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# Low-cost accelerograph units as earthquake alert devices for Mexico City: how well would they work?

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**Resumen**

Recientemente se ha propuesto la utilización de unidades acelerográficas de bajo coste como dispositivo de alerta sísmica para la Ciudad de México. Este tipo de unidades dispararía la alarma cuando la aceleración del suelo alcanzara un nivel prefijado, en principio 4 gal, lo que para sismos importantes sucedería durante la onda P o en el inicio de su coda. En este trabajo se ha evaluado el desempeño de este tipo de unidades a partir de los acelerogramas registrados en el periodo 1985 - 2008 en las estaciones SCT y CDAO, ubicadas en la zona de lago de Ciudad de México. Como se preveía, el tiempo de alerta (la diferencia entre el tiempo de disparo del dispositivo y el de inicio de la parte intensa del movimiento), $T_A$, aumenta, para sismos regionales, con la aceleración máxima, *PGA*. Para los registros analizados (con *PGA* > 4 gal) $T_A$ varía entre -20 y 45 s, correspondiendo el máximo $T_A$ al terremoto de Michoacán de 1985. Salvo algunas excepciones $T_A$ es superior a 15 s para todos aquellos sismos que produjeron *PGA* > 20 gal. Este dispositivo podría ser útil para mitigar los daños humanos de un sismo siempre y cuando un tiempo de alerta entre 15 y 45 s fuese suficiente para poner en práctica medidas de seguridad previamente establecidas, lo cual podría ser práctico para escuelas de una a tres plantas. Además el dispositivo podría utilizarse para detener y/o cerrar de forma segura instalaciones críticas antes de la llegada del movimiento sísmico de mayor amplitud.

**Palabras clave:** Alerta sísmica, tiempo de alerta, aceleración máxima, Ciudad de México.

**Abstract**

Recently, low-cost accelerograph units have been proposed as earthquake alert devices for Mexico City. These units would trigger when the acceleration reaches a pre-established level, presumably 4 gal. For significant earthquakes, this would occur during P wave or in the early part of its coda. We test the performance of such a unit on accelerograms recorded in the period 1985 - 2008 at SCT and CDAO, two lake-bed sites in Mexico City. As expected, the alert time (the time of arrival of intense ground motion minus the trigger time), $T_A$, for regional earthquakes is found to increase with the *PGA*. $T_A$ of the recorded accelerograms (with *PGA* > 4 gal) ranges between about -20 and 45 sec; the largest values of $T_A$ correspond to the 1985 Michoacan earthquake. With some exceptions, $T_A$ is greater than ~15 sec for earthquakes which produced *PGA* > 20 gal. The device may be useful in mitigating injuries and loss of lives if an alert time of 15 to 45 sec is sufficient to put in to effect pre-established safety measures. This may be practical for one- to three-storey public school buildings. The device would be useful for shutting critical facilities before the arrival of large-amplitude ground motion.

**Key words:** Seismic alert, alert time, peak ground acceleration, Mexico City.

## Introduction

On 19 September, 2008, the 23rd anniversary of the Michoacan earthquake of 1985, the authorities of Mexico's Federal District announced plans to install 10,000 units of an earthquake alert device in Mexico City. The proposed device would trigger when the acceleration at the site of installation reaches a threshold, presumably 4 gal. For large earthquakes one expects this to occur during P-wave or its coda, before the arrival of large-amplitude S-wave group, thus providing an alert with some lead time. Here we investigate the performance of such a device using recorded strong-motion data of earthquakes during 1985 - 2008 at two lake-bed sites in Mexico City: Secretaría de Comunicaciones y Transportes (SCT) and Central de Abastos (CDAO). Peak ground acceleration (*PGA*) during these recordings exceeded 4 gal on, at least, one of the three orthogonal components. We assume that the trigger level of the proposed device is 4 gal. Our goal is to investigate the alert time that such device would provide. The conclusion based on SCT and CDAO data may, generally, apply to other lake-bed sites in the Valley of Mexico also.

As it is well known, an early warning system for Mexico City from subduction earthquakes along the Guerrero coast has been in operation since August 1991 (Espinosa-Aranda *et al*., 1995). The system, called the Seismic Alert System (SAS), issues public and restricted alerts for M ≥ 6 and 5 ≤ M < 6 earthquakes, respectively. To some extent the proposed devices would compete and their function would overlap with that of the SAS. For this reason, we also discuss the performance of the SAS based on the same strong-motion dataset.

## Expected Alert Time

At regional distances, large-amplitude ground motion follows the arrival of S wave. Thus, if a sensor triggers during P wave or its coda, then there is some lead time before the arrival of the intense part of the ground motion. This lead time can be used as an alert time. If an alert is sought only for earthquakes which produce large ground motions and, hence, pose threat to the society, then the sensor should trigger only when the motion exceeds a certain threshold. At a fixed threshold the sensor may trigger: (1) after the arrival of S wave, (2) in the coda of P wave, or (3) at the arrival of P wave. Case (1) provides no alert time. The alert time for case (2) is less than (S - P) time. The largest alert time, equal to (S - P) time, is obtained in case (3). For earthquakes occurring at the same focus, the strength of the source, as reflected by the *PGA* at the site, would determine which of the cases would be realized. In other words, the alert time would be directly related to the *PGA*. Thus, potentially more destructive earthquakes (larger *PGA*) would have larger alert times. It is clear, however, that the alert time will always be less or equal than (S - P) time. It also follows that for local earthquakes the alert time will always be small, irrespective of *PGA*.

We note that the intense motion at regional distances, often, does not begin at S wave. For this reason, we will measure the arrival time of intense motion as the time when the energy in the signal becomes 5% of the total energy of the record.

## Data

SCT and CDAO accelerographic stations have been in operation since 1985. The instrumentation at both sites, including trigger level and pre-event memory, has changed over time. The accelerograph at SCT has been operated at trigger level, $A_T$, and pre-event memory that have varied between 2 and 7 gal and between 4 and 40 sec, respectively. At CDAO, $A_T$ has varied between 1 and 5 gal, while the pre-event memory has remained fixed at 4 sec. We note that even when $A_T$ was set at 7 gal, the records include that portion of strong motion where the acceleration first reaches 4 gal. This is because of the pre-event memory. In particular, records with $A_T$ = 7 gal correspond to local events, thus a pre-event memory of 4 sec was enough to record completely the intense part of the ground motion. During the great Michoacan earthquake of 1985, $A_T$ and pre-event memory at both sites were 4 gal and 4 sec, respectively. Clearly, the values of $A_T$ and pre-event time would affect the record length before acceleration reaches 4 gal.

Table 1 lists the events which produced at least 4 gal at SCT and/or CDAO and Fig. 1 shows the location of these events. *PGA* values at both stations are given in Table 2. We note that *PGA* was greater than or equal to 4 gal on, at least, one component during 31 earthquakes at SCT and 32 at CDAO in the period September 1985 - August 2008 (23 years). We discarded five of these earthquakes due to poor quality of the records. We, nevertheless, list them in Tables 1 and 2, and plot them in Fig. 1 for the sake of completeness.

Some of the events with *PGA* > 4 gal were not recorded because the accelerographs malfunctioned or because the memory was full. An unfortunate example is the earthquake of 21 September, 1985 ($M_w$ 7.6), for which there is no recording at SCT. Thus, 31 and 32 as the number of earthquakes during which the ground motion exceeded 4 gal at SCT and CDAO is a lower bound.

## Analysis

To test the performance of the proposed device, we investigate the alert time, $T_A$, that it would provide based on recorded data. We define $T_A$ as the difference between the arrival time of the intense part of the ground motion, $T_I$, and the trigger time, $T_T$. As mentioned above, it is convenient to measure $T_I$ as the time when the energy in the accelerogram, $A(t)$, reaches 5% of the total energy, where total energy is given by

$$\int A^2(t)\cdot dt \qquad (1).$$

We define $T_T$ as the time when $A(t)$ on any component reaches 4 gal. Thus, the alert time, $T_A$, is given by

$$T_A = T_I - T_T \qquad (2).$$

Generally, $T_T$ values for the three components differ. We take the smallest of the three values of $T_T$ to compute $T_A$, and we only compute $T_A$ for the horizontal components. Fig. 2 illustrates the concepts defined in the previous paragraph. With one exception, $T_T$ is larger on the Z component than on the horizontal components (*i.e*., the 4-gal threshold is exceeded later in the vertical component than in the horizontal ones). The exception is the inslab

**Table 1**

Earthquakes which have produced accelerograms with *PGA* ≥ 4 gal at SCT and/or CDAO
(September 1985 - August 2008)

| No. | Date | Lat °N | Lon °W | H (km) | $M_w$ | Type[1] | Δ(km)[2] | SCT[3] | CDAO[3] |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 85/09/19 | 18.14 | 102.71 | 17 | 8.0 | T | 402 | Y | Y |
| 2 | 85/09/21 | 17.62 | 101.82 | 22 | 7.6 | T | 345 | NR | Y |
| 3 | 85/12/02† | - | - | - | - | L | - | Y | NR |
| 4 | 86/01/04† | - | - | - | - | L | - | Y | NR |
| 5 | 86/01/05 | 19.41 | 99.44 | 1 | 3.5 | L | 33 | Y | NR |
| 6 | 86/04/30 | 18.40 | 102.95 | 26 | 6.9 | T | 417 | NR | Y |
| 7 | 86/05/05* | 17.96 | 102.79 | 17 | 5.9 | T | 417 | NR | R |
| 8 | 88/02/08 | 17.45 | 101.19 | 22 | 5.8 | T | 306 | NR | Y |
| 9 | 89/04/25 | 16.61 | 99.43 | 16 | 6.9 | T | 309 | Y | Y |
| 10 | 89/05/02* | 16.68 | 99.41 | 15 | 5.5 | T | 301 | NR | R |
| 11 | 90/05/11 | 17.12 | 100.87 | 21 | 5.5 | T | 311 | R | Y |
| 12 | 90/05/31 | 17.12 | 100.88 | 18 | 5.9 | T | 312 | Y | Y |
| 13 | 90/11/16† | - | - | - | - | L | - | Y | NR |
| 14 | 93/05/15 | 16.47 | 98.72 | 16 | 5.5 | T | 325 | NR | Y |
| 15 | 93/10/24 | 16.65 | 98.87 | 26 | 6.6 | T | 304 | Y | Y |
| 16 | 94/05/23 | 18.02 | 100.57 | 50 | 6.2 | IS | 215 | Y | Y |
| 17 | 94/12/10 | 17.98 | 101.52 | 50 | 6.4 | IS | 297 | Y | YL |
| 18 | 95/09/14 | 16.48 | 98.76 | 16 | 7.3 | T | 324 | Y | Y |
| 19 | 95/10/09 | 18.79 | 104.47 | 17 | 8.0 | T | 566 | Y | Y |
| 20 | 96/02/25 | 15.60 | 98.30 | 15 | 7.1 | T | 428 | Y | Y |
| 21 | 96/07/15 | 17.33 | 101.21 | 27 | 6.6 | T | 317 | Y | NR |
| 22 | 97/01/11 | 18.34 | 102.58 | 40 | 7.1 | IS | 382 | Y | Y |
| 23 | 97/05/22 | 18.37 | 101.82 | 54 | 6.5 | IS | 305 | Y | R |
| 24 | 97/07/19* | 16.00 | 98.20 | 15 | 6.7 | T | 387 | NR | R |
| 25 | 98/02/03* | 15.90 | 96.25 | 32 | 6.3 | IS | 491 | R | R |
| 26 | 98/04/20 | 18.35 | 101.19 | 64 | 5.9 | IS | 246 | YL | Y |
| 27 | 99/06/15 | 18.13 | 97.54 | 61 | 6.9 | IS | 217 | Y | NR |
| 28 | 99/06/21 | 18.15 | 101.70 | 53 | 6.3 | IS | 304 | Y | Y |
| 29 | 99/09/30 | 16.03 | 96.96 | 47 | 7.4 | IS | 436 | Y | Y |
| 30 | 99/12/29 | 18.00 | 101.63 | 50 | 5.9 | IS | 305 | Y | Y |
| 31 | 00/07/21 | 18.11 | 98.97 | 50 | 5.9 | IS | 142 | Y | Y |
| 32 | 00/08/09 | 18.07 | 102.56 | 32 | 6.5 | IS | 390 | R | Y |
| 33 | 01/10/08 | 17.00 | 100.09 | 8 | 5.8 | U | 283 | Y | Y |
| 34 | 02/04/18* | 16.75 | 101.06 | 6 | 6.7 | T | 356 | NR | R |
| 35 | 03/01/22 | 18.62 | 104.12 | 10 | 7.5 | T | 532 | Y | Y |
| 36 | 04/01/01 | 17.27 | 101.54 | 17 | 6.0 | T | 346 | Y | NR |
| 37 | 04/06/14 | 16.19 | 98.13 | 20 | 5.9 | T | 369 | Y | Y |
| 38 | 06/08/11 | 18.50 | 101.06 | 58 | 6.0 | IS | 226 | Y | R |
| 39 | 07/04/13 | 17.22 | 101.35 | 37 | 6.0 | IS | 336 | Y | Y |
| 40 | 07/04/13 | 17.22 | 101.30 | 36 | 5.3 | IS | 332 | Y | NR |
| 41 | 08/04/28 | 17.89 | 100.10 | 55 | 5.8 | IS | 195 | NR | Y |

[1]Type of earthquake: T, shallow-dipping interplate thrust; IS, inslab (normal-faulting or steeply dipping thrust); U, crustal continental upper-plate; L, local (Valley of Mexico).

[2]Average epicentral distance to SCT and CDAO sites.

[3]Availability/quality of records at SCT and CDAO. Y: record used in this study; R: record removed from further analysis due to poor quality; YL: record with *PGA* < 4 gal on each of the three components; NR: record not available.

† Local event whose location and magnitude are not available.

* Event not used in the analysis due to poor recording.

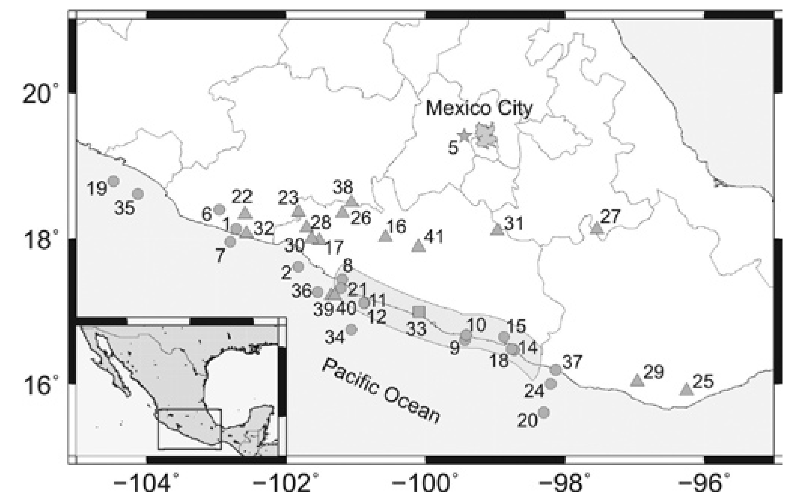


Fig. 1. Map showing the location of the earthquakes which produced recordings with $PGA \geq 4$ gal at SCT and/or CDAO stations in the period 1985 - 2008. Symbols indicate the type of earthquake; circle: interplate; triangle: inslab; square: crustal continental upper-plate; star: local (Valley of Mexico). Events are labeled according to numbers given in Table 1. Contour gives the area covered by the Seismic Alert System (SAS) of Mexico City. The boundaries of states are delineated.

earthquake of Copalillo (21 July, 2000, $M_w$ 5.9), during which the 4-gal threshold is first reached in the P wave recorded on the Z component.

As discussed earlier, $A(t)$ = 4 gal may occur at the beginning of the intense motion. In this case $T_A$ will be zero. It is also possible that $A(t)$ = 4 gal occurs after the arrival of the intense part of the motion. In this case $T_A$ will be negative. For reasons mentioned above, the alert time, $T_A$, will depend on $A_T$ and pre-event memory. To test the sensitivity of the results we analyzed those accelerograms which were recorded with small $A_T$ and large pre-event memory. These records were reprocessed at larger values of $A_T$ and smaller values of pre-event time. Our tests show that the effect of different values of $A_T$ and pre-event memory on the alert time is small, typically less than 2 sec. Thus, we present results based on the original accelerograms. Fig. 3 illustrates the accelerograms of the Michoacan and Copalillo earthquakes at SCT along with trigger time, $T_T$, and the arrival time of the intense part of the ground motion (5% of the total energy), $T_I$. The figure also shows the time at which the energy is 50% of the total.

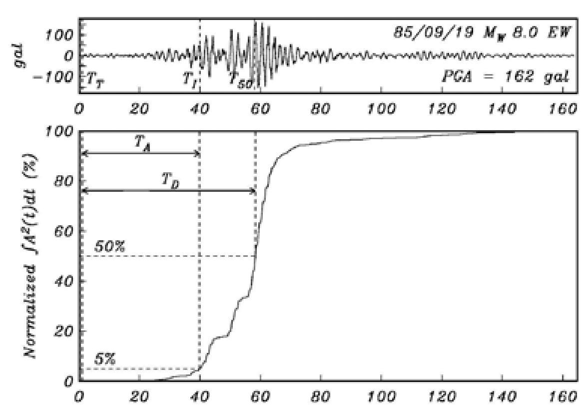


Fig. 2. Illustration of the definitions used in the analysis. The trace in the top frame is the EW component of the accelerogram at SCT station from the earthquake of 19 September, 1985, $M_w$ 8.0, Michoacan. The bottom frame illustrates the normalized cumulative energy of the accelerogram (equation 1). The three vertical dashed lines in each frame from left to right define the trigger time, $T_T$, the time when the energy is 5% of the total, $T_I$, and the time when the energy is 50% of the total, $T_{50}$. The alert time, $T_A$, is measured on the horizontal components as the difference between $T_I$ on each component and the smallest of the $T_T$ values measured on the three components. The time $T_D$ is defined as the difference between $T_{50}$ and the smallest of the $T_T$ values measured on the three components.

**Table 2**

*PGA* and alert time $T_A$ at SCT and CDAO

| | | | | | SCT | | | | CDAO | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **No.** | **Date** | **$M_w$** | **Type** | **Δ (km)** | **NS** | | **EW** | | **NS** | | **EW** | |
| | | | | | ***PGA* (gal)** | **$T_A$ (sec)** | ***PGA* (gal)** | **$T_A$ (sec)** | ***PGA* (gal)** | **$T_A$ (sec)** | ***PGA* (gal)** | **$T_A$ (sec)** |
| 1 | 85/09/19 | 8.0 | T | 402 | 92.2 | 34.7 | 162.0 | 39.8 | 65.9 | 43.8 | 76.4 | 41.1 |
| 2 | 85/09/21 | 7.6 | T | 345 | - | - | - | - | 46.7 | 32.3 | 31.0 | 35.2 |
| 3 | 85/12/02 | - | L | - | 8.5 | 1.8 | 7.4 | 1.6 | - | - | - | - |
| 4 | 86/01/04 | - | L | - | 10.1 | 0.0 | 4.3 | 0.1 | - | - | - | - |
| 5 | 86/01/05 | 3.5 | L | 33 | 8.2 | 0.1 | 8.2 | 0.1 | - | - | - | - |
| 6 | 86/04/30 | 6.9 | T | 417 | - | - | - | - | 15.8 | 10.0 | 32.3 | 8.3 |
| 7 | 86/05/05* | 5.9 | T | 417 | - | - | - | - | 4.9 | - | 6.3 | - |
| 8 | 88/02/08 | 5.8 | T | 306 | - | - | - | - | 5.4 | -0.8 | 9.7 | 0.7 |
| 9 | 89/04/25 | 6.9 | T | 309 | 39.9 | 9.4 | 37.5 | 9.4 | 27.8 | 18.5 | 34.3 | 17.6 |
| 10 | 89/05/02* | 5.5 | T | 301 | - | - | - | - | 4.0 | - | 4.2 | - |
| 11 | 90/05/11 | 5.5 | T | 311 | 4.4 | - | <4 | - | <4 | - | 5.4 | -5.1 |
| 12 | 90/05/31 | 5.9 | T | 312 | 8.7 | 1.1 | 5.4 | 3.0 | 9.5 | 1.3 | 15.6 | 1.6 |
| 13 | 90/11/16 | - | L | - | 8.3 | -0.3 | <4 | - | - | - | - | - |
| 14 | 93/05/15 | 5.5 | T | 325 | - | - | - | - | 9.7 | 4.3 | 10.1 | 10.0 |
| 15 | 93/10/24 | 6.6 | T | 304 | 11.5 | 8.9 | 10.2 | 7.7 | 13.2 | 10.1 | 9.3 | 3.6 |
| 16 | 94/05/23 | 6.2 | IS | 215 | 6.7 | 2.4 | 6.1 | 3.6 | 8.2 | 0.4 | 8.5 | 0.1 |
| 17 | 94/12/10 | 6.4 | IS | 297 | 10.8 | 2.2 | 15.0 | 1.7 | <4 | - | <4 | - |
| 18 | 95/09/14 | 7.3 | T | 324 | 25.9 | 21.5 | 31.7 | 19.3 | 37.1 | 15.9 | 32.2 | 19.0 |
| 19 | 95/10/09 | 8.0 | T | 566 | 10.5 | 3.4 | 8.6 | 6.2 | 13.8 | 18.3 | 19.8 | 15.8 |
| 20 | 96/02/25 | 7.1 | T | 428 | 6.4 | -2.7 | 6.4 | -3.7 | 6.2 | -1.1 | 5.9 | -4.6 |
| 21 | 96/07/15 | 6.6 | T | 317 | 6.7 | 5.7 | 4.7 | 6.6 | - | - | - | - |
| 22 | 97/01/11 | 7.1 | IS | 382 | 11.3 | 8.8 | 12.0 | 10.9 | 23.3 | 14.8 | 24.1 | 7.1 |
| 23 | 97/05/22 | 6.5 | IS | 305 | 4.3 | 4.9 | 4.2 | -1.6 | 5.1 | - | 4.6 | - |
| 24 | 97/07/19* | 6.7 | T | 387 | - | - | - | - | <4 | - | 4.3 | - |
| 25 | 98/02/03* | 6.3 | IS | 491 | 4.5 | - | <4 | - | 4.1 | - | 5.0 | - |
| 26 | 98/04/20 | 5.9 | IS | 246 | <4 | - | <4 | - | 4.8 | -20.3 | 4.7 | -18.8 |
| 27 | 99/06/15 | 6.9 | IS | 217 | 30.2 | 19.7 | 29.9 | 19.1 | - | - | - | - |
| 28 | 99/06/21 | 6.3 | IS | 304 | 5.5 | -3.1 | 4.5 | -5.3 | 5.7 | -1.3 | 7.4 | 0.5 |
| 29 | 99/09/30 | 7.4 | IS | 436 | 35.4 | 23.6 | 20.4 | 25.6 | 32.2 | 30.5 | 29.7 | 37.4 |
| 30 | 99/12/29 | 5.9 | IS | 305 | <4 | - | 4.8 | -2.0 | 5.2 | -17.1 | 5.3 | -7.2 |
| 31 | 00/07/21 | 5.9 | IS | 142 | 16.0 | 16.8 | 21.2 | 16.9 | 17.0 | 16.8 | 12.3 | 17.4 |
| 32 | 00/08/09 | 6.5 | IS | 390 | 9.2 | - | 8.7 | - | 15.9 | 3.3 | 17.0 | 6.3 |
| 33 | 01/10/08 | 5.8 | U | 283 | 5.7 | -2.0 | 5.7 | -2.6 | 5.4 | 0.1 | 5.0 | 1.9 |
| 34 | 02/04/18* | 6.7 | T | 356 | - | - | - | - | 4.5 | - | 4.2 | - |
| 35 | 03/01/22 | 7.5 | T | 532 | 21.6 | 9.3 | 17.2 | 14.4 | 18.0 | 10.4 | 20.4 | 11.8 |
| 36 | 04/01/01 | 6.0 | T | 346 | 4.2 | -0.5 | 5.3 | 0.4 | - | - | - | - |
| 37 | 04/06/14 | 5.9 | T | 369 | 7.3 | 2.7 | 6.5 | 0.2 | 6.6 | -1.5 | 6.3 | -1.1 |
| 38 | 06/08/11 | 6.0 | IS | 226 | 4.3 | -6.3 | 4.5 | -5.5 | 4.5 | - | 6.1 | - |
| 39 | 07/04/13 | 6.0 | IS | 336 | 11.6 | 1.9 | 11.4 | 3.0 | 13.2 | 3.5 | 9.9 | 3.0 |
| 40 | 07/04/13 | 5.3 | IS | 332 | <4 | - | 4.6 | -11.5 | - | - | - | - |
| 41 | 08/04/28 | 5.8 | IS | 195 | - | - | - | - | 7.2 | -2.7 | 4.4 | -2.8 |

* Event not used in the analysis due to poor recording.

In Fig. 4 the alert time, $T_A$, is plotted as a function of *PGA* for both SCT and CDAO. The two horizontal components are shown separately for each station. In the figure interplate, inslab, continental crustal (near the coast of Guerrero), and local earthquakes in the Valley of Mexico are shown by different symbols. The plot suggests that all data may be grouped together. The figure shows that greater the eventual *PGA*, larger is the expected $T_A$. This implies that the amplitudes of S-wave group and P-wave group scale together. If for an earthquake the amplitude of P-wave group is large, then it is detected early and, hence, $T_A$ is large. For the same earthquake the amplitude of S-wave group will also be large and, hence, the relationship between $T_A$ and *PGA* seen in the figure.

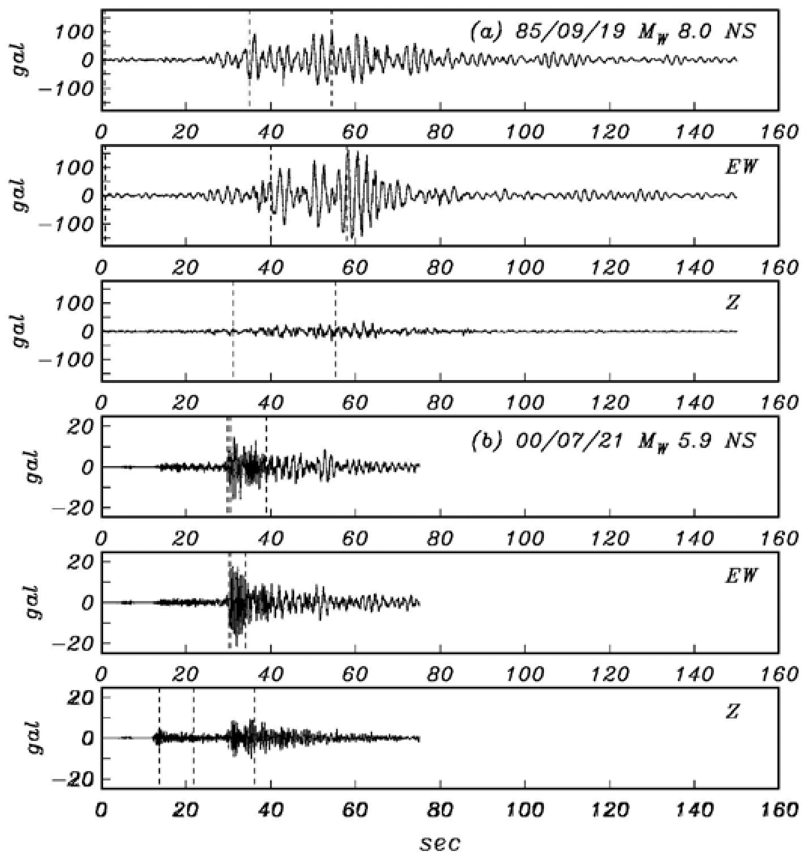


Fig. 3. Three component accelerograms at SCT from earthquakes of (a) 19 September, 1985, $M_w$ 8.0, Michoacan (upper three frames), and (b) 21 July, 2001, $M_w$ 5.9, Copalillo (bottom three frames). The three vertical dashed lines in each frame from left to right define the trigger time, $T_T$, the time when the energy is 5% of the total, $T_I$, and the time when the energy is 50% of the total, $T_{50}$. For Michoacan earthquake $T_T$ is close to the origin and $T_{50}$ is near the *PGA*. For the inslab earthquake of Copalillo $T_T$ is minimum on the Z component. The alert time, $T_A$, is measured on the horizontal components as the difference between $T_I$ on each component and the minimum of the three $T_T$ values.

Damage to buildings in the lake-bed zone of the Valley of Mexico from large, coastal, interplate earthquakes, probably, results from the long-duration, nearly harmonic ground motion. The collapse occurs because of fatigue from long-duration cyclic loading. We define $T_D$ as the difference between the time when energy is 50% of the total, $T_{50}$, and the smallest of the three values of trigger time, $T_T$ (Fig. 2). For coastal earthquakes $T_{50}$ may be close to the time of the *PGA* (see Fig. 3 for the Michoacan earthquake recording at SCT). In Fig. 5 $T_D$ is plotted as a function of *PGA*. As expected, $T_D$ is greater than $T_A$. There is large dispersion in the data due to the variability of the signal during the intense part of the motion, which, in turn, is a consequence of source and path effects. Note in Fig. 3, for example, the difference in the intense part of the ground motion during the interplate, Michoacan earthquake (H = 17 km, Δ = 402 km) and the inslab, Copalillo earthquake (H = 50 km; Δ = 142 km) (events 1 and 31 in Table 1 and Fig. 1).

## Discussion and conclusions

To evaluate the performance of the proposed earthquake alert device we have defined the alert time, $T_A$, as the difference between the time of beginning of the intense part of the ground motion (measured as the time when the energy becomes 5% of the total) and the trigger time. We assume that the trigger level is 4 gal. An analysis based on higher threshold levels would have resulted in shorter alert times and *vice versa* (however, a lower threshold level is not desirable for increasing alert time since it would also increase the number of false alerts, as it is discussed below).

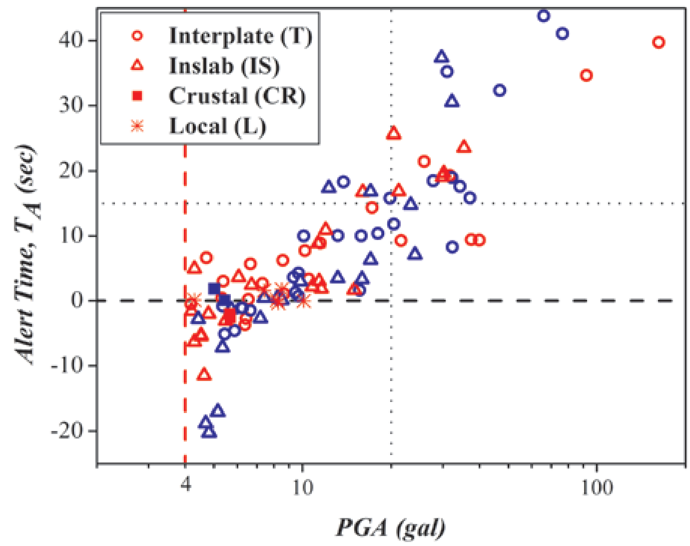


Fig. 4. Alert time, $T_A$, versus *PGA* for the two horizontal components of SCT and CDAO. Symbols are the same as in Fig. 1. Red symbols: SCT; blue symbols: CDAO. Red dashed line indicates the 4-gal threshold at which the device triggers. The two dotted black lines correspond to *PGA* = 20 gal and $T_A$ = 15 sec (see text).

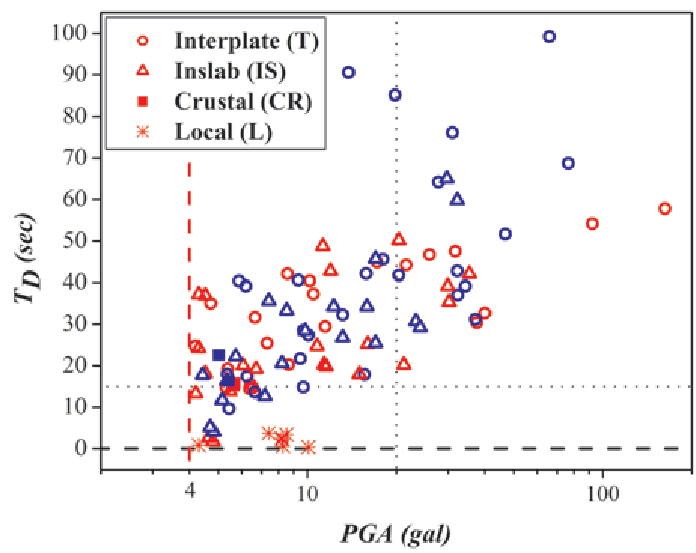


Fig. 5. $T_D$ versus *PGA* for the two horizontal components of SCT and CDAO. $T_D$ is the difference between the time when energy attains 50% of the total, $T_{50}$, and the trigger time, $T_T$. Symbols are the same as in Fig. 4. Large dispersion in the data results from the variability in signal characteristics which, in turn, is a consequence of source and path differences.

As one would have expected, the larger the *PGA*, the greater is the alert time, $T_A$. To understand the performance of the device, let us assume that a unit was installed on the ground floor of a one- to three-storey school building near SCT before September 1985. (Several hundred one- to three-storey school buildings were damaged and many collapsed during the Michoacan earthquake. Luckily, there were few casualties because the earthquake occurred at 7:18 am, when the schools were still not open. The damaged schools have been retrofitted.) Let us also assume that pre-established safety procedures were being followed during each earthquake which triggered the device. With a 4-gal threshold, the device near SCT would have triggered at least 31 times due to earthquakes in the period September 1985 - August 2008 (23 years). $T_A$ would have been negative for 7 out of the 31 events (*i.e.*, the beginning of the intense part of the motion would have already passed at the time of the alert). In these cases, the alert and the associated safety measures would have been in vain (though they may have served as earthquake drills). Even a large, positive alert time for these earthquakes (say, from a system such as the SAS) would have been of little benefit since the *PGA* would have been less than 10 gal. For 16 earthquakes, $T_A$ would have been between 0 and 15 sec. For these earthquakes, the alert device could have been useful in shutting critical facilities, but it would have been difficult to reach a previously-assigned safe place within the alert time. During 5 events $T_A$ would have been greater than 15 sec and the *PGA* would have exceeded 20 gal (earthquakes of 19/09/1985, Michoacan, $M_w$ 8.0; 14/09/1995, Copala, $M_w$ 7.3; 15/06/1999, Tehuacan, $M_w$ 6.9; 30/09/1999, Oaxaca, $M_w$ 7.4; and 21/07/2000, Copalillo, $M_w$ 5.9). For a small building and persons trained by previous drills, $T_A > 15$ sec probably would have been sufficient to reach a safe area. For the truly destructive 1985 earthquake of Michoacan, the alert time would have been about 40 sec. We recall, however, that $T_A$ refers to the beginning of the intense motion. Thus, even if persons had reached a safe place only after $T_A$, they would have avoided being exposed to the complete train of high-amplitude strong motion (Fig. 3) in an unsafe place. Similar conclusions are reached from the data recorded at CDAO.

In Table 3 we compile alert time, $T_A$, at other lake-bed sites in the Valley of Mexico where the Michoacan earthquakes of 19 and 21 September, 1985 were recorded. $T_A$ would have been in the range of 38 - 44 sec and 30 - 36 sec during these two earthquakes except at CDAF site. During these earthquakes CDAF had a trigger level of 8 gal, and a pre-event memory of only 4 sec. As a consequence, the records from CDAF start after the arrival of the intense part of the ground-motion (4-gal threshold is exceeded in the first 1.5 sec of the horizontal components for both events), thus providing underestimated $T_A$ values. Thus, Table 3 gives us some assurance that the results from SCT and CDAO may, generally, be valid for all lake-bed sites in the Valley of Mexico.

An issue of concern is that the device may trigger due to cultural noise. A check of the maintenance log book of SCT shows eight triggers at a threshold level of 4 gal between 19 April 2006 and 18 August 2007. Of these eight triggers, three were caused by earthquakes and the rest originated from cultural noise. Clearly, it would be desirable to equip the alert devices with filters that discriminate between earthquake ground motion and the motion caused by cultural noise, thus reducing false alerts. A higher threshold level is not desirable for reducing false alerts since it would also decrease the alert time.

The proposed device seems well suited to stop critical services and equipments during an earthquake before the arrival of intense motion. It would, however, be useful in mitigating injuries and loss of lives only to the extent that an alert time of 15 to 45 sec can be fruitfully utilized to implement safety measures. This issue is critical and must be given careful consideration before any deployment. We reiterate that the device will not be useful for local earthquakes, as they will result in negative or small alert time. Even a repeat of 1912, Acambay earthquake (M 7.0, $\Delta \sim 100$ km) will, at most, give an alert time of ~12 sec.

**Table 3**

*PGA* and alert time, $T_A$, at other lake-bed sites where the 19 and 21 September 1985 Michoacan earthquakes were recorded

| Date | $M_w$ | Type | Station | NS | | EW | |
|---|---|---|---|---|---|---|---|
| | | | | ***PGA* (gal)** | **$T_A$ (sec)** | ***PGA* (gal)** | **$T_A$ (sec)** |
| 85/09/19 | 8.0 | T | CDAF[1] | 76.5 | 11.0 | 91.1 | 16.6 |
| | | | TLHB | 136.0 | 43.9 | 107.0 | 43.1 |
| | | | TLHD | 118.0 | 41.7 | 112.0 | 39.1 |
| | | | TXSO | 103.0 | 38.9 | 103.0 | 40.3 |
| 85/09/21 | 7.6 | T | CDAF[1] | 40.6 | 10.5 | 29.0 | 12.3 |
| | | | TLHD | 49.4 | 35.9 | 51.6 | 35.2 |
| | | | TXCL | 33.9 | 32.9 | 32.9 | 30.8 |
| | | | TXSO | 38.6 | 34.0 | 34.7 | 33.6 |

[1]See text for a description of CDAF recordings.

It is instructive to note that, had the SAS been in operation since 1985, it would have issued public alert for only two of the seven earthquakes listed in Table 2 which produced *PGA* > 20 gal at SCT, namely for the earthquakes of San Marcos (25/04/1989) and Copala (14/09/1995). The SAS, in fact, issued a public alert for the Copala earthquake with an alert time of 72 sec (Espinosa-Aranda *et al*., 1995) as compared to ~20 sec for the alert device under scrutiny. It is possible that the SAS would have missed the Michoacan earthquakes. The reason, of course, is the limited spatial coverage of the SAS, as the sensors cover only the coast of Guerrero.

Table 4 compares the SAS and the earthquake alert device analyzed here. Both systems have merits and deficiencies. A detailed evaluation of the performance of the SAS and a strategy for its improvement is given in Iglesias *et al*. (2007). A thorough evaluation of any proposed alert system is essential before its implementation. This is because future changes are costly and, socially, confusing. We suggest that the proposed earthquake alert undergo a rigorous analysis before the authorities make a final decision. It should also be remembered that the SAS, in spite of current deficiencies (Iglesias *et al*., 2007), is already in place. Would public schools receive alerts from both systems? A careful thought should be given about the public confusion which will inevitably result from the operation of two alert systems.

**Table 4**

A comparison of the Seismic Alert System (SAS) with the proposed earthquake alert device (EAD)

| Concept | SAS | EAD | Comments |
|---|---|---|---|
| Coverage | Only for events along Guerrero coast | No geographical limitation on the source | EAD: local events will trigger it with small or negative alert time |
| Trigger level | 5 ≤ M < 6: restricted alert<br>M ≥ 6: public alert | 4 gal at the site of installation (assumed) | SAS: no information on *PGA* in the city<br>EAD: *PGA* locally ≥ 4 gal, no information on M |
| Alert time | ~60 to 80 sec | -20 to 45 sec | EAD: alert time depends on the eventual *PGA* for regional earthquakes |
| Complexity of the system | Elaborate infrastructure and expensive maintenance | Simple and robust, device needed at each site of interest | SAS: general alert for the city<br>EAD: site specific alert |
| Frequency of alert from earthquakes | 08/1991 – 09/2008:<br>50 restricted alerts<br>13 public alerts [1] | 09/1985 – 08/2008:<br>~40 estimated alerts at SCT and CDAO | |
| False alerts | Frequent, mostly caused by difficulty in accurate estimation of magnitude [2] | Very frequent at SCT and CDAO due to trigger from local cultural noise | EAD: at the trigger level of the device (~4 gal) persons may feel the event. If so, then it will serve only to confirm the human perception |
| Missed alerts | Frequent, mostly caused by the difficulty in accurate estimation of magnitude [2] | Events with low acceleration during P-wave group but with high *PGA* will result in small alert time (*e.g.*, event 9) | SAS: serious impact (alert is general for the city)<br>EAD: not as serious issue (alert is site specific) |

[1] http://www.cires.org.mx
[2] Iglesias *et al*. (2007)

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