# BASE SHEAR IN TALL BUILDINGS DURING EARTHQUAKE JULY 28, 1957 IN MEXICO CITY

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## SYNOPSIS

Great experience was gained after damage produced by the strong earthquake taking place in Mexico City in July 28, 1957, in spite of the absence in the city area of strong motion seismographs. The damage observed in numerous buildings has lead the author to enforce former assumptions concerning the acceleration and dominant period induced in building foundations by the soil mass in the lacustrine area.

The author describes a method, to evaluate the most probable base shear, used in Tower Latino Americana in which it was taken in consideration the participation of the modes of vibration of the building. A method of comparison based on the maximum impulse is discussed. This method may be applied also when the velocity or acceleration spectrum is unknown, and only the maximum acceleration and dominant period during certain earthquakes may be estimated from previous history in the past.

The two methods are compared in conjunction with the base shear measured during the earthquake of July 28, 1957 in the 43 - storey Tower Latino Americana in Mexico City. The behaviour of the 23 - storey building Aseguradora Anahuac is also considered.

## GENERAL CONSIDERATIONS

In the seismic design of tall buildings it is important to know the order of magnitud of the probable maximum base shear as related with the flexibility and mass of the building. The understanding of the base shear with flexibility and mass distribution with height is one of the most important items to be taken into consideration in the proper seismic design of tall buildings. A very rigid building will give better response to an earthquake than a more flexible building, therefore conclusions might follow to think that the most flexible structure would be the fittest to survive an earthquake. However, this is not the case because a very flexible structure has large accelerations

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and correspondingly large displacements. In the upper floors whip action may develop that may be detrimental to the building. Partition walls, mechanical installations and curtain walls should be carefully considered in selecting the flexibility of a building. Therefore, taking into account the various problems involved in the response of a building to a certain ground movement the concept of the "controlled flexibility" should be introduced in order to obtain the answer to the proper seismic design of a tall building. Because of the above mentioned reasons we should design flexibility and mass distribution through out the height of the building in such a way as to produce the lowest possible shears in conjunction with allowable displacements in all and each one of the floors. The total response of the building to certain ground movement is measured at the base by the base shear, knowing this value the dynamic design of a building may be achieved by one of several procedures with reasonable accuracy.

Because of the complexity of the ground movements we may arrive to the conclusion that in the particular case of a tall building it is necessary to consider the specific earthquake or ground movement at the location the building is going to be constructed and not just an earthquake of certain intensity with characteristics corresponding to other subsoil conditions. Even in the same region the ground movement may assume very different characteristics from one place to another. Furthermore, in exactly the same location ground movements may be completely different for earthquakes with apparently the same intensity. Therefore, one may conclude that no refinement in dynamical structural analysis is justified until we know, for each region, the envelope of ground movements or rather that of the velocity or acceleration spectrums. Moreover, this envelope may be different for different intensity earthquakes in the same location. Therefore, the only hope to design in certain region with better accuracy would be to be prepared to learn to know several acceleration spectrums corresponding to that location and for the strongest earthquakes. Using the acceleration spectrum envelope for an area with same subsoil conditions we could be able to make an approximate design for the next ground movement.

In spite of the large complexity involved, and the need of strong motion seismographs to understand better the ground movements that may affect seismic design of buildings, we may use past experience during destructive earthquakes in order to make a reasonable guess on the maximum forces causing damages in buildings that apparently were under designed, and to observe the behaviour of those buildings where more advanced methods of design were applied.

The two procedures presented in this paper to determine approximately the base shear in tall buildings have the aim to make a better approach to the problem in question. In spite of the complete lack of seismographs in Mexico City to measure strong motion earthquakes, quantitative conclusions may be drawn in order to visualize the best procedure to be used in seismic design of tall buildings and gain judgement as to the way flexibility and masses should be distributed through out the height of the building to obtain more economical and better seismic resistant structures. The general philosophy that may be applied to design the structure of a tall building against seismic forces is out of the scope of this paper, however, the conclusions drawn concerning the way the base shear is developed during an earthquake as a function of the mechanical properties of the frame, gives a clear concept of the way seismic forces enter in the structure of a tall building.

Seismic design in Mexico City is in a stage in which unfortunately no precise specific rules can be set forth, for any building and earthquake. It is the author's opinion that seismic design still requires the use of substantial judgement and experience with past earthquakes, in spite that the mechanics of how an earthquake movement enters a building might be fully understood. In those places where the ground movements are not recorded with strong motion seismographs the task becomes even more difficult. Furthermore, in places like Mexico City, where subsoil conditions assume variation from the lacustrine area (5,6) to the firm ground the acceleration spectrums computed from strong motion accelerographs(1) for different places within the city area, will obviously show different; even in the lake area variations may be of importance (2)(3). The fact is recognized from the last earthquake July 28, 1957 since the earthquake was registered stronger in certain particular area of the city than in other areas, in spite of similar subsoil characteristics in the lacustrine city region

From the observation of fifty five buildings over 8-storey height in the area shown in Fig 1, where the largest damaged occured; eleven buildings were partially destroyed, collapsed or their structures suffered so strongly that they had to be demolished or condemned permanently. From these eleven buildings six had reinforced concrete structure and the rest steel structure. Fifteen buildings in the same area suffered considerable damage and their structures had to be reinforced, they suffered very large damage in their interiors and curtain walls; four of them have a steel structure. Nineteen of the buildings observed were strongly damaged in their interiors and curtain walls, but no damage or very minor damage was observed in their structure. Some of these buildings had to be abandoned momentarily for repairs. All the buildings mentioned above were on either timber or concrete pile foundations.

From above mentioned observations the author concluded that nothing specific may be stated concerning the type of building material performing better during the earthquake. However, it is recognized that steel building structures appeared to show more ductibility under extreme conditions because of the reserved strength in the steel structure, but large displacements of them produced a strong damage in the interior installations and curtain walls. Thus, it is obvious that seismic design of tall buildings is an important function of displacements compatible with the elements that go into the buildings. If costly secondary elements fail during an earthquake, the result is unsatisfactory since the resisting structure has not fulfilled its duty.

The author strongly believes from past experience, that next earthquake with same intensity in Mexico City, may affect the lacustrine city area in different places which may be damaged just as strongly as those observed in July 28, 1957. This experience shows that for the time being in Mexico City, it is very difficult to assume an acceleration spectrum as a function of the building periods in order to achieve a more accurate seismic design.

As a matter of course, if a good number of velocity or acceleration spectrums were available from observations in the foundation of buildings and the related behaviour of their structures were known in the lake area; the study of this information would lead to an envelope spectrum that could be used with judgement as the upper limit to design structures within that investigated area. Unfortunately, in Mexico City no observations have been made on the line mentioned above and because of the non-common subsoil conditions it is difficult to guess on any configuration of the acceleration spectrum There appears a good reason to believe that the accelerations may remain practically constant in certain range of the building periods. Therefore, it is unjustified, for the moment, to take any compromise to build up a more refined theory, that may be applied to achieve a more precise seismic design of tall buildings using a variable acceleration spectrum.

The only reliable experience has been the observed damage to buildings during past earthquakes, registered in the so called M-Mercalli-Cancani-Sieberg scale of intensity VII corresponding to ground accelerations on the order of 25 cm/sec$^2$.

These destructive earthquakes registered in the past 60 years including the last of July 28, 1957 make a total of four (4). The last mentioned earthquake originated larger ground accelerations only in certain zone of the lacustrine city area. This acceleration computed in building foundations appears to have been on the order of 50 cm/sec$^2$, therefore in this area and according to above mentioned scale the earthquake may be registered as one of eighth degree. From observations of damaged building in the lacustrine area it appears that the earthquake waves of July 28, 1957 suffered certain reflection, because of the configuration of the basin of the Valley of Mexico (5,6); thus adding up to twice its intensity in the most seriously damaged part of Mexico City. The acceleration of 50 cm/sec$^2$ given above has been computed back from damaged or slightly damaged buildings and is a number on which it is generally agreed upon by several engineers understanding earthquake seismic design.

The author stated elsewhere (4) that up to 1956 his experience was that destructive periods during strong earthquakes in the lacustrine area may range between 1.5 and 2.5 sec with the most frequent of 2.0 sec, as used to compute the 43-storey Tower Latino Americana. The observations after last earthquake have given him more confidence on the above statement. Moreover, he has observed from behaviour of several buildings that Mexico City subsoil produces, fortunately, considerable damping. Therefore the adding up of stresses in structures during an earthquake appears to be of secondary importance in building design. This means that a building during an earthquake may follow very closely the individual random impulses produced in its foundation as related with capacity of wave transmition into the building during the time these impulses are applied. The time of application of the destructive maximum impulses may range between 0.4 and 0.6 sec., with the most frequent of 0.5 sec., hence inducing correspondingly certain specific momentum into the building proportional to the portion of the mass excited.

During last earthquake in Mexico City, July 28, 1957, the author added some more experience observing the behaviour of buildings that have been designed with more rational procedures as commonly applied in the past in Mexico City. One of these buildings was the 43-storey Tower Latino Americana where no damage at all was observed This building is located in the area, Fig 1, where damage to buildings showed a ground motion corresponding to an acceleration on the order of 50 cm/sec$^2$.

In the Tower mentioned above the base shear measured by the deformation of the first floor was of 500 Ton corresponding to only 0.0333 g, meaning that the flexibility of the building played a very important part in the base shear. Since otherwise, an acceleration of 50 cm/sec$^2$ should have induced a base shear of 750 Ton . This building rests on concrete point-bearing piles at a depth of 32 mts from the ground surface, it has two basements and the foundation slab extends into the lacustrine volcanic clay deposit to a depth of 13 mts(7).

The 23-storey steel structure building of the insurance company Aseguradora Anahuac(8) also on a concrete point-bearing pile foundation was designed with base shear corresponding to 0.036 g, and following the same philosophy of design as used in the Tower mentioned above. This building also located in the zone of highest intensity during the July 28, 1957 earthquake, Fig 1, passed the seismic movement very well with not a single glass window broken. However, it was recognized from a detailed survey of the building after the earthquake that the structure was stressed to not less than the designed shear forces. Unfortunately, no measuring devices were attached to the first floor.

The discussion that follows has the aim to show two methods by which the base shear may be approximately computed taking into account the mechanical properties of flexibility and mass distribution of the building. The first method called the $c_p$ Method is based on an analysis of the modes of vibration of the building using the acceleration spectrum. It is discussed and applied for what is known concerning the last earthquake in Mexico City. The second method called the I-Method is based on a maximum single impulse during the earthquake. Both methods have been applied to the two above mentioned buildings for comparison of results, and conclusions are drawn at the end of this paper.

## The $c_p$ - Method:

Assume that the acceleration spectrum for a particular site is known, and that it may be represented by the following expression:

$$A_n = f(T_n) \tag{1}$$

in which $T_n$ is the fundamental or any other mode of vibration of the building.

On the other hand, the modes of vibration of the structure $T_n$ are known. The way the different modes participate in the vibration is also known, that is to say, the "coefficient of participation $c_{pn}$" for each individual mode of vibration of the building is known. With this information it has been shown(9) that the maximum base shear for each mode of vibration may be computed by:

$$S_n = c_{pn} A_n M \tag{2}$$

The next step is to investigate how these shears add up to produce the maximum possible base shear in which all the shears for the significant modes of vibration of the structure are considered. The maximum values obtained by(2) can not be simply added because they do not apply simultaneously during the earthquake movement. The simple summation of these values will give the theoretical upper limit of the total shear that might be developed at the base of the building only in that very particular case when times for the different modes of vibration are in such a way distributed during vibration as to permit this maximum condition to take place. However, this value improbable to take place is too high to be considered for design purposes, and since the times at which the shears may take place for the different modes of vibration of the building are unknown, it appears that the best way to find out the most probable value in this case is by using the following equation(11,12):

$$S_b = \sqrt{\Sigma S_n^2} \tag{3}$$

that is to say:

$$S_b = M \sqrt{\Sigma (c_{pn} \cdot A_n)^2} \tag{4}$$

In case of Mexico City the value of $A_n$ is unknown as a function of $T_n$. The best assumption that may be made up to date is to assume $A_n$ approximately constant and on the order of 50 cm/sec$^2$ for the range of periods considered, that is partially justified if we consider that the strongest earthquake epicenters are located far from the city and that there is a large damping effect in the foundations because of subsoil conditions in the lacustrine area(6). Thus for Mexico City so far we may use the following expression for the most probable maximum base shear:

$$S_b = A_o \cdot M \sqrt{\Sigma c_{pn}^2} \tag{5}$$

Applying this equation with information given in Table I for the 43-storey Tower, we obtain 512 Ton for the base shear.

TABLE I

| Mode | $T_n$ | $C_{pn}$ | $(C_{pn})^2$ | |
|---|---|---|---|---|
| 1st | 3.660 | 0.6140 | 0.3773 | $M = 15{,}561.1$ Kg sec$^2$/cm |
| 2nd | 1.540 | 0.2220 | 0.0492 | $A_o = 50$ cm/sec$^2$ |
| 3rd | 0.975 | 0.0753 | 0.0057 | $\sqrt{\sum} = 0.657$ |
| 4th | 0.710 | 0.0222 | 0.0006 | $S_b = 512$ Ton |
| | | $\sum =$ | 0.4328 | |

The value computed by this method is surprisingly close to the value of 500 Ton. measured at the first floor of Tower Latino Americana.

Table II gives the case for the 23-storey building mentioned before.

TABLE II

| Mode | $T_n$ | $C_{pn}$ | $(C_{pn})^2$ | |
|---|---|---|---|---|
| 1st | 2.21 | 0.733 | 0.5380 | $M = 11{,}894$ Kg sec$^2$/cm |
| 2nd | 0.80 | 0.153 | 0.0235 | $A_o = 50$ cm/sec$^2$ |
| 3rd | 0.50 | 0.077 | 0.0059 | $\sqrt{\sum} = 0.752$ |
| | | $\sum =$ | 0.5674 | $S_b = 447$ Ton |

The value computed for the base shear in this building is of 447 Ton against 422 Ton that was the base shear design value corresponding to 0.036 g. As mentioned before the building suffered no damage during earthquake July 28, 1957.

## The I-Method:

Considering that during an earthquake in the lacustrine area of Mexico City, the destructive shear induced in buildings is applied by impulses in times from 0.4 to

0.6 sec., corresponding to ground accelerations of 50 cm/sec$^2$. The shear wave will travel with velocity $V_n$ in the building during the impulse time (13, 14) Fig 2. The value of the shear wave velocity depends on the rigidity $K_n$ and mass $M_n$ of each floor and is given by the following expression:

$$V_n = h_n \sqrt{K_n/M_n} \qquad (6)$$

in which $h_n$ is the floor height, $K_n$ the rigidity of the floor (Kg/cm) and $M_n$ the corresponding mass.

Furthermore, if $m_n$ is the mass per unit height of the n-th floor and $\Delta t_n$ is the increment of time for the seismic wave to travel the height $h_n$ of that floor then the mass $M_n$ per floor may be expressed as follows:

$$M_n = m_n \cdot V_n \cdot \Delta t_n \qquad (7)$$

Now assume the building receives an impulse through its foundation of duration $t_o$; hence, the corresponding momentum induced in the building will be:

$$S_b \cdot t_o = e\,[\Sigma\, m_n \cdot V_n \cdot \Delta t_n]\, v_o \qquad (8)$$

in which $v_o$ is the velocity of the foundation and $e$ is a damping or effective coefficient which value depends on the type of structure considered.

The shear wave will travel up to the upper stories of the building until

$$t_o = \Sigma \Delta t_n \qquad (9)$$

and will excite all those floor masses included in this time. The interpretation of above formula (8) may be read as follows:

$$S_b = e \cdot A_o \cdot \sum_{o}^{t_o} M_n \qquad (10)$$

in which $A_o$ represents the average acceleration movilizing the floor masses $M_n$ during time of impulse $t_o$.

Applying this concept to the 43-storey Tower Latino Americana, the results given in Table III are obtained.

TABLE III

| sec<br>$t_o$ | Floors excited | Kg.sec$^2$/cm<br>$M_n$ | cm/sec$^2$<br>$A_o$ | Ton<br>$A_o \cdot M_n$ | e | Ton<br>$S_b$ |
|---|---|---|---|---|---|---|
| 0.4 | 17 | 8.724 | 50 | 435 | 0.95 | 414 |
| 0.5 | 21 | 9.935 | 50 | 496 | 0.95 | 472 |
| 0.6 | 24 | 10.817 | 50 | 542 | 0.95 | 515 |

The shear measured at the base was of 500 Ton as compared with values given in the last column of Table III.

In the case of the 23-storey building, Table IV, the following is obtained:

TABLE IV

| sec<br>$t_o$ | Floors excited | Kg.sec$^2$/cm<br>$M_n$ | cm/sec$^2$<br>$A_o$ | Ton<br>$A_o \cdot M_n$ | e | Ton<br>$S_b$ |
|---|---|---|---|---|---|---|
| 0.4 | 16 | 9.135 | 50 | 465 | 0.85 | 395 |
| 0.5 | 19 | 10.333 | 50 | 516 | 0.85 | 440 |
| 0.6 | roof | 11.813 | 50 | 592 | 0.85 | 503 |

It was recognized that during earthquake July 28, 1957 the induced base shear was at least the design base shear of 422 Ton or certain larger value.

The damping or effective coefficient "e" may be larger for some type of building structures than for others. For example the Tower Latino Americana has a steel structure of rolled steel sections with riveted connections therefore the assigned value was taken $e = 0.95$. In case of the Aseguradora Anahuac Building with a pre-fabricated steel structure in which the members; columns and girders, are constructed with plates and angles riveted together, and joint connections also riveted, it is justified to assume that at least the damping effect in this building is 10% higher than for the first type of steel structure, thus justifying the reason to use $e = 0.85$. In comparison the value of 'e" for an all welded steel structure may be taken on the safe side as one.

## CONCLUSIONS:

From experience of the behaviour of tall buildings during destructive earthquakes in Mexico City a few general and practical conclusions may be obtained concerning tall buildings in the lacustrine area.

1.- Large damping effect takes place, because of subsoil characteristics in the lacustrine area.

2.- The acceleration may be considered for practical purposes approximately constant for all the periods of vibration of the structure with a value on the order of 50 cm/sec$^2$, as estimated in the last earthquake of July 28, 1957.

3.- Destructive ground periods may range between 1 5 and 2.5 sec with corresponding impulses between 0.4 and 0.6 sec.

4.- The $c_p$ -Method shows that modes of vibration more than the third contribute but very little in the base shear, moreover when damping effect is considered by assuming an approximately constant acceleration spectrum.

5.- The i -Method shows that the order of magnitud of the maximum base shear may be computed by means of the individual impulses set in the foundation during an earthquake.

6.- The reasonable agreement in the results of the $c_p$-Method and the i-Method, appears to substantiate the fact of large damping effect taking place in buildings during earthquakes in the lacustrine area of Mexico City.

Strong efforts are been made toward the installation of several strong motion seismographs in the foundations of buildings located in the lacustrine area and surroundings. Therefore, it is hoped that in the future it may be possible to bring up to date more precise information about the velocity and acceleration spectrums. Also it is expected to have a city regulation concerning the installation of several devices at different floor levels in order to measure the maximum relative displacements between floors in tall building and learn more on their real behaviour and general damping characteristics in steel and reinforced concrete structures.

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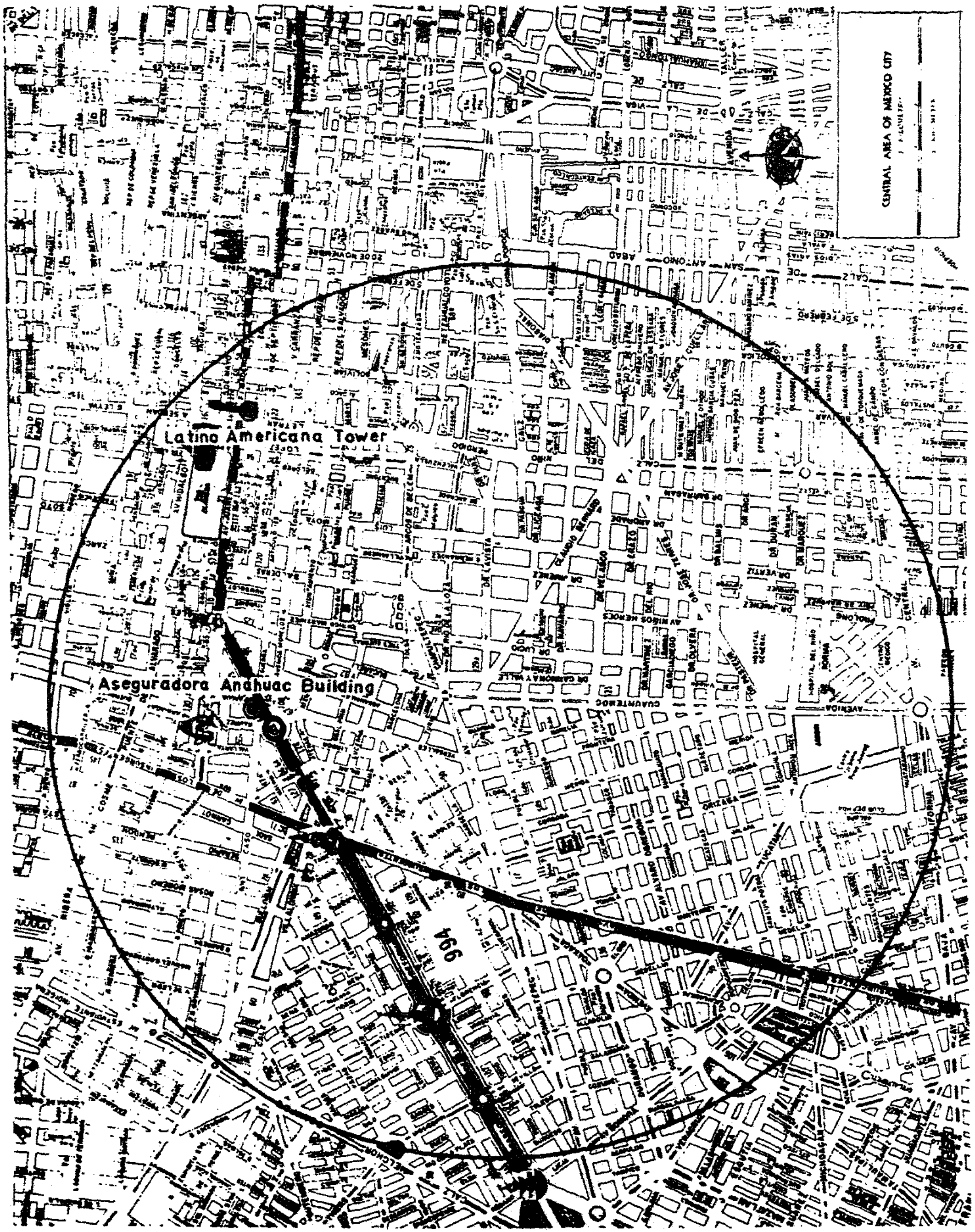
CENTRAL AREA OF MEXICO CITY
Latino Americana Tower
Aseguradora Anahuac Building
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FIG. 1

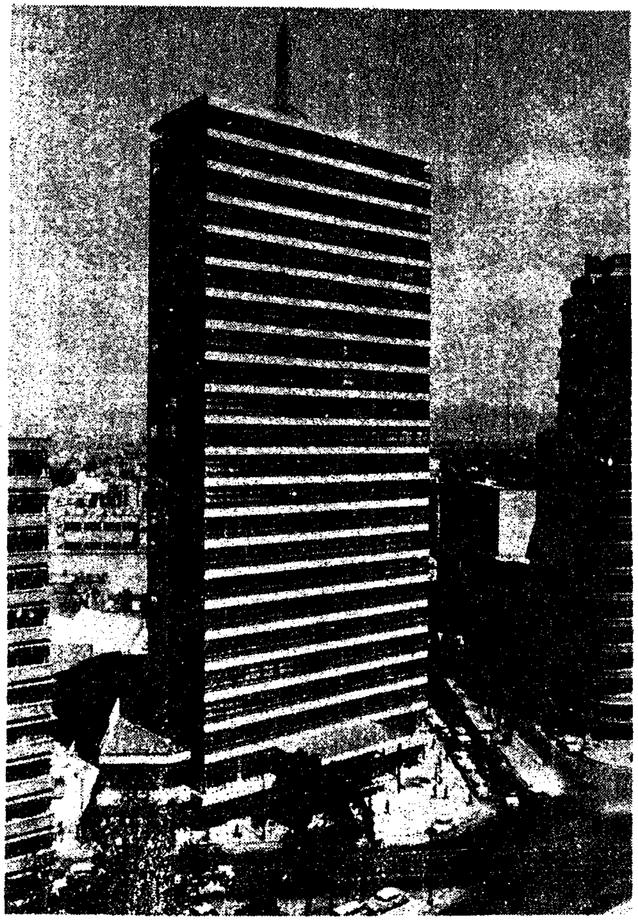
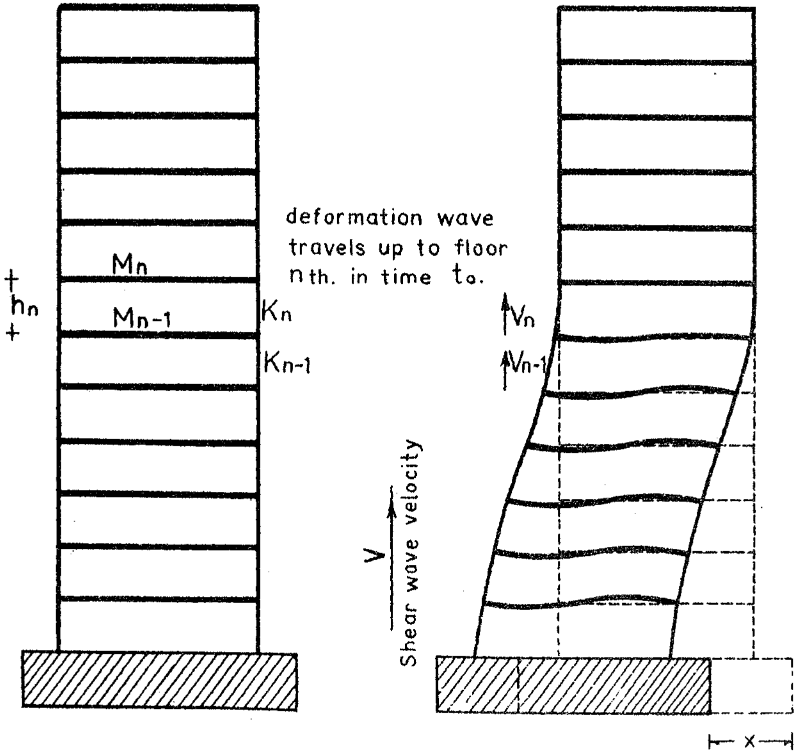


Photo. 2 Aseguradora Anahuac, S. A.
México, D. F.



x = foundation displacement in the impulse time $t_o$

$$t_o < \frac{T}{4}$$

T = fundamental period of building

fig. 2

Photo. 1 Torre Latino Americana
México, D. F.