

THE RELATIVELY LIGHT DAMAGE PRODUCED BY TWO STRONG MOTION EARTHQUAKES IN  
SOUTHERN MEXICO

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SUMMARY

Several strong motion earthquakes have occurred in Southern Mexico producing rather slight damage in weak adobe and masonry construction similar to that which caused almost 20,000 victims during the February 4, 1976 Guatemala earthquakes. A theoretical model that was developed to study the behavior of masonry walls under earthquake excitation, once they are loose at the base and acting as solid blocks, show conditions under which collapse is, or is not, reached. Some walls of real dimensions do not fall even when the recorded accelerations are multiplied by four in order to reach peak accelerations of nearly 1 g.

1. Introduction. Given the characteristics of modern strong motion instruments, the peak acceleration of an earthquake is one of the first parameters that can be directly determined in an accelerogram and it is often mentioned to describe with a single value the severity of the motion. Although several other measures of intensity, related to peak velocity, energy, spectral properties, etc, have been proposed and regarded as more appropriate, (Refs 1-3) peak acceleration almost inevitably reminds of the old efforts to correlate increasing acceleration with increasing effects or even the intuitively appealing notion of "more acceleration, more damage"

That peak acceleration can be very high and damage slight or negligible has also been clearly shown by several strong earthquakes of magnitude up to 7.8, which have occurred in the Pacific Coast of Mexico in the last few years. Among these earthquakes, which were recorded at various epicentral distances in SMA-1 (Kinematics) accelerographs, two were selected for inclusion in this paper: one that was felt in Acapulco, Mexico (16.87 N, 99.93 W) on October 6, 1974, with a peak acceleration of 0.55 g; the other is the high magnitude (MS = 7.8) earthquake which occurred in the southern part of the State of Oaxaca, Mexico, on November 29, 1978, Fig 1. This is the event that became notorious after having been predicted with proper accuracy in location and magnitude less than two years before it occurred, Ref 4.

The combination of magnitude, depth and epicentral distance to inhabited areas for these two earthquakes would ordinarily suggest a high damage potential, particularly in adobe housing and modest masonry construction that prevails in the affected areas, where adobe uses and characteristics are entirely similar to those that produced about 20,000 victims during the February 4, 1976 Guatemala earthquake. If damage is expressed in terms of

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number of houses with collapse in at least one wall, it was surprisingly low even for the weakest adobe houses (Ref 5).

Although it is generally accepted that the duration of strong ground shaking is also related in some way to damage potential and that short earthquakes that produce almost no damage even for high accelerations have been observed (Ref 6) a quantitative relationship involving those factors is still lacking. In order to throw some light on those questions, this paper describes the model that has been developed to study the response of certain types of masonry construction under earthquake excitation.

2. Construction types and mode of failure. The construction type under consideration is widely used in poor areas and may be described in a few words: masonry and weak mortar. It may be built of adobe, usually 40 to 60 cm thick, and mud joints, or any other combination of materials which result in relatively thick, heavy walls and low strength. However, it is adobe that constitutes an example of extremes in mechanical resistance: to a volumetric weight of approximately  $1.8 \text{ ton/m}^3$ , are associated a compressive strength of less than  $20 \text{ kg/cm}^2$  (Ref 7) and less than  $5 \text{ kg/cm}^2$  in tension

When these factors coincide with excessive length between lateral supports the usual mode of failure is overturning, which may often take place by rotation of the upper, practically rigid, part of the wall about an horizontal axis normal to its cross section. This rotation becomes possible after the vertical cantilever has broken at the base.

This mode of failure may be regarded as frequent in unreinforced masonry walls without sufficient lateral restraint and, as in common adobe housing, it occurs even when support in only one direction is provided by perpendicular walls that have separated by the early development of vertical cracks (Refs 8, 9).

3. Mathematical modelling. The cross-section of the potentially overturning wall has been represented by a rigid rectangular block of thickness  $2a$  and height  $2b$ , capable of rotating about either of its lower corners as it is excited by the motion of the ground on which it rests (Fig 2). This implies that a plane horizontal crack has already developed and, as a consequence, the block has separated from the foundation or lower portion. It is also assumed that density is uniform over the wall and that friction is high enough to prevent sliding. These assumptions are considered to reflect quite closely the actual properties and behavior of real masonry walls of the same type. In this paper only one component of horizontal ground motion is considered to be acting on the wall.

If the angle of rotation of the vertical axis of symmetry is represented by  $\theta$ , it is clear from Fig 2 that the problem becomes statically unstable when  $\theta > \alpha$ , being  $\alpha$  half the angle formed by straight lines from the centroid to the two lower corners. When  $\theta < \alpha$  the problem is statically stable and governed by the well known differential equation of an inverted pendulum. For the rectangular block in Fig 2, and considering angles small enough to be

replaced by their sine, and their cosine by unity, this equation is  $\ddot{\theta} - A\theta = -A\alpha$  where points indicate derivation with respect to time and  $A = 3g/4L$  ( $g =$  acceleration of gravity;  $L = (a^2 + b^2)^{1/2}$ ). In the case of earthquake excitation the right-hand member incorporates the ground acceleration  $\ddot{x}$  to become:  $\ddot{\theta} - A\theta = B\ddot{x} - A\alpha$ , where  $B = 3/4L$ . As shown in Ref 10, which is the basis for this development, the equation has the following solution for initial conditions  $\dot{\theta}_0$  and  $\theta_0$ :

$$\theta(t) = \left( \theta_0 - \alpha + \frac{BE}{A + \omega^2} \right) \cosh \sqrt{A}t + \frac{1}{\sqrt{A}} \left( \dot{\theta}_0 + \frac{BD\omega}{A + \omega^2} \right) \sinh \sqrt{A}t + \alpha - \frac{BD}{A + \omega^2} \sin \omega t - \frac{BE}{A + \omega^2} \cos \omega t$$

The excitation has been assumed to be  $\ddot{x} = D \sin \omega t + E \cos \omega t$  ( $D$  and  $E$ , constants). The extension from this solution to the case of earthquake excitation is routinely obtained through the use of the FFT algorithm.

4. Earthquakes and masonry wall characteristics. The most significant information about the selected earthquakes is presented in Table 1. Because the peak acceleration of the other horizontal component of the Acapulco earthquake was considerably less, only the E-W component was of interest. Table 2 shows the dimensions of the cross-section of the walls that have been considered. These dimensions are representative of those of the masonry and adobe construction most often encountered in the areas that experienced strong motion. The last two lines in Table 2, marked with an asterisk, pertain to hypothetical walls of slenderness ratios ( $b/a$ ) much higher than the actual ones included in the same table. These artificial walls are included in order to better exemplify the possible outcomes of the procedure used, because the horizontal acceleration components of the ground motion which have served as excitation do not cause overturning of the three walls with realistic dimensions.

Only two wall thicknesses are represented in Table 2: 40 and 15 cm, which are those of the most common types of adobe and clay brick, respectively. The height of the brick wall was restricted to about 131 cm in order to have the same  $b/a$  as the second adobe wall in Table 2. This height was used for hypothetical walls (thicknesses of 5 and 10 cm).

5. Numerical results. The computed response to the E-W component of the Acapulco earthquake is shown in Fig 3, where the accelerogram appears at the top. These responses are those of the first three walls in Table 2 and are expressed in terms of the angular velocity  $\dot{\theta}$  and the angular displacement  $\theta$ . (In all pertinent figures the time history of these two variables appear next to one another, together with the proper wall identification data between them. To simplify reference, each pair of time histories has been labeled A, B and C from top to bottom.

In Fig 3 the following observations may be made: a) There is no motion of the wall until ground acceleration reaches a certain level and the onset of motion is almost simultaneous for A, B and C. b) All the angular displacements are less than 1 degree. c) No angular velocity reaches 20 deg/sec. d) None of the walls fall and all of them come back to rest in less than 3 seconds. e) The response of wall B has considerably more oscillation cycles than that of A, even if latter is more slender. f)

For equal  $b/a$  ratios (walls A and C) the response of the smaller wall has more and wider cycles.

To present the results obtained for the NS component of the Oaxaca earthquake acting on the same walls, Fig 4 has been organized in the same way as Fig 3. The examination of Fig 4 leads to the following conclusions: a) The onset of motion does not occur simultaneously for A, B and C. b) All angular displacements are again less than 1 degree. c) Angular velocities are less than 20 deg/sec. d) Although no wall topples over, their motion lasts more than 6 seconds; in all 3 cases the duration of motion is longer than for the Acapulco earthquake, which has a peak acceleration (0.55 g), more than twice that of the Oaxaca earthquake (0.23g). Furthermore, e) and f) are the same as for Fig. 3.

Since not a single fall of the walls (of real dimensions) studied was produced with the two selected earthquakes, some artificial means to reach overturning were tried:

i) By multiplying the acceleration ordinates of the Oaxaca earthquake (NS component, top of Fig 3) by a factor of 4 and applying this magnified accelerogram to the previously considered wall which showed the most pronounced response (Case B in Figs 3 And 4,  $b/a = 7$ ).

The result of this experiment is shown in Fig 5A. It may be observed that even the magnified accelerogram, with a peak acceleration of 0.88g does not lead to collapse, but the response is much more lively, lasts longer than 12 seconds and there is still motion (diminishing) at the end of the excitation. Again, the angular velocities are within  $\pm 20$  deg/sec, though the maximum deviation from the vertical reaches more than 2 degrees.

ii) By increasing the slenderness ratio without modification of the accelerogram. The effects of this are shown for  $b/a = 13.125$  (Fig 3B) and  $b/a = 26.25$  (Fig 3C).

It is interesting to note that for the same  $b$  (Figs 2C and 3C) the increase of the slenderness ratio from 8.75 to 13.125 results in shorter motion time, fewer cycles, once full stop lasting about 0.7 sec, somewhat smaller velocities and angular displacements with approximately the same maximum values.

Fig 3C, representing extreme slenderness, is the only example in which overturning occurs. This is shown at the end of the plots by arrows, which indicate a very rapid increase in both  $\dot{\theta}$  and  $\theta$ .

6. Conclusion. The mathematical model that has been developed to study the behavior of some types of adobe and masonry construction under earthquake excitation gives insight into the nature of the response that may lead to collapse.

The wider range of uses for the modal (Ref 11) and the understanding it provides about certain dynamic phenomena justify some refinements already underway (12).



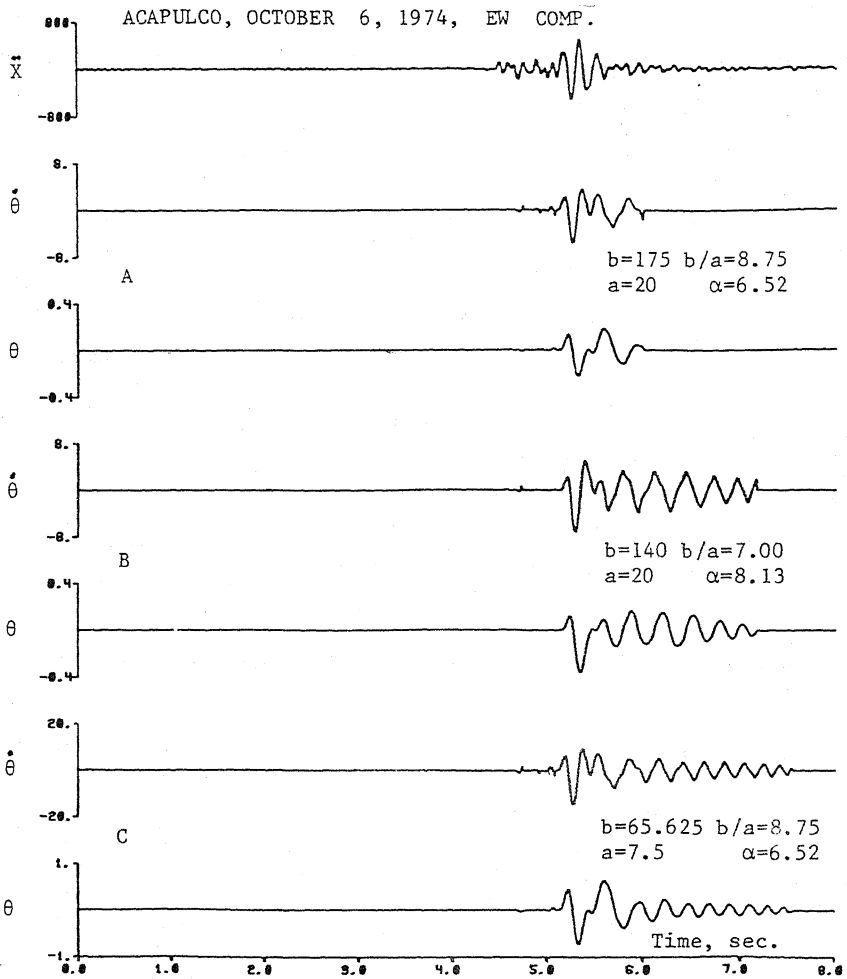


Fig 3 Computed response of three rigid walls subjected to the EW component of the October 1974 earthquake.  
 ( $\theta$  in degrees,  $\dot{\theta}$  in degrees/sec)



