PERIODS OF BUILDINGS OF MENDOZA CITY (ARGENTINA)

by

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ABSTRACT:

In this paper the measurement of periods of 106 buildings of Mendoza City (Argentina) is analysed.

The analysis is divided into:

a) Selection of "Typical Models of Buildings" in order to study the influence of walls, shear walls, frames and foundations on the value and the variation of fundamental period of buildings.

b) Taking into account the above conclusions the statistical analysis of the experimental measurement of building period of Mendoza City (Argentina) has been made , with a discussion of the result.

The conclusions of part a explain the significance of different variables and their arrangements used in statistical analysis of period measurement of building carried out in different seismic areas.

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NOMENCLATURE

T = fundamental period of building
H = height of building
L = horizontal dimension of building
Δ = wall area ratio = $\frac{\text{horizontal section wall area}}{\text{plant area}}$
δ_{st} = top building displacement by horizontal forces equal to weight of building masses
k_s = shear stiffness
k_ϕ = rocking of foundation
$f(h)$ = mode of vibration in level at height h
n = number of stories
H_p = height of each story
A_f = foundation area
a, b, c, d = coefficient of statistical correlation
C = seismic coefficient
E = Youngs Modulus
G, G_W = Transversal Modulus
N = Number of experimental determinations

INTRODUCTION:

The analysis of the seismic effect requires the knowledge of the dynamic parameters of the buildings to be considered. One of the most important of these parameters is the fundamental vibration period of the buildings, which is nothing but the unit of time with which the vibrator measures and estimates the kinematics of the seismic motion. (1°) The up to date codes recognise its importance and include it explicitly as a variable to assign the seismic coefficient of a design.

The period may be determined by a dynamic analysis of the design or more simply by means of empirical formulas which are a consecuence of experimental determinations carried out in different seismic areas. These empirical formulas represent the influence of the materials, the building techniques and the particularities of the foundation of the studied buildings. The results obtained sometimes lead to apparent disparities which originate difficulties when you wish to apply them // through out professional practice in zones different to those they / correspond to. (2°) (3°) (4°)

In order to get acquainted with the dynamic characteristics of / the buildings, the Municipality of Mendoza City financed the experimental determination and the analysis of the fundamental periods of //

vibration of all buildings in that city over 15 meters high.

In this report the results, experimentally obtained, and their a nalysis are given. The latter are based on the peculiarity of the loads and structures of the buildings in the zone, forming typical buildings in which the period of vibration and its variability are studied with a simplifying criterium. With the results from these typical buildings the experimental determinations are statistically analysed.

EXPERIMENTAL DETERMINATIONS:

Of the different experimental methods which may be applied to de termine the periods of vibration: resonance tests, free vibrations by impulse or initial displacement, and microvibrations, the latter was exclusively used because of the simplicity of the technique to be em- ployed . For this purpose the movement generated in the buildings by the wind, traffic, elevators, etc. was recorded by means of portable HOSAKA ESS-6B seismographs which consist of an electromagnetic transdu cer , an electronic amplifier and recorder on smoked paper (fig.1).The time was controled by the recording speed. Figure 2 shows some of the recordings that were obtained.

The numerical value of the fundamental period was computed using the average of several periods. These numerical values are represented as a function of the height in fig. 3.

In some examples it has been possible to obtain some values of // the damping, which have varied between 1 and 1,5% of critical damping.

PERIODS AND DEFORMABILITY OF VIBRATING SYSTEMS

The continuous vibrating systems used for the analysis of the de formability , and period of the typical buildings is : (fig. 4)

distribution of uniform masses m.
shear stiffness k_s; rocking of the foundation k_ϕ, and traslation of the foundation k_t.
The differential equation of vibration modes is the well known :

$$m\omega^2 f(h) + \frac{d}{dh}\left[k_s \frac{d}{dh}\left(f(h) - \phi_o h - f(o)\right)\right] = 0 \qquad (1)$$

with the also well known border conditions:

1. Traslation of the foundation produced by the base shear
$$k_t f(o) = k_{so} \frac{d}{dh}\left[f(h) - \phi_o h - f(o)\right]_{h=o}$$
2. Zero top shear
$$k_s \frac{d}{dh}\left[f(h) - \phi_o h - f(o)\right]_{h=H} = 0$$
3. Base rocking owing to base turning moment
$$k_\phi \phi_o = \int_o^H k_s \frac{d}{dh}\left[f(h) - \phi_o h - f(o)\right] dh$$

A special case of equation (1) , is to assume the potential variation of the shear stiffness k_s with degree n :

$$k_s = k_{so}\left(1-\frac{h}{H_1}\right)^n = k_{so} x^n \quad ; \quad H \leq H_1$$

$$x^n \frac{d^2 f(x)}{dx^2} + n x^{n-1} \frac{df(x)}{dx} + p^2 f(x) + n x^{n-1} H_1 \phi_o = 0$$

$$\text{where } p^2 = \frac{m\,\omega^2 H_1^2}{k_{so}}$$

The vibration period which is : $T = \frac{2\pi H_1}{p}\sqrt{\frac{m}{k_{so}}}$

If in the assumed vibration system there only exists shear stiffness k_s and traslation of constant stiffness k_t , without any rocking of the foundation, you get: $\cos\left[\omega H\sqrt{\frac{m}{k_{so}}}\right] = \frac{f(o)}{f(1)}$

The recording of movement of top and base of tested buildings showed:

Hence : $\frac{f(o)}{f(1)} < 0.1$

$$0.92\,\frac{\pi}{2} \leq \omega H\sqrt{\frac{m}{k_s}} \leq \frac{\pi}{2}$$

From which you conclude that for the tested buildings the foundation traslation given by the stiffness k_t has little importance in the vibration period and it is disregarded in the latter analysis.

A simple way to determine the fundamental vibration period, as a function of the deformability of the building, is to apply the relation between the vibration period T and the static displacement of the top , as a consecuence of the set of horizontal forces equivalent to the weight of the acting masses , δ_{st}, which for the assumed potential variation of the shear stiffness k_s , with order n is :

$$\delta_{st} = \frac{mg H_1^2}{2\,k_{so}}\left[2\int_o^H \left(\frac{H}{H_1}-\frac{h}{H_1}\right)\left(1-\frac{h}{H_1}\right)^{-n}\frac{dh}{H_1} + \frac{k_{so}}{k_\phi}\,\frac{H^3}{H_1^2}\right]$$

Applying this to different examples you obtain the well known relations

$[T]$= seg. $[\delta_{st}]$= cm.

1. One degree of freedom vibrator
   $T = 0.2\sqrt{\delta_{st}}$
2. Vibrating system with : $k_\phi = \infty$; k_s = cte.
   $T = 0.18\sqrt{\delta_{st}}$
3. Vibrating system with $k_\phi = \infty$, n = 1 , $k_{top} = o$
   $T = 0.167\sqrt{\delta_{st}}$
4. Vibrating system with $k_\phi = \infty$, n = 2 , $k_{top}/k_{so} = 0.1$
   $T = 0.164\sqrt{\delta_{st}}$
5. Vibrating system with $k_\phi = \infty$, n = 2 , $k_{top}/k_{so} = 0.01$
   $T = 0.16\sqrt{\delta_{st}}$
6. Vibrating system with n = o , $k_s \frac{H}{k_\phi} = 0.4$
   $T = 0.174\sqrt{\delta_{st}}$
7. Vibrating system with n = o , $k_s \frac{H}{k_\phi} = 2{,}5$
   $T = 0.169\sqrt{\delta_{st}}$

8. Vibrating system with n = o , $k_S \frac{H}{k_\phi} = \infty$

$$T = 0.164\sqrt{\delta_{st}}$$

From the given values of the previous analysis, the relation period-displacement in the typical buildings, the following is adopted.

$$T\,[seg] = 0{,}17\ \sqrt{\delta_{st}\,[cm]} \qquad (2)$$

BUILDING DEFORMABILITY AND VIBRATION PERIOD

The type of construction used in Mendoza City is: reinforced concrete structure with inner and outer partitions of masonry of solid and / hollow bricks. The seismic horizontal forces are absorbed by the frame (columns and girders) and the shear concrete walls.

The mean height between stories is $H_p = 3$ m.

The set of loads originates a mean uniform load of q = 1100 kg/m^2, for each story of which 550 kg/m^2 correspond to the structure 400 kg/m^2 to partitions and 150 kg/m^2 to floor and ceiling.

The stiffness is assumed to be of shear type, and formed by the brick partitions, the shear concrete walls, the columns, and the box of the stairs and elevators. To the building deformability, the rocking effect must be added.

Now, the influence of each of these elements on the displacement and vibration period are analysed:

a) Brick walls influence:

Let **A** be the area of each story and A_w the area of an horizontal section of brick walls built in one definite direction, then $\Delta = A_w/A$ is defined as the wall area ratio. If G_w is the wall shear modulus, for the building with uniform characteristics for every story, the top displacement will be :

$$\delta_{st} = \frac{q\ H_P}{\Delta\ G_w}\ \frac{n(n+1)}{2}$$

Ex. Assuming:

$$G_w = 4500\ kg/cm^2\ (5°)\ (6°)\ , \qquad \Delta = 0{,}06$$

we have:

$$T = 0.042\sqrt{n(n+1)}$$

formula which is practically lineal with the n number of stories or / its equivalent, the total height of building, H.

b) Shear concrete walls influence:

If shear concrete walls are disposed so as to absorb the horizontal seismic forces, their influence on the deformability is a consecuence of the way they have been designed.

It will be assumed that the length of shear wall L is a constant throughout the whole building, while the thickness will vary according to the needs in the design. If for reasons of simplicity the seismic coefficient C and the stresses τ are kept constant for all levels and if, besides, it is assumed that the length L of shear walls is important enough to considerer the shear, with G_t modulus, preponderant on the deformation, then the top displacement will correspond to a variable wall area ratio linearly increasing as the levels are lesser, and

$$\delta_{st} = \frac{H_p \tau}{C\, G_t} n$$

is obtained,

and the period $T = 0{,}17 \sqrt{\frac{H_p \tau}{C G_t}} \sqrt{n}$

This formula shows that the period increases according the square root of the height, or its equivalent, the number of stories n.

c) Column and frame influence:

Let a system of columns disposed modularly according to a distance L_p in the considered direction and λL_p in the normal direction to that one.

Rectangular columns with the ratio of dimension β are assumed; these columns have been designed with a material of a Modulus E, only for the axial load with allowable stress σ. It is also assumed that the columns don't rotate at floor levels. In these conditions, the top displacement of the building with n stories is:

$$\delta_{st} = \frac{H_p}{\left(\frac{Eq}{\sigma^2}\right)\left(\frac{\lambda}{\beta}\right)\left(\frac{L_p}{H_p}\right)^2} \sum_{i=1}^{n} \frac{1}{i}$$

If the columns are design for an axial load and a moment produced by the seismic forces, with a relative excentricity $\varepsilon = \frac{e}{h} = C \frac{H_p}{2h}$ according to the column dimension h, a relative increase of the column section of a value ξ, is necessary

$$\varepsilon \sqrt{\xi} = C \frac{H_p}{2L} \sqrt{\frac{\sigma_b \beta}{q \lambda}}$$

For reasons of simplicity the seismic coefficient C is assumed constant at all levels.

On the other hand, the girders are not sufficiently stiff to avoid the rotation of the columns, and there is an increase of displacement as a result of this.

If R/R_b is the relative stiffness of the column at its bottom, and R/R_t at its top then the increase of displacement is: (7°)

$$r = 4 + 3\left[\frac{R}{R_t} - \frac{\left(1 + \frac{R}{R R_b}\right)^2}{1 + t_1\left(\frac{R}{R_t} + \frac{R}{R_b}\right)}\right]$$

changing the top displacement according to:

$$\delta_{st} = \frac{H_p r}{\left(\frac{Eq}{\sigma^2}\xi^2\right)\left(\frac{\lambda}{\beta}\right)\left(\frac{L_p}{H_p}\right)^2} \sum_{i=1}^{n} \frac{1}{i}$$

Ex. For:

$\beta = \lambda;\ \frac{L}{H_p} = 2{,}5;\ \sigma = 70\ kg/cm^2;\ q = 1{,}1\ t/m^2;\ c = 0{,}1;\ E = 2\times10^5\ kg/cm^2;\ \xi^2 = 5;\ \frac{R}{R_b} = \frac{R}{R_t} = 1;\ r = 2{,}5$

is obtained

$$T = 0.39 \sqrt{\sum_{i=1}^{n} \frac{1}{i}}$$

The variation of which with the number of stories is relatively small.

d) Rocking foundation influence:

The evaluation of the influence of the foundation is a great problem owing to the difficulty of simplifying the behavior of the soil (8o).

As it was previously established the rocking effect will be the only one considered, neglecting the effect of traslation.

In such a case δ_{st} is : $\delta_{st} = \dfrac{q H_p^2 (n+1)}{2 k_f \Delta f \rho^2}$

where:

$$\Delta f = \frac{Af}{A} = \frac{\text{foundation Area}}{\text{story Area}} = \text{foundation area ratio}$$

which may be :

1. proportional to the total wall area ratio of walls in contact with the foundation

   Ex. $\Delta f = 1,5 \Delta$

2. a function of the load on the foundation $\Delta f = \dfrac{nq}{\delta_t}$

where δ_t = soil stress used in foundation design

ρ = radius of gyration of plant area A

variable between 0.5 L and 0.29 L , where L is the length of the building in the direction considered.

k_f = coefficient of elastic non-uniform compression of the foundation.

$k_f \cong$ 2 to $2,5 \dfrac{E_t}{\sqrt{A}}$ for square and rectangular 1,2 foundation, respectively

E_t = Young's Modulus of Soil

Ex.

with $\Delta f = 0.20$, $\rho^2 = \dfrac{L^2}{8}$, L = 25 m. $\sqrt{A} = \dfrac{L_b}{\sqrt{2}}$; $E_t = 3\,t/cm^2$

$T = 0,015 \sqrt{n^2 (n+1)}$

is obtained.

The period vibration is proportional to the 3/2 power of the number of stories or its equivalent, the total height of the building.

If Δ_f is proportional to the number of stories, then the variation is almost lineal to the total height.

The foundation soil of the tested building is quite uniform: a layer or dry and compact silty clay of approximately 5 or 10 m. thick that rests on a thick layer of gravel.

Typical Building:

In the tested buildings the influence of brickwalls , shear walls, columns and rocking foundation are added, and according to the characteristics of each building, one or other will be preponderant in the determination of δ_{st} .

In order to estimate the variation of the period, according to the characteristics of the building, one typical model building will be considered.

This model building will include peculiarities which have been observed in buildings of the City of Mendoza.

This model building has a rectangular plant, the principal directions of which have the following characteristics:

I) Large brickwall panels forming the outer side walls which provide a high wall area ratio: $\Delta = 0{,}10$. Generally this is the longest direction.

II) In the normal direction to the latter, the building has a lesser wall area ratio $\Delta = 0.04$, the structure is formed by columns and girders, which practically receive all the vertical loads, which correspond to the seismic effect in that direction. On the ground floor there are no partitions.

As a consequence , the foundation area ratio becomes approximately:

$$\Delta_f = 1{,}5\Delta + 0{,}05\, n$$

The columns mentioned in II have influence on the stiffness of the direction expresed in I.

Applying the relation period-top displacement , and estimating each influence as it has been previously established.

$$T = 0{,}17 \sqrt{\frac{q H_p^2 n^2 (n+1)}{2 k_f \Delta_f \rho^2} + \frac{q H_p n (n+1)}{2 \Delta G_w}} \qquad (3)$$

is obtained for the direction I.

The values adopted are those previously mentioned , excepting $G_w =$ 8000 kg/cm^2 in order to considerer the influence of the concrete walls that form the stair cases and elevator boxes. Equation 3 has been plotted as a function of the total height of the building ($H = n\,Hp$) in fig. 5 .

For the direction II.

$$T = 0{,}17 \sqrt{\frac{q H_p^2 n^2 (n+1)}{2 k_f \Delta_f \rho^2} + \sum_{i=1}^{n} \frac{H_p}{\frac{\Delta G_w}{iq} + \left(\frac{E q \xi^2}{r \sigma^2}\right)\left(\frac{\lambda}{\beta}\right)\left(\frac{L_p}{H_p}\right)_i}} \qquad (4)$$

is obtained ,

where $L = 12$, $\sqrt{A} = \sqrt{2}\ L$ and $\frac{L_p}{H_p} = 2$

This equation is also plotted in fig. 5.

The plotting of fig. 5 shows that straight lines are the roughest representation of the relation period-building height of the adopted building model. These lines do not go through the origin.

As to the other variables, the influence of the wall area ratio and the horizontal dimension L through k_f and Δ , are the most outstanding.

These variables Δ and L have an influence proportional to the / power $-\frac{1}{2}$, on the period of the building, and one or other will be more important according to the relation of modulus E_t and G_w . Equation 3 and 4 of fig. 5 could have also been obtained , considering other / pairs of values of E_t and G_w .

The results of this model building will be kept in mind for the statistical analysis of experimental determinations.

STATISTICAL ANALYSIS

We previously selected the variables and their influence on the vibration period of the considered buildings, now it corresponds to establish the correlation between the experimental results and variables of significant influence, in a simple way.

The height H of all the tested buildings is known, whereas the dimension L and wall area ratio Δ is only known for some of them. To / overcome this obstacle , first a correlation T and H has been made and then the influence of others variables has been analysed.

For the correlation T and H , Equations (3) and (4) have been taken into account, adopting :

$$T = aH + b$$

as the empirical regression curve , and applying the method of least squares to determine the coefficients a and b (9°)

$$\Sigma\,(\text{error})^2 = \sum_{i=1}^{N} (T_i - a\,H_i - b)^2 \rightarrow \text{minimun}$$

$$\frac{\partial}{\partial a}\Sigma = 0 \quad ; \quad \frac{\partial}{\partial b}\Sigma = 0$$

for the 106 tested buildings, N = 212 and

$$T = 0.0143\ H + 0.044 \qquad (5)$$

is obtained.

The mean value of the system is :

$$T_m = 0,368 \text{ seg.}$$
$$H_m = 22,68 \text{ m.}$$

and the correlation coefficient:

$$\alpha = \frac{\Sigma(T-T_m)(H-H_m)}{\sqrt{\Sigma(T-T_m)^2\,\Sigma(H-H_m)^2}} = 0{,}92$$

which shows the strong lineal dependence of the period in relation to the height of the building.

Nevertheless, by inspecting fig. 5 , the dispersion of the //

measured periods is found to increase with the height ; this agrees // with what the curves (3) and (4) indicate.

So as to keep in mind the above consideration, the method of // weighted deviation from empirical regression curve has been used , and the linear correlation T , H , leads to

$$\sum_{i=1}^{n}\left(\frac{\text{error}}{H}\right)^2=\sum_{i=1}^{N}\left(\frac{T_i-aH_i-b}{H_i^2}\right)\rightarrow \text{minimun}$$

whence:

$$T = 0{,}0121\ H + 0{,}094 \qquad (6)$$

with a mean value of the system equal to :

T_m = 0,335 seg.

H_m = 20 m.

The weighted deviations from the regression T., H have been / // arranged according to their value and the cumulative distribution curve has been plotted in fig. 6.

This curve does not show symmetry , in other words, it is not a Gauss distribution.

In order to analize the presence of a dominant direction in the tested buildings, which might be the directions of the typical building, two sets of values have been made up: the first set, formed by the minor periods of each building, and the second, the set of the major periods of each building.

Applying the least square with the weighted distribution method to these sets (N = 106) .

for the minor periods

$$T = 0.0106\ H + 0.091 \qquad (7)$$

for the major periods

$$T = 0.0137\ H + 0.096 \qquad (8)$$

are obtained.

It is to be noted that the coefficients of (6) are the mean values of the coefficients of (7) and (8).

An indication of the influence of other variables, results from the analysis of the maximum weighted deviation values. For this purpose two sets have again been made up , each one containing 21 values: the first one with those that originate the 10% (0 - 0,1) of the cumulative distribution curve of fig. 6 ; and the other with those that originate the final 10% (0,9 - 1,0)of the same curve.

To each one of these sets, the least squares weighted method has been applied (N = 21) , and

for the first 10%

$$T = 0.0102\ H + 0,034 \qquad (9)$$

for the last 10%

$$T = 0,0178\ H + 0,098 \qquad (10)$$

are obtained as regression lines.

These two lines embraced the 90% of the determinations, and represent the grouping of extreme conditions of the variables which have not been considered.

Analyzing the characteristics of the direction of the building to which the above sets belong, certain peculiarities arrise, such as : for the first 10% there is an custanding dimension of a mean value of 33,6 m. with large panels of brickwalls forming the outer side walls , while for the last 10% , a minor dimension of a mean value of 13,6m. / appears , with no walls in that direction on the ground floor. In both cases there are stair cases and elevator boxes.

From this, the existance of foundation and building stiffness influence can be derived, in agreement with what is pointed out by equations (3) and (4) . As to the stiffness of the building, the brick / / wall panels without any interruption from top to bottom , have an custanding influence. This stiffness is added to the stiffness due to // stair cases, elevator boxes and columns.

Taking into account this conclusion.

$$T = H \sqrt{\frac{c}{L} + \frac{d}{1+30\Delta}}$$

is adopted as regression line, in which L is the length of the building in the considered direction, in meters, Δ is the wall area ratio of the panels which occur throughout the whole height H of the building and which are placed in the considered direction ; for the tested buildings $0 \leq \Delta \leq 0,06$; coefficient 30 is a consecuence of a previous correlation between the buildings represented by equations (9) and (10); c and d are coefficients to be determined by the least square method:

$$\sum_{i=1}^{N} \left(\frac{T^2}{H^2} - \frac{c}{L} - \frac{d}{1+30\Delta} \right)^2 \rightarrow \text{minimun}$$

whence , and for N = 90

$$T = H \sqrt{\frac{0.0031}{L} + \frac{0.00019}{1+30\Delta}} \qquad (11)$$

is obtained.

This is the correlation line which represents the experimental determinations. The amount of dispersion is given by

$$\sigma = \sqrt{\frac{\Sigma \left(T - H\sqrt{\frac{c}{L} + \frac{d}{1+30\Delta}}\right)^2}{N}} = 0,026$$

this dispersion is plotted in fig. 7.

For this same set of determinations ($N \doteq 90$) correlation analysis between T , H and T , H , L have been carried out in order to determine the improvement of adding or not another variable. The results are:

$$T = 0.0157\,H + 0.020 \quad ; \quad \sigma = 0.095$$

$$T = 0.068\,\frac{H}{\sqrt{L}} \quad ; \quad \sigma = 0.098$$

Equation (12) is similar to (5) which tells us that the set N = 90 // from which equation (12) was obtained, is a representative set of the total number of experimental determinations. The values of these dispersions show how the introduction of another variable improved the / correlation.

CONCLUSIONS:

The experimental determinations of the vibration period of 106 buildings in the city of Mendoza (Argentina) show that there exists an custanding influence produced by the height of the building, and also by the foundation and the stiffness of the building, itself.

The tested buildings are constructed of reinforced concrete structure with external and internal brickwall panel (of solid and hollow bricks) while H varies between 15 and 55 m.

Several formulas can be obtained by means of statistical analysis from experimental , according to the variables which are considered:

a) Height H , in meters.

$$T = 0.012\,H + 0.09$$

with the lines which embraced 90% of the determinations

$$T = 0.010\,H + 0.09$$

$$T = 0.018\,H + 0.10$$

plotted in fig. 3.

b) Height H , length of the building in the direction considerd L, in meters.

$$T = 0.07\,\frac{H}{\sqrt{L}}$$

c) Height H , length of the building L , and wall area ratio Δ adimentional, of the panel without interruption from top to bottom ,

$$T = H\sqrt{\frac{\quad}{L} + \frac{0.0002}{1+30\,\Delta}}$$ plotted in fig. 7

The dispersion is :

$$\sigma = 0{,}03$$

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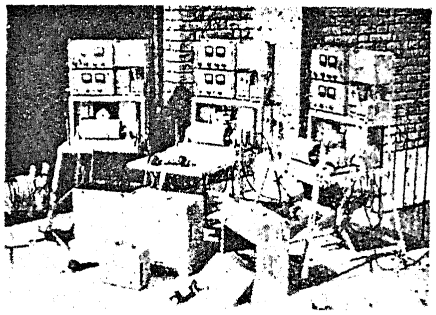

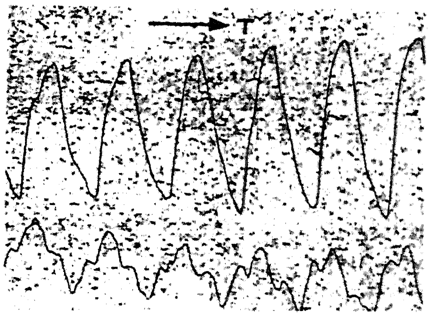

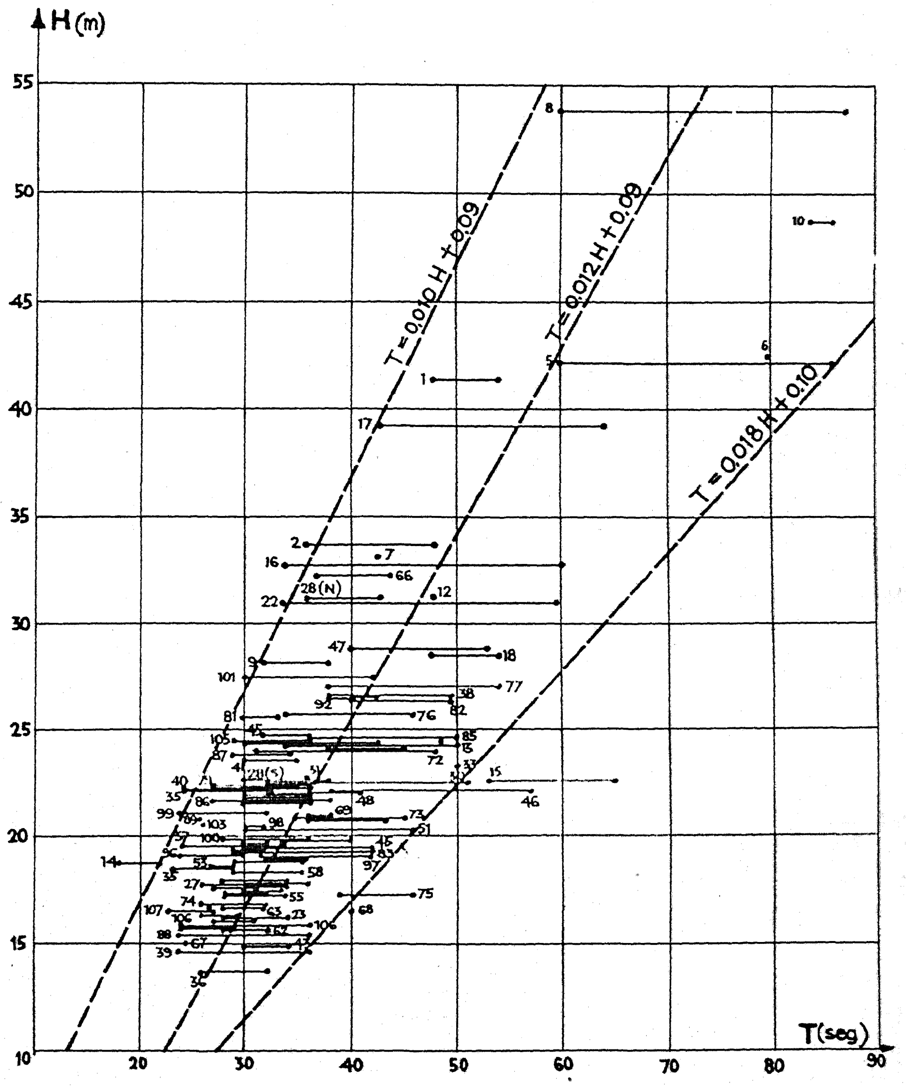

FIG. 3_ STATISTICAL ANALYSIS_CORRELATION T, H .

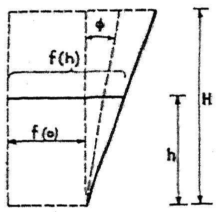

FIG. 4
VIBRATING SYSTEM

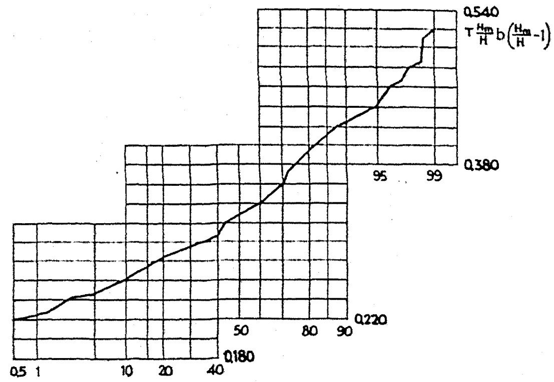

FIG. 6 _ STATISTICAL ANALYSIS _ CORRELATION T, H.
ACUMULATIVE DISTRIBUTION CURVE

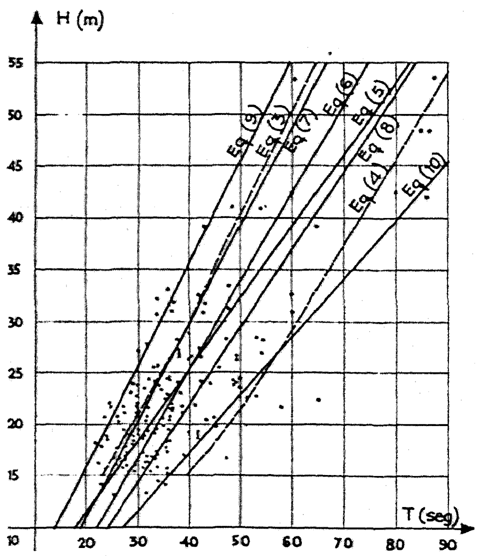

FIG. 5

STATISTICAL ANALYSIS
CORRELATION T, H.

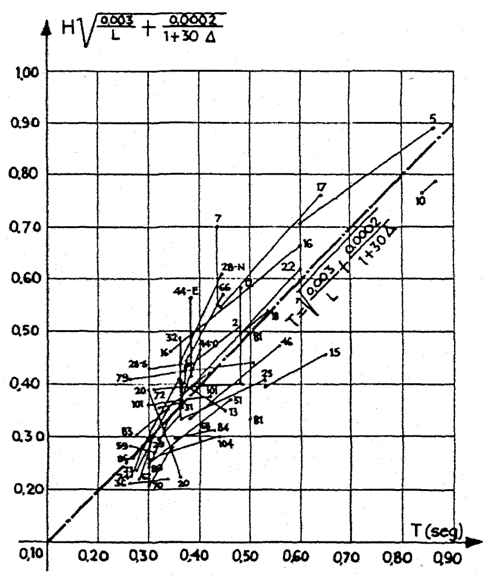

FIG. 7

STATISTICAL ANALYSIS
CORRELATION T, H, L, Δ.