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The Seismic Early Warning System of Mexico (SASMEX): A Retrospective View and Future Challenges

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The earthquake early warning system of Mexico, SASMEX, has 30 years of uninterrupted and successful operation. During this time, the system recorded ~9,800 earthquakes and broadcast 111 alerts. Alerting was simplified recently, avoiding the emission of two types of alerts. Only earthquakes above a magnitude threshold, dependent on distance to the target city are alerted. SASMEX disseminates early warnings using dedicated receivers, public loudspeakers, multi-hazard radios, and participating TV and radio stations. It is estimated that ~25 million people receive alert messages from SASMEX. Cell-broadcasting messaging, necessary for the timely delivery of alerts, is not implemented by the local cellular phone operators. The addition of cell phone communication would increase the number of users benefitting from the system. SASMEX does not publish ground motion predictions at the time of issuing the alert. Instead, it distributes a map of peak ground acceleration in Mexico City ~1 minute after the arrival of strong motion, via electronic messaging. The accepted practice for the population in general is to evacuate at the sound of the alert. This is useful in schools and low-rise buildings, where people are generally drilled to evacuate rapidly. It is not effective in high-rise buildings and where large numbers of people concentrate. Finding protection and not trying to evacuate may be a better option, as it is recommended by other seismic early warning systems. The damaging 19 September 2017 earthquake underlined the difficulties of alerting earthquakes at close distances. Using a different sound of the alert or a countdown may be advisable, so people understand they have less time than normally assumed. There are few social studies on the use of the alert. It is suggested to conduct these studies to explore better ways to use and communicate the seismic alert, including automatic processes to shut down hazardous facilities.

Keywords: EEWS, SASMEX, Mexico, hazard reduction, alert dissemination

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INTRODUCTION

The Seismic Early Warning in Mexico (SASMEX) is a pioneer in the effort of warning the population of impending large earthquakes. The system began operations in August 1991 and in August 1993 it became the first seismic early warning system (EEWS) in the world to openly broadcast seismic alerts to the general population via subscribing radio and television stations (Espinosa-Aranda et al., 2009). The Center for Instrumentation and Seismic Recording, CIRES (Centro de Instrumentación y Registro Sísmico, in Spanish), is the non-profit organization that was made responsible by the government of Mexico City to develop, build, and install the system. Since its foundation, SASMEX

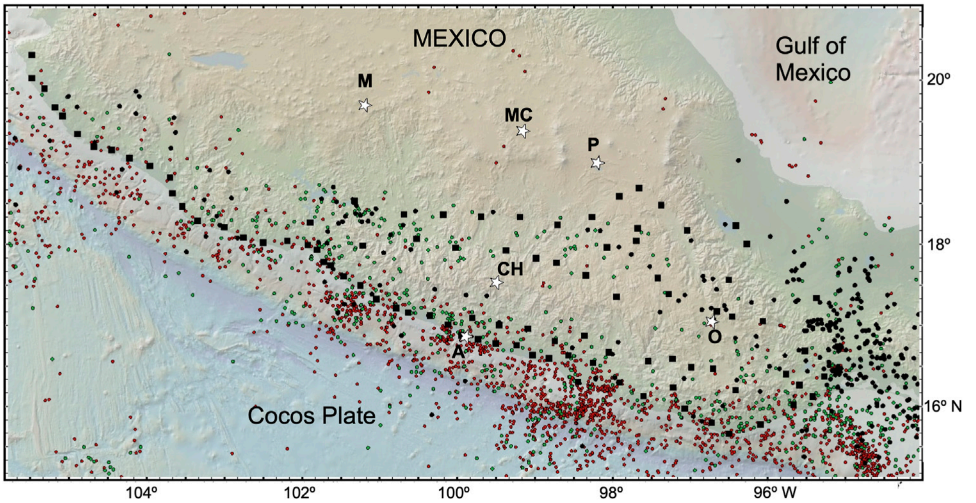


FIGURE 1 | Location of accelerographs of the EEWS in Mexico (black squares). White stars are the cities subscribed to SAMEX that broadcast alerts: A, Acapulco; Ch, Chilpancingo; M, Morelia; MC, Mexico City; O, Oaxaca; and P, Puebla. Earthquakes from the catalog of the Seismological Service of Mexico from 1 January 1970 to 31 December 2021: focal depths from 0 to 30 km (red dots), 30–70 km (green dots) and deeper than 70 km (black dots).

has screened ~9,800 earthquakes and has issued 111 alerts 8 (http://www.cires.org.mx/sasmex_historico_n.php). The system was one of the several risk reduction measures undertaken by the Mexican government after the disastrous earthquake of 19 September 1985. Originally, SASMEX was designed to warn only Mexico City of large earthquakes in the Guerrero seismic gap, immediately to the south of the city. This segment of the subduction zone has not experienced large earthquakes for many decades. It was assumed that seismic energy build-up in this region would generate eventually a large and damaging event (McCann et al., 1979; Singh et al., 1981).

EEW systems are the victim of a distance paradox. Cities are more prone to be damaged the closer they are to destructive earthquakes. However, the closer cities are to the epicenter, the less time there is to warn the population. In this respect, Mexico City represents a very advantageous scenario to operate an EEWS. The city is in an area of very high seismic activity and is frequently affected by the presence of large earthquakes. Since historical times, Mexico City has suffered extensive damage caused by earthquakes at distances of over 300 km (Suárez et al., 2020). The reason for this high seismic exposure is that the city was built on the soft clays of a lakebed drained over the past 500 years. Incoming seismic waves are highly amplified in the soft sediments, inducing large and long-lasting amplification of the ground, that are unusual for relatively distant earthquakes (*e.g.*, Bard et al., 1988; Kawase and Aki, 1989; Ordaz and Singh, 1992; Chávez-García and Bard, 1994; Wirgin and Bard, 1996; Reinoso and Ordaz, 1999).

The potential of a large earthquake in the Guerrero gap led to the construction of the Mexican EEWS, originally called SAS (Sistema de Alerta Sísmica) (Espinosa-Aranda et al., 2009; Cuéllar et al., 2014). It was estimated that the time elapsed between the detection of a large earthquake in the subduction zone and the arrival of the strong-motion seismic waves in Mexico City, would allow at least 60 s for the population to take protective actions. Thus, twelve stations were installed along the Guerrero subduction zone as the initial effort of the Mexican EEWS. During the first years of operation, it became clear that large earthquakes outside of the area covered by the initial system and felt strongly in Mexico City were not being properly alerted. To be effective, the system was expanded to be able to warn against earthquakes coming from other seismic sources, outside of the Guerrero gap. From the initial twelve stations, the system began an ambitious expansion in 2010 (Espinosa-Aranda et al., 2011).

Today, SASMEX has 97 stations distributed in southern Mexico that monitor not only the subduction zone but also the earthquakes that occur within the subducted slab of the Cocos plate, at depths between 50 and 180 km (**Figure 1**). These seismic events frequently cause damage to population centers in continental Mexico. Recent articles review the history, current distribution, and operational characteristics of SASMEX (*e.g.,* Espinosa-Aranda et al., 2009; Suárez et al., 2018).

After 30 years of operation, it is worthwhile to take a retrospective look and to assess the performance of SASMEX, and to reflect on future developments that could expand and serve better its purpose and mission, from both a technical and a social point of view. This paper makes a brief review of its development and achievements and proposes several avenues to improve its performance and social impact, not only in Mexico City but also in other cities in southern Mexico that have become part of the system.

THE STRUCTURE AND GROWTH OF SASMEX

In 30 years of uninterrupted operation, the system has been very successful. There is only one false alert issued since its inception.

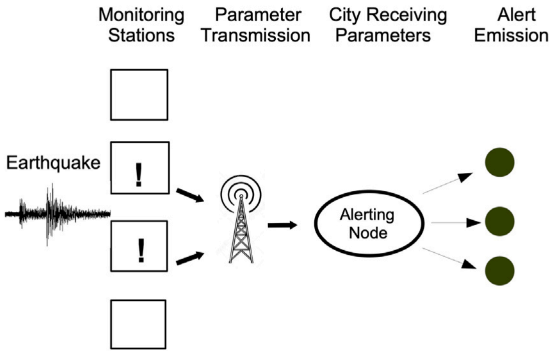


FIGURE 2 | Schematic operation of SASMEX. The dedicated accelerographs continuously monitor ground motion. When two adjoining stations exceed the pre-established thresholds of acceleration during an earthquake, the empirical parameters associated to moment magnitude are sent to central facilities at participating cities via radio links. These nodes then emit the alert to users using the various communication modes.

In the early development stage, when the system was still under testing, it was ordered by the local authorities for the system to go public. An alert was issued on 16 November 1993 when no earthquake occurred. Interestingly, many people in Mexico City consider this as the typical example of a false alert (Allen et al., 2018; Allen and Melgar, 2019). I consider that the worst-case scenario is when a large and damaging earthquake occurs, and no alert is broadcast; no such failure has been experienced by SASMEX in 30 years.

Today, besides Mexico City, five other cities in southern Mexico receive SASMEX seismic alerts: Acapulco, Chilpancingo, Morelia, Oaxaca, and Puebla (**Figure 1**). The 97 accelerographs that are exclusively designed and dedicated to SASMEX cover the Mexican subduction zone and the continental region of central Mexico, where earthquakes occur in the downgoing Cocos plates. In contrast with other early warning systems, SASMEX does not receive data from the National Seismological Service (SSN) or the other regional seismic networks in Mexico (*e.g.,* Kamigaichi et al., 2009; Given et al., 2018).

The Mexican seismic alerting system is based on a straightforward process. Three algorithms running in parallel at the sensing stations continuously monitor the strong motion data in three time intervals of the accelerograms, referenced to the arrival of the *P* and *S* waves: 2(*S-P*), *S-P,* and in the first 3 seconds after the detection of the *P* wave. Essentially, the algorithms measure the logarithm of the peak ground acceleration and the cumulative acceleration. These parameters are calibrated empirically to a moment magnitude threshold (Cuellar et al., 2017a; Cuellar et al., 2017b; Cuellar et al., 2018). When the threshold estimated by any of the algorithms surpasses the established values at two adjoining stations, the parameters are sent to the central facilities in the participating cities to emit the alert (**Figure 2**). A distance versus magnitude criterion decides which cities should broadcast an alert, depending on their distance to the epicenter. In this respect the system is binary: it simply issues an acoustic tone warning the population of an impending large earthquake, screening earthquakes with magnitudes smaller than the threshold.

Unlike other EEW systems, SASMEX does not transmit accelerograms in real time to the central facilities that decide whether to alert or not. Each SASMEX station works independently and transmits via radio communication links only the parameters that are used to calibrate the magnitude threshold (Espinosa-Aranda et al., 2009; Cuellar et al., 2017a; Cuellar et al., 2017b; Cuellar et al., 2018; Suárez et al., 2018) (**Figure 2**). Hence, data transmission and the communication infrastructure are kept to a minimum and are simple and robust. This is important in a country where internet access to remote sites is faulty or inexistant. Central stations installed in the cities where the alert is issued receive these parametric data from the field stations and independently decide when to issue the alert.

DISSEMINATION OF THE ALERT MESSAGES

Dedicated Receivers

Initially, SASMEX broadcast alerts through 25 participating radio and television stations and 205 dedicated receivers built by CIRES. These instruments receive the seismic warning signal via radio links and activate built-in loudspeakers to disseminate the alert locally. However, the high capital cost and maintenance fees of the dedicated receivers severely limited the coverage and the number of people that received the alerts. Suárez et al. (2009) documented that only 76 schools out of 5,500 had a dedicated receiver in Mexico City. Considering that schools were the prime target for an EEWS in Mexico, this situation was unacceptable. The introduction in 2010 of ~90,000 multi-hazard radio receivers exponentially increased the number of people receiving the alerts. These radios are similar to the National Weather Radio of the National Oceanographic and Atmospheric Administration (NOAA) using the Specific Area Message Encoding (SAME). Today, all public elementary schools in Mexico City use these radios to receive the alert. Since 2015, the government of Mexico City decided to broadcast the alerts in ~12,600 loudspeakers distributed throughout the city. It is estimated that about 25 million people now receive the alerts issued by SASMEX.

Initially, the Mexico City government instructed CIRES, the parent organization responsible for SASMEX, to issue two types of alerts: preventive and public. Preventive alerts were broadcast only to the dedicated receivers for earthquakes with body wave magnitudes $5.0 < m_b < 6.0$. Alerts for earthquakes $m_b \geq 6.0$ were broadcast also by the participating radio and television stations as public alerts. Later, the government changed the magnitude ranges, requesting preventive alerts be issued for earthquakes $5.0 < m_b < 5.5$ and public for magnitudes greater than 5.5. This two-tiered system of alerts was confusing to the public and, predictably, SASMEX algorithms could not estimate magnitude in real time with this precision (Suárez et al., 2009). As a result, preventive alerts were issued frequently for events smaller than magnitude 5.0.

The technical innovations that multiplied the dissemination of preventive and public alerts made the distinction between them obsolete. SASMEX adopted a criterion of emitting a single alert based on a magnitude threshold criterion, calibrated as follows to a moment magnitude threshold and epicentral distance, D, to the target city: $Mw > 5.0$ for $D < 250$ km; $Mw > 5.5$ for $D < 350$ km; and $Mw > 6.0$ for $D \geq 350$ km. As a result of this change, fewer alerts are issued for small magnitude earthquakes, as was the case with the preventive alerts (Suárez et al., 2009).

Alert Messages *via* Cell Phones

SASMEX messages are not broadcast *via* cell phones, as in Japan and in *ShakeAlert* in California and the Pacific Northwest of the United States (Given et al., 2018). After the destructive 19 September 2017 earthquake, the Mexican government launched an experiment to issue warnings through a cell phone application called *911*. Subscribers were able to sign up and download the application freely. The experiment was predictably unsuccessful because the alerts were sent via regular messaging service without prioritizing their delivery. The number of subscribers increased rapidly and the delays in receiving the alert were often in the order of tens of seconds, making the system unusable. The government suspended the application after a few months.

Cell-broadcast messaging for cell phones is not available in Mexico because the local operators do not offer this service. Negotiations are underway between the government and cell phone operators to collaborate with SASMEX. In contrast, in Japan several cellular phone companies started to transmit EEW messages in 2009 (Kamigaichi et al., 2009). The availability of this service in Mexico would broaden the number of users that receive the alert in a timely manner and enhance the benefits of the EEWS. However, the large availability of cell phones and the corresponding broad distribution of the alert will underline the need to establish clear policies and protocols for the population, depending on their local circumstances.

PREDICTION OF GROUND MOTION IN REAL TIME

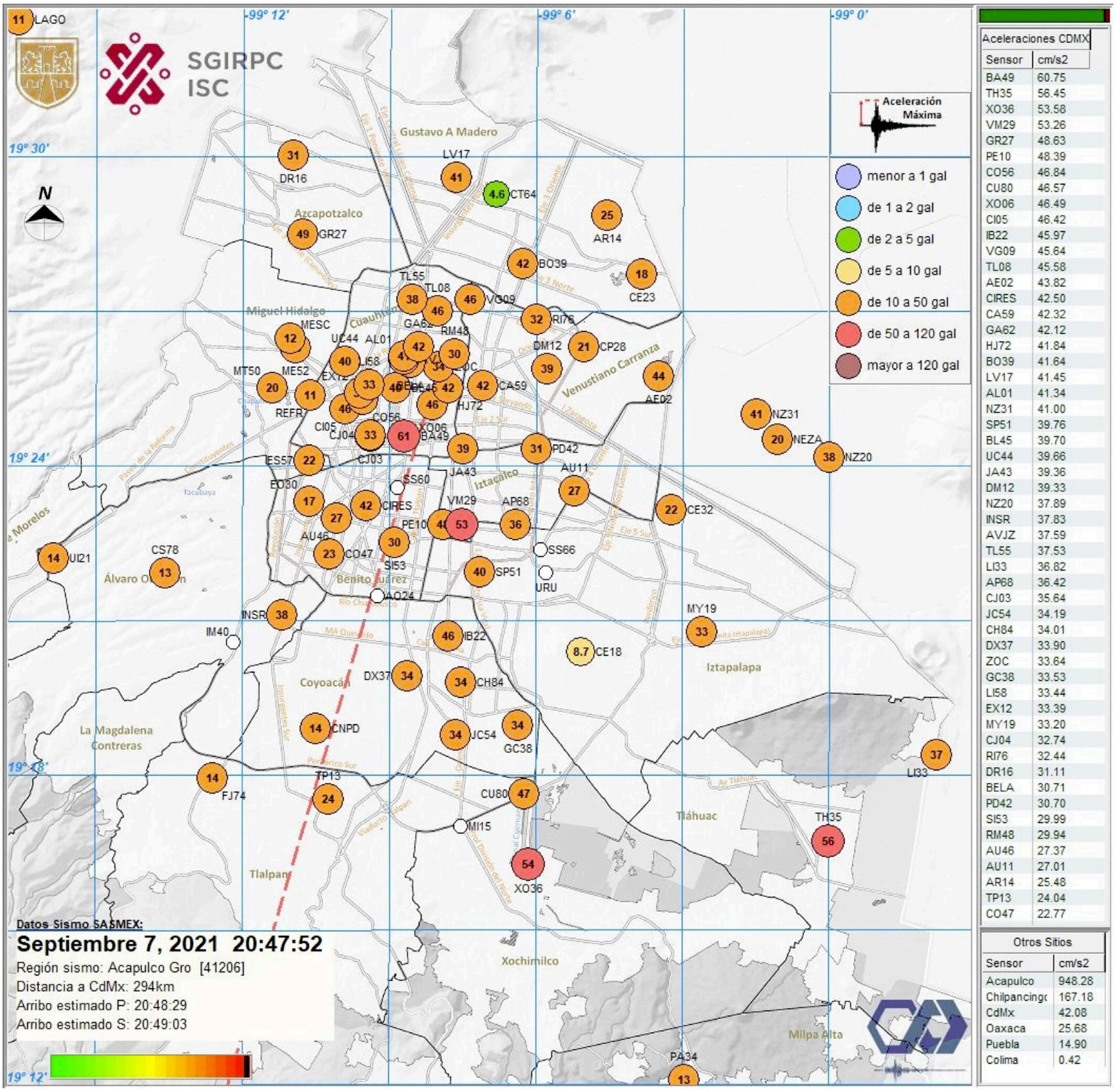
t has been discussed in recent years, whether SASMEX should follow other seismic early warning systems and predict the expected ground motion at the target cities for the earthquakes alerted. Some members of the scientific community argue that this is an important drawback and that SASMEX should begin to publish ground motion predictions simultaneously to the broadcast of alerts. Other voices, like this author, prefer to maintain a simple and straightforward manner of issuing alerts, without publishing predicted accelerations that potentially may confuse users, if these notices are not properly conveyed and disseminated. A reliable prediction of ground motion issued at the same time as the alert needs an accurate location and magnitude estimate within a few seconds after the origin time. The recent experience of the 2019 Ridgecrest, California earthquake highlights the difficulties to estimate ground motion in real time, even with a very dense seismic network as the one used by *ShakeAlert* (Chung et al., 2020).

This is particularly important considering the dramatic variability of seismic soil response in Mexico City to incoming seismic waves. Sites located in the central part of the city, sitting on the soft clays of the now dried-up lake, experience much larger intensities and durations of seismic motion than other sites located in what used to be the shore of the lake or the highlands (e.g., Reinoso and Ordaz, 1999). Singh et al. (1981) showed that spectral ratios on lakebed sites have relative amplifications that vary between 8 and 56 times. Seismic response differences between the lake and the highlands may represent variations of three to four units in the modified Mercalli intensity. Thus, authorities and users of the alert would need to know precisely where they are in the city, from a geotechnical point of view, to know what seismic intensity to expect a few seconds before the arrival of the strong motion.

Besides these considerations, there are two main reasons why SASMEX does not publish predictions of the intensity of seismic motion. As explained before, SASMEX does not calculate magnitudes and bases the emission of alerts on a magnitude threshold. The accurate estimation of magnitude would require a denser sensor network than currently available and to radically modify the architecture of SASMEX. More importantly, the civil protection authorities responsible for SASMEX have never requested and do not see the need for the prediction of expected ground motion, issued in real time at the time of the alert. Once a seismic alert is received by the authorities, several actions are put immediately in motion, instructing the institutions responsible to attend emergencies to be on guard and ready to act.

Instead of predicting ground acceleration in real time, the authorities requested that CIRES report the observed peak ground accelerations within a few seconds after the arrival of the strong motion waves. CIRES also runs the strong motion seismic network in Mexico City called RACM (Red Acelerográfica de la Ciudad de México). When an alert is issued, SASMEX puts the strong motion network on alert, and its stations report the peak ground acceleration at several key sites in the city. The measured peak ground acceleration values in Mexico City are published via *WhatsApp* and *Telegram* within the next minute after the arrival of the strong ground motion (**Figure 3**). In the recent 23 June 2020 earthquake (*Mw* 7.1) in southern Mexico, the report of measured peak ground accelerations was disseminated by CIRES 1 minute after the arrival of the *S* waves in Mexico City (Suárez et al., 2021). Thus, rather than providing authorities with maps of predicted ground motion, the integrated early warning system and the strong motion stations provide the authorities measured and reliable peak ground acceleration data with which to plan civil protection measures and rescue missions, within a few seconds after the strong motion is felt in the city (**Figure 3**).

The electronic messages showing the locations and value of recorded peak accelerations are sent to federal and local civil protection officials and to members of the scientific and engineering community. It is being considered to make these messages available to a broader constituency. Also, CIRES is evaluating how to calculate the duration of the strong shaking and to publish an additional map with this estimate in parallel to the peak accelerations report. Duration of strong shaking is an important parameter in Mexico City to rapidly assess potential damage in buildings after an earthquake. This is due to the very long



Datos Sismo SASMEX:
Septiembre 7, 2021 20:47:52
Región sismo: Acapulco Gro [41206]
Distancia a CdMx: 294km
Arribo estimado P: 20:48:29
Arribo estimado S: 20:49:03

Aceleraciones CDMX	
Sensor	cm/s2
BA49	60.75
TH35	56.45
XO36	53.58
VM29	53.26
GR27	48.63
PE10	48.39
CO56	46.84
CU80	46.57
XO06	46.49
CI05	46.42
IB22	45.97
VG09	45.64
TL08	45.58
AE02	43.82
CIRES	42.50
CA59	42.32
GA62	42.12
HJ72	41.84
BO39	41.64
LV17	41.45
AL01	41.34
NZ31	41.00
SP51	39.76
BL45	39.70
UC44	39.66
JA43	39.36
DM12	39.33
NZ20	37.89
INSR	37.83
AVJZ	37.59
TL55	37.53
LI33	36.82
AP68	36.42
CJ03	35.64
JC54	34.19
CH84	34.01
DX37	33.90
ZOC	33.64
GC38	33.53
LI58	33.44
EX12	33.39
MY19	33.20
CJ04	32.74
RI76	32.44
DR16	31.11
BELA	30.71
PD42	30.70
SI53	29.99
RM48	29.94
AU46	27.37
AU11	27.01
AR14	25.48
TP13	24.04
CO47	22.77

Otros Sitios	
Sensor	cm/s2
Acapulco	948.28
Chilpancingo	167.18
CdMx	42.08
Oaxaca	25.68
Puebla	14.90
Colima	0.42

FIGURE 3 | Example of map sent *via* WhatsApp, Telegram, and internet messaging showing the observed peak ground acceleration in stations of the strong motion network of Mexico City for the 7 September 2021 Acapulco earthquake (Mw 7.2). These maps are sent to authorized users about 1 minute after the arrival of the strong ground motion in Mexico.

duration of high accelerations observed in the soft soils of Mexico City that have shown to damage buildings due to the repeated shaking of the structure (e.g., Zeevart, 1964; Meli et al., 1985).

REACTING TO THE ALERT: PROTOCOLS AND GUIDELINES

The unwritten instruction, and now common practice in Mexico, is for everyone to evacuate immediately at the sound of the seismic alert. Schools regularly conduct drills to vacate the premises on clearly marked evacuation paths, and the students are directed by designated civil protection personnel to pre-established meeting points. A similar practice is followed in government buildings and many private institutions. The practice to evacuate stems from the tragic memory of children who, during the 1985 earthquake, perished under the roof of their schools. Furthermore, schools in Mexico are normally low-rise buildings, two or three stories high. Considering that in Mexico City the time between the sound of a seismic alert and the arrival of the strong ground motion is at least 50 s for subduction earthquakes, this practice of evacuating low rise buildings may be a sound measure.

In contrast, it is difficult to conduct a full evacuation in this time span in buildings higher than about two or three floors, even when drills are conducted routinely. Evacuation times depend, among other factors, on the number of people in the building, the width and number of the emergency staircases and on the level of training of both the people in the building and the designated leaders of the evacuation (*e.g.,* Pauls, 1987). The time needed to evacuate buildings safely has been completely overlooked by the civil protection authorities. Thus, in the case of high-rise buildings, evacuation at the sound of an alert may not be always the best option. In contrast, *ShakeAlert* encourages the population to Drop, Cover and Hold-On (DCHO) until the strong shaking passed (McBride et al., 2021). Although warning times for earthquakes in the Cascadia subduction zone may be 50–80 s (McGuire et al., 2021), this practice is advisable due to the proximity of the seismic sources to the target population centers in California, where warning times for *ShakeAlert* range from a few seconds to no more than 15 s. Clearly, evacuation with these short warning times is not a plausible option in most cases. Moreover, a study of the Hayward Fault earthquake in California suggests that DCHO could prevent some the estimated nonfatal injuries (Porter et al., 2018; Sutton et al., 2020).

Perhaps the more important pending assignment for SASMEX is the establishment of procedures and protocols that are adequate for different institutional requirements, building types and locations, that instruct the public how to react in the case of an earthquake. After 30 years of SASMEX operations, authorities have not established specific guidelines and protocols on how different population sectors or institutions should react to a seismic alert. Arjonilla (1998), a sociologist who is an expert in public safety, was critical of the way the Mexican seismic alert system was being deployed without considering the potential users. Arjonilla (1998) considered the EEWS as an important tool to save lives and injuries. However, she argued that its implementation should be accompanied by ¨solid planning and preparation on the part of the community¨. Unfortunately, this advice is yet to be followed.

In the statutes of Mexico City describing the requirements to elaborate internal civil protection programs in residential dwellings, the only requirement is that buildings higher than 30 m or with a built area of more than 6.000 m^2, should install EEWS receivers approved by the government (TR-SGIRPC-PIPC-VMCH-004-2019TR-SGIRPC-PIPC-VMCH-004-2019). In the case of commercial and public facilities, the guidelines indicate that a seismic alerting system should be included in the common areas of commercial malls, buildings that in case of structural failure may constitute a significant danger, buildings that are essential during emergencies such as hospitals, schools, transportation centers, police, firefighter stations, and similar critical facilities (TR-SGIRPC-PIPC-EST-002-2019TR-SGIRPC-PIPC-EST-002-2019). The same norm also requires that buildings that host more than 250 people, such as churches, sports facilities, and any other establishment hosting massive public shows, should also have a seismic alerting system. The norms described here are only for Mexico City, the federal civil protection authorities have not issued any regulation or norm regarding the use or emission of earthquake seismic alerts.

Although not explicitly stated in the norms, the underlying assumption is that people would evacuate the premises at the sound of the seismic alert. This begs the question: Is it possible to evacuate a stadium, a movie theater, or a church in 60 s? Very likely, not. Thus, these general guidelines are neither helpful nor practical. Hospitals, for example, should have specific protocols and trained personnel to react to an alert, tailored to their specific needs. Surgeons should know beforehand how to react to a seismic alert before or during medical procedures, as well as the technicians responsible for support equipment. The procedures and actions to take during a seismic alert should be included in their civil protection manuals and protocols; the same may be said about facilities housing police, firefighters, or paramedics, for example.

The guidelines issued by UNISIDR (United Nations International Strategy for Disaster Reduction) indicate as a key element in early warning systems, the importance that the population are fully aware of the usefulness of the alert and the knowledge on what to do once the warning is issued. Cochran and Husker (2019) stress the public must be fully aware of what actions they should take when an alert is received. Also, the use of SASMEX should be considered not only to emit an audible sound to warn the population, but to put in place also automatic processes to close pipelines with flammable materials or to stop the subway or other massive transport system. The establishment of specific protocols may help to save more lives in the case of future major earthquakes. The main emphasis in the development of EEWS everywhere has been to improve the scientific and technical aspects of the system and worry about the societal uses and benefits afterwards. SASMEX has not been alien to this and 30 years after its creation clear social guidelines continue to be missing. In contrast, before investing in a nationwide EEWS, New Zealand first conducted a survey to understand whether the public considered an EEWS useful and acceptable, asking also when early seismic warnings should be communicated (Becker et al., 2020).

The pending task for civil protection authorities in Mexico, at both the local and federal level, is to focus on establishing norms that focus on the best protective actions to recommend to the users of the alerts issued by SASMEX.

THE CHALLENGE OF NEARBY EARTHQUAKES

The original mission of SASMEX to monitor subduction zone earthquakes conveyed the idea that warning times available in Mexico City were at least 50 s. Thus, the algorithms were designed

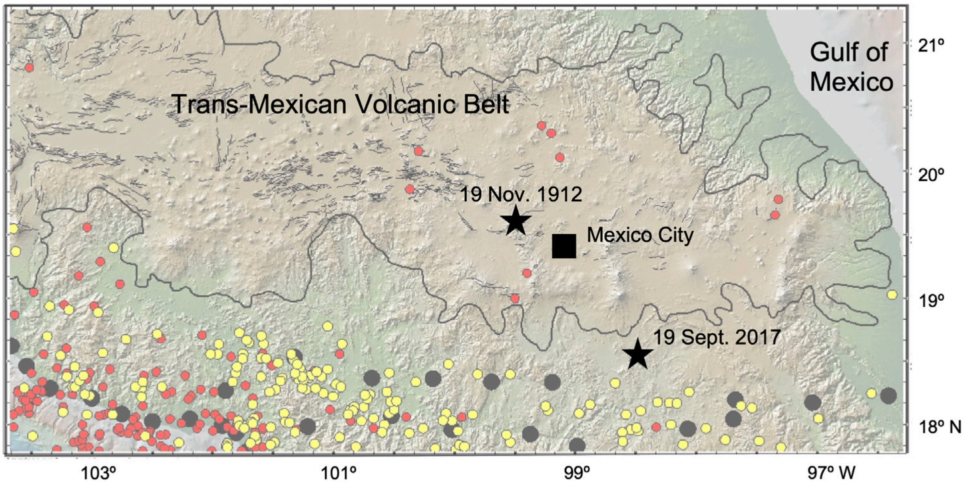


FIGURE 4 | Location of the 19 September 2017 (*Mw* 7.1) and 19 November 1912 (*Mw* 6.9) earthquakes relative to SASMEX accelerographs (solid black circles) and Mexico City (black square) from the same catalog and period as **Figure 1**. The yellow dots represent in-slab earthquakes and red dots are events shallower than 30 km. The black solid line represents the boundary of the Trans-Mexican Volcanic Belt, and the short black lines in it are mapped faults. The 1912 earthquake took place in one of these crustal faults.

to wait for the arrival of the *S* wave to estimate the magnitude threshold. It was obvious that earthquakes occurring inland, within the subducted slab, would offer a shorter warning time than subduction events. However, the earthquake of 19 September 2017 (*Mw* 7.1) was a shocking wake-up call on the challenges presented by earthquakes that occur close to Mexico City. This destructive earthquake was located ~100 km to the south of the city, at a hypocentral depth of 55 km. The closest SASMEX accelerographs were located above the hypocenter at approximately the same distance as the epicentral distance to Mexico City (**Figure 4**).

As a result of this geometry, the seismic alert was heard in Mexico City at the same time or a few seconds after the arrival of the strong seismic shaking. The reason was the location of the earthquake near the city and that the algorithm at the time triggered on the accelerations recorded in the *S-P* time (Cuellar et al., 2017b). The newly developed algorithm that triggers on the first 3 s of the *P* wave (Cuellar et al., 2018) was being tested and not installed yet in SASMEX sensing stations. However, had it been installed, the 3 s algorithm would have given no more than 10 s of warning in some parts of the city. Today, this faster algorithm is deployed in all inland SASMEX stations. Admittedly, estimating magnitude using only the first 3 s of the *P* wave is difficult (Colombelli et al., 2012; Colombelli et al., 2014). However, the algorithm now used in inland station can predict magnitude thresholds.

Unfortunately, in its 26 years of continuous operation, SASMEX was unable to give advance notice to the public for the only earthquake that resulted in substantial damage and loss of life in Mexico City. Santos-Reyes (2019) conducted a careful statistical analysis of the public reaction to this short warning times. His results show that the confidence in SASMEX decreased dramatically after the 19 September 1985 earthquake.

This experience showed that the network of SASMEX accelerographs covering these deep intraplate earthquakes needs to be densified. However, it also made clear that the idea of monitoring crustal earthquakes, as has been frequently discussed, presents serious challenges. CIRES has presented the government with several proposals to include coverage for these crustal earthquakes that take place in the Trans Mexican Volcanic Belt. The Acambay event (*Mw* 6.9) that took place on 19 November 1912, 80 km from Mexico City, is given as an example for the need to instrument this region (**Figure 4**). However, the future installation of these new SASMEX accelerographs should be accompanied by a careful consideration of how to broadcast the alert. It cannot be done in a business-as-usual manner as if these earthquakes were in the subduction zone. Furthermore, to have a timely alert of a few seconds in Mexico City, the number of accelerographs should be much denser than it is now in the south.

The public is used to periods of between 50 and 130 s to evacuate their buildings; this is certainly not the case for nearby events. One option is that earthquakes with warning times in Mexico City of less than 20 s, for example, have a warning signal with a different sound than subduction earthquakes. This would make the population aware that the time before the arrival of strong shaking is shorter than usual. A second option would be to introduce a count-down in the warning signal. In this manner, the public would know exactly how much time they have and be prepared. The results of the study by (Santos-Reyes, 2019) of SASMEX perceived performance during the two earthquakes of September 2017, indicates the importance of informing the public of the time between the alert and the initiation strong shaking. This second option has been discussed with the local civil protection authorities and it is agreed that it has *pros* and *cons* to it. In any case, the public must be massively educated to these innovations in disseminating the alert.

Whatever mechanism is chosen to differentiate seismic alert signals from earthquakes close to the city, the practice of automatic evacuation at the sound of the buzz is not always the more adequate response. In these cases, where the time of opportunity to evacuate buildings is very short, even for low-rise buildings like the primary schools, a practice like the DCHO used by *ShakeAlert* is probably the best option. School children in Japan are well drilled to duck under their work benches at school to protect their heads. The population should be well trained and prepared to act depending on their circumstances, the type of earthquake, and the resulting available warning time. This requires a well-coordinated, effective, and universal educational program and clearly established procedures and protocols that instruct people on how to react.

CONCLUSIONS

Undoubtedly, SASMEX has been very successful tool in the 30 years of continuous operations. It has developed instrumentation and algorithms adapted to the local infrastructure and technical capabilities. Once it started operations, after the initial development phase, it has successfully identified all large earthquakes in the area covered by the network and issued the corresponding seismic alert. Outside of the initial stages of testing, SASMEX has issued no false alerts. The system has expanded the emission of the alert to other five cities in Mexico, and it is rapidly becoming a nationwide tool for civil protection at the national level. It is fair to say that the public trusts the system, although studies in this respect are sadly lacking. However, proof of this trust is that people react to the sound of the alert and evacuate.

Unfortunately, in the case of the only earthquake that caused severe damage and loss of life in Mexico City, SASMEX was unable to provide sufficient time to warn the population of the approaching strong seismic shaking. The close distance to the epicenter and the ensuing brief warning time, stressed the importance of considering other ways of broadcasting the alert signals for earthquakes that due to the short epicentral distance, offer little time for the population to take protective measures. Although many news media reported the reasons of the short warning times for the 19 September 2017 earthquake, public confidence in the system decreased (Santos-Reyes, 2019).

The elimination of broadcasting public and preventive alerts, based on a rigorous measure of magnitude, which the algorithms were unable to distinguish, has decreased the number of alerts issued and the public is accustomed to receiving an alert whenever an earthquake is felt. This prevents the ¨crying wolf¨ syndrome that could eventually lead to loss of credibility of the alerting system (Reddy, 2020). The practice instituted since the advent of SASMEX for the automatic evacuation of buildings should be reconsidered and recommended only where there is sufficient time to do so. In high rise buildings and other facilities that are difficult to fully evacuate safely, even with the long lead times allowed by subduction earthquakes in Mexico City, should be convinced of adopting the DCHO practice that is the recommended behavior in the alerting systems of Japan and the United States.

There are few sociological studies on the optimal reaction and use of the alert by the public. These studies conducted by specialists in disaster prevention will help to determine the best course of action for different segments of the population and type of institution. The guidelines offered today by the authorities are very general and not conducive to best use of SASMEX. This is an important pending task since the initial stages of its implementation. These studies should consider guidelines for specific users, particularly those that are crucial after disastrous events, like hospitals, police, paramedics, and other type of personnel that are crucial in the immediate response to disasters. Studies of people´s reaction in other EEWS are examples that should serve to make SASMEX more people oriented based on specific and useful recommendations (e.g., Dunn et al., 2016; Nakayachi et al., 2019).

In addition, it is yet to be explored what actions should be taken that go beyond the emission of an audible tone. The automatic closing of gas lines, stoppage of public transportation, manage elevators in high rise buildings, controlling production lines and other actions that may be taken automatically to protect the population. There are many avenues to explore in order to make a more intense use of the seismic alert in Mexico that go beyond the knee-jerk reaction of escaping from buildings (Santos-Reyes and Gouzeva, 2020). From a seismological and engineering point of view, SASMEX has proved itself to be a reliable and robust system. The task ahead should concentrate in putting the population at the center of the discussion, exploring the best options to react and to implement norms and regulations that are conducive to saving lives and preventing injuries.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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