% rate it as “very helpful”). The very high helpfulness rating by users who did not feel shaking and those receiving the alert after shaking (Fig. 5) also demonstrates the educational and informational value of the alerts. Users also expect and want alerts for

low-intensity shaking (36, 39), making the BeAware-type alerts a critical element of an EEW system.

It is encouraging that 28% of recipients who received a TakeAction warning reported following the recommended DCHO action. This is higher than in previous surveys. Only 6% reported following DCHO when receiving an alert for an earthquake in southern California (36), similar to the 8% who reported doing DCHO in the last earthquake they felt before EEW being operational in the United States (44). Users are also tolerant of overalerting (39), i.e., receiving an alert despite not feeling shaking during an earthquake (Fig. 5). One possibility for EEW systems might therefore be to deliver intrusive TakeAction-like alerts at lower shaking thresholds for larger earthquakes. This could improve warning times for TakeAction alerts and mitigate some of the alerting challenges in the largest earthquakes.

Central to the future success of AEA is the result that 84% of users responding report that they will trust the AEA system more next time, and only 3% say less. Trust in an alert is one of the key factors promoting compliance with the recommended actions (25), and it also supports the application of phone-derived data to this work.

AEA demonstrates that globally distributed smartphones can be used to detect earthquakes and issue warnings at scale with an effectiveness comparable to established national systems. Large earthquakes remain the most important and challenging for all EEW systems, and the global implementation of AEA supports efforts to improve detection with rapid, large-scale data collection and feedback to algorithms. In the future, the AEA detection system could also provide additional information and products that could reduce hazards. Small earthquake detections in regions without seismic networks could help characterize faults and associated hazards beneath urban environments. The dense, local, and real-time ground motion observations could provide rapid post-earthquake maps of shaking intensity similar to ShakeMap, which are critical to emergency response (33, 35). Aggregated observations of shaking over multiple earthquakes could support improved regional hazard models globally. Delivering these products, with the support and trust of users, will help build community awareness of earthquake hazards and strategies to reduce them.

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SUPPLEMENTARY MATERIALS

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Materials and Methods; Figs. S1 to S17; Tables S1 to S13; References (48–52); Data S1 to S4; Movie S1; Audio S1 and S2

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