EXPERIMENTAL RESULTS ON THE DYNAMIC DEFORMATION OF MULTI-STOREY BUILDINGS

H. Sandi(I), G. Şerbănescu(I)

Abstract

Results obtained on the basis of simultaneous recording of small intensity vibrations on full-scale multi-storey buildings, are presented. Statistical data have permitted to derive empirical formulae for flexural and torsional fundamental periods. The fundamental natural shapes presented a practically linear dependence on height. The simultaneous recording of horizontal displacements and slab rotations permitted to estimate the contributions of bending and shear distortions and of foundation compliance to the overall displacements and to the fundamental periods. Conventional values of the ground compliance factor were derived as functions of the foundation dimensions. These values satisfy scale conditions given by the continuum mechanics applied to the deformable half-space. The relative amplitude of horizontal vibrations have permitted to check the conventional eccentricities adopted for the design seismic forces.

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Synopsis

Simultaneous recording of small intensity vibrations on full-scale structures were performed in order to evaluate the contributions of various structure and ground distortions to the overall displacements and to the dynamic characteristics of multi-storey buildings. Theoretical aspects related to the microtremors and induced structural vibrations are discussed. Experimental techniques, results obtained, and conclusions referring to aseismic design are then presented.

1. Introduction

Multi-storey buildings with reinforced concrete shear walls have been currently built in Romania, as in other countries with extensive seismic areas, during last years. The aseismic design of such buildings is usually based on the linear theory of structural dynamics; seismic design forces are presented therefore in terms of the natural vibration periods and shapes of structures.

The analysis of normal modes of vibration is a quite difficult task, especially for complex multi-storey buildings with shear walls. It requires an evaluation of several parameters related to the dynamic deformability of structure and ground, for which poor information is generally available. The uncertainty of the assumptions on these parameters leads to the necessity of organizing full-scale experimental investigations, which are single capable to yield final results of satisfactory reliability and accuracy in this view.

The scope of full-scale investigations can be largely extended. It can be related not only to the analysis of natural periods and shapes, but also to the analysis of torsional effects, of the importance of foundation compliance, etc.

Full-scale dynamic tests on multi-storey buildings are not an easy task, because artificial high intensity vibrations of actual buildings can be excited only with considerable technical difficulties. Low intensity vibrations produced by the permanent ground motion provide therefore a very convenient possibility to avoid this kind of difficulties, especially for extensive research programs. Results obtained by such means are representative for the elastic behaviour of structures, i.e. for the basic assumptions adopted at present in design.

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Small intensity vibrations have been utilized to determine fundamental periods of buildings, in several countries, as the United States [11], Japan [4], [1o], Chile [1], etc.

At the Building Research Institute in Bucharest, a more complex program of experimental full-scale investigation of typical multi-storey buildings [8], [9], has been organized. The research program has been intended to furnish statistical data concerning:

- the fundamental periods and shapes for flexural and torsional vibrations;
- the dynamic deformability of the foundation system, and the ground compliance factor;
- the importance of dynamic torsional effects;
- specific features of the multi-storey buildings, as dynamic systems.

The scope of following paragraphs is related to some theoretical aspects of the vibration phenomenon, to the experimental techniques adopted throughout the program, to the results obtained, and to some conclusions, derived for the practical design of multi-storey buildings.

2. Stationary Small Intensity Vibrations of Structures

Small intensity ground movements (currently referred to as microtremors) induce in actual buidings a stationary process of vibrations. The irregular features of these vibrations involve the necessity of considering them as random vibrations. Spectral components of these stationary vibrations, having frequencies near the natural (especially the fundamental) frequencies, are strongly amplified by the structural dynamic system, which acts on the input motion as an attuned filter. For this reason, vibrations induced by microtremors (especially at the higher storeys of tall buildings)have well-marked dominant frequencies, which are in good agreement with the natural (especially fundamental) frequencies of buildings. The phenomenon can be theoretically explained by the theory of stationary vibrations with continuous energy spectrum [2], [7].

The structure will be assumed to have classical eigen-modes of vibration. In this case, the relative displacements of structure points to ground, will be represented by the vector U(t),

$$U(t) = \Sigma_r X_r q_r(t), \qquad (1)$$

where $\underline{r}$ denotes the index assigned to any natural mode,

X_r - the corresponding eigen-vector, and

q_r - the coordinates of the vector U(t), related to the base formed by the eigen-vectors.

The coordinates $q_r(t)$ are given by the expression

$$q_r(t) = \int_{-\infty}^{t} d_r(t-z)\, \ddot{u}_o(z)\, dz \qquad (2)$$

with

$$d_r(t) = - \frac{a_r}{\omega_r'} e^{-n_r \omega_r t} \sin \omega_r' t \qquad (3)$$

and

$$a_r = \frac{X_r^T M X_o}{X_r^T M X_r} \qquad (4)$$

where

X_r^T denotes the transposed eigen-vector X_r,

ω_r - the circular frequency of the r-th normal mode, $\omega_r' = \omega_r \sqrt{1-n_r^2}$

n_r - the fraction of critical damping in the r-th mode,

$\ddot{u}_o(t)$ - the ground acceleration,

M - the mass matrix,

X_o - the vector representing the rigid-body displacements of the structure, compatible with the unit static displacement on the ground motion direction.

The response of the structure to a random stationary input is also a random stationary motion, due to the fact that the damping is different from zero, for any normal mode. The power spectral densities [2] of the input $\ddot{u}_o(t)$ and of the coordinate $q_r(t)$ satisfy in this case the relation

$$S(q_r;\omega) = \frac{a_r^2}{\omega_r^4} \frac{1}{\left(1 - \frac{\omega^2}{\omega_r^2}\right)^2 + 4\, n_r^2 \frac{\omega^2}{\omega_r^2}} S(\ddot{u}_o;\omega) \qquad (5)$$

Cross-densities of the normal coordinates can be assumed to equal zero, due to the weak cross-correlations of $q_r(t)$.

In case of a rather uniform spectral power density of the input $\ddot{u}_o(t)$ in vicinity of a value $\omega = \omega_r$, the power spectral density of the coordinate $q_r(t)$ will vary practically proportionally with the dynamic factor occurring in the right member of (5), i.e. in case of low structural damping, the dependence of q_r on time will be quite similar to a sine-function. The analysis of microtremor accelerograms shows that the power spectral densities of such motions varies slowly indeed for frequencies near the natural frequencies of current buildings; it results therefore that, for each mode of vibration, the building motion is not very different from resonant vibrations.

In view of the small importance of non-diagonal terms of the power spectral density tensor of normal coordinates, the power spectral density of the displacement u(t) at any point of the structure, may be expressed by means of the diagonal terms of that tensor,

$$S(u;\omega) \cong \Sigma_r\, x_r^2\, S(q_r;\omega) \qquad (6)$$

where x_r represents the component of the eigen-vector X_r, at the point dealt with.

For tall buildings, the sequence a_r generally decreases rapidly, while the sequence ω_r increases rapidly. It follows that, for the upper points of such buildings (where the fundamental mode has the most important contribution) only the first term in the relation (6) is to be taken into account practically: the motion of the upper points of the structure is little different from a sine-function motion with a period which equals the fundamental period of the building. This fact gives the possibility of evaluating the fundamental periods of buildings, for different kinds of vibrations, by analyzing the records of corresponding motions, obtained at the upper points of those. Simultaneous records of motions at different points of buildings give the possiblity of determining, in a similar way, the normal shapes for horizontal (flexural), vertical, or torsional vibrations.

An example of rather complete set of records of various kinds of motions is given in fig. 1. Such record sets provide data for detailed analyses of structural behaviour.

3. Dynamic Deformability of Tall Buildings

In order to analyze the dynamic deformability of tall buildings, structures can be usefully reduced in mind to dynamically symmetric cantilever beams, elastically fixed in the ground [3]. The overall displacements of idealized structures result in this case from the following types of distortions:

- structural distortions:
  a. vertical elongation,
  b. pure bending distortion,
  c. pure shear distortion,
  d. torsional distortion;
- ground distortions (displacements at the base level):
  e. vertical translation,
  f. tilting (rotation in a vertical plane),
  g. horizontal translation,
  h. rotation in the horizontal plane.

Vertical vibrations are due to distortions a and e, horizontal (bending-shearing) vibrations are due to distortions b, c, f, g, occurring in any principal vibration plane of the building, while torsional vibrations are due to distortions d and h.

If a building is imagined to execute sinusoidal vibrations corresponding to any fundamental normal mode, one can evaluate with satisfactory accuracy the stiffness characteristics of structure and ground from the ratios of top and base amplitudes and from the motion frequency. This facts gives the possibility of determining structural characteristics on experimental basis. Following relations can be adopted in this view:

a. Vertical Vibrations

The structure is reduced to continuous, constant cross-section bar, for which top and base vertical amplitudes (u_n and u_o) and corresponding circular frequencies ω_v are available.

The ground stiffness modulus for vertical translations will be

$$C_z A_f = \frac{Q}{g} \omega_v^2 \frac{\sqrt{\left(\frac{u_n}{u_o}\right)^2 - 1}}{\arccos \frac{u_o}{u_n}} \qquad (7)$$

The stiffness modulus of structural cross section will be

$$E A = \frac{Q}{g} \omega_v^2 \frac{H}{\left(\arccos \frac{u_o}{u_n}\right)^2} \qquad (8)$$

where:

Q is the total weight of the building,
H - its height
A_f - the area of building foundation,
C_z - the conventional soil stiffness for vertical translations,
g - the acceleration of gravity.

b. Torsional Vibrations

The structure is reduced to a continuous, constant closed cross-section bar, for which top and base rotatory amplitudes (I) (ψ_n and ψ_o) and corresponding circular frequencies ω_t are available.

The ground stiffness modulus for rotatory displacements will be

$$C_\psi I_{of} = \frac{J_o}{g} \omega_t^2 \frac{\sqrt{\left(\frac{\psi_n}{\psi_o}\right)^2 - 1}}{\arccos \frac{\psi_o}{\psi_n}} \qquad (9)$$

The stiffness modulus of structural cross section will be

$$G I_t = \frac{J_o}{g} \omega_t^2 \frac{H}{\left(\arccos \frac{\psi_o}{\psi_n}\right)^2} \qquad (10)$$

where:

J_o is the second order moment of dead loads with respect to the vertical axis of the structure,
I_{of} - the polar moment of inertia of the foundation area,
C_ψ - the conventional soil stiffness for horizontal rotations,

(I) Buildings with weak exterior walls should be reduced to thin-wall open cross section bars.

c. Combined Bending-Shearing Vibrations

The structure is reduced to a continuous, constant cross section bar, for which top and base linear (v_n and v_o) and tilting (φ_n and φ_o) amplitudes, as well as circular frequencies ω_h are available. According to experimental data, the amplitudes of linear and tilting displacements are assumed to have a linear dependence on height, when deriving inertia forces.

The linear amplitudes will be assumed the expression

$$u(z) \cong u_o \frac{H-z}{H} + u_n \frac{z}{H} \tag{11}$$

which leads, for distributed inertia foces, to the expression

$$f(z) \cong f_o \frac{H-z}{H} + f_n \frac{z}{H} \tag{12}$$

The effects of rotatory inertia will be neglected for fundamental vibration modes.

The hypotheses adopted lead to the conclusion that the rotatory amplitude φ_o is due to ground compliance only (ground stiffness modulus $C_\varphi A_f$), while the difference $\varphi_n - \varphi_o$ is due to pure structural bending. Similarly, the amplitude v_o will be due to ground compliance only (ground stiffness modulus $C_x a_f$), while the difference $v_n - v_o$ will be due to the additional effects of foundation tilting, flexural distortion, and shearing distortion of the structure.

The ground stiffness modulus for tilting displacements will be

$$C_\varphi I_f = \frac{Q H}{g} \omega_h^2 \frac{v_n}{3 \varphi_o} \left(1 + \frac{v_o}{2 v_n}\right) \cong \frac{Q H}{g} \omega_h^2 \frac{v_n}{3 \varphi_o} \tag{13}$$

The ground stiffness modulus for horizontal translations will be

$$C_x A_f = \frac{Q}{g} \omega_h^2 \frac{v_n}{2 v_o} \left(1 + \frac{v_o}{v_n}\right) \cong \frac{Q}{g} \omega_h^2 \frac{v_n}{2 v_o} \tag{14}$$

The bending stiffness modulus of structural cross section will be

$$E\,I = \frac{Q H^2}{g} \omega_h^2 \frac{v_n}{8(\varphi_n - \varphi_o)} \left(1 + \frac{v_o}{3 v_n}\right) \cong \frac{Q H^2}{g} \omega_h^2 \frac{v_n}{8(\varphi_n - \varphi_o)} \tag{15}$$

The shearing stiffness modulus of the same section will be

$$\frac{G A}{k} = \frac{Q H}{g} \omega_h^2 \frac{v_n}{3 (v_n - v_o)_s} \left(1 + \frac{v_o}{2 v_n}\right) \cong \frac{Q H}{g} \omega_h^2 \frac{v_n}{3 (v_n - v_o)_s} \tag{16}$$

The difference of linear amplitudes corresponding to shear distortions, $(v_n - v_o)_s$ can be evaluated from

$$(v_n - v_o)_s = v_n - v_o - (v_n - v_o)_M - \varphi_o H \tag{17}$$

where the term corresponding to pure bending will be

$$(v_n - v_o)_M = \frac{11}{15} H (\varphi_n - \varphi_o) \left(1 + \frac{4 v_o}{11 v_n}\right) \cong \frac{11}{15} H (\varphi_n - \varphi_o) \tag{18}$$

The sense of parameters occurring in relations (13)-(16) is clear from previous cases, a. and b.

4. Experimental Techniques

The measuring and recording equipment, used for the experimental analysis of small intensity·vibrations, must satisfy, beside general technical conditions referring to precision, limitation of distortions, mechanical resistance, etc., two main specific conditions:

- high sensitivity, satisfactory for linear vibration amplitudes of the order 10^{-7} m.,
- adaptibility for combined measurements, in order to permit .rect recording of relative displacements, rotations, relative rotat-.ons, etc.

At present, the seismometric apparatus used in this view, must ave electro-magnetic components, which are indispensable for assuring e necessary sensitivity and recording accuracy. The electro-magnetic components could be based on active or passive transducers. The solution with active transducers (based on permanent magnets), although less free from linear frequency distortions, has the advantages of easy handling, mechanical resistance, absence of noise, and practically illimited possibilities of electrically combining several signals, with reduced distortions. Such remarkable qualities recommend it for extensive use in this field.

In the Building Research Institute, measurements of microtremor vibrations were performed with VEGIK seismometers (active transducers, nominal period for horizontal measurements about 1 sec., electro-magnetic damping of about 70% critical). Two magneto-electric oscillographs POB 12M, 6 channels each, equipped with GB III galvanometers, were used for recording [6]. The maximum amplification of the system was 3200.

For natural frequencies measurements, one single seismometer, located at the top level of the building, has been used every time. For the analysis of fundamental natural shapes and of structural deformability, several seismometers, located at different points, were simultaneously used. Relative displacements and angular vibrations have been measured with coupled seismometers, connected in series, so that each seismometer was in opposite phase with its pair. The ratios of impedances of transducers, conductors, and oscillographs had values which permitted to assume, with sufficient reliability, that the electrical series connection would furnish, when recording, sums or differences respectively, of local amplitudes, corresponding to the seismometers locations.

As an illustrative example, fig. 2 presents the various configurations of seismometer locations, adopted for obtaining, on a 12 storey building (with two symmetrically disposed staircases), the set of records presented in fig. 1. The basic configurations shown in the figure offered the capability of recording: simultaneous horizontal displacements in transverse or longitudinal planes, displacements and rotations at base and roof levels in the same planes, simultaneous slab rotations in vertical planes or in the horizontal one (torsional vibrations), vertical displacements of building axis at the ground and roof levels, simultaneous vertical displacements on one of the building staircases.

Natural frequencies of buildings have been obtained from recordings, as dominant frequencies of the vibratory motions, fundamental natural shapes have been derived by comparing simultaneously recorded amplitudes, while the contributions of the various types of distortions to the linear roof displacements, as well as the corresponding stiffness moduli, have been evaluated by means of the relations (7)-(18), previously presented.

5. Experimental Results

The research program has included more than 5o multi-storey R.C. buildings. For all these buildings, the fundamental periods for bending-shearing vibrations, corresponding to the main vibration planes, have been determined. 2o buildings have been investigated by means of the more complex techniques, described previously. For latter ones, fundamental shapes, relative contributions of different distortions to the linear amplitudes, and values of the conventional ground stiffness factor C_φ, have been also determined.

The fundamental periods of vibration presented values between o.2 and o.7 seconds for practically all investigated buildings. For any structural type, these values are well correlated with the total number of storeys (with a relatively low dispersion of results). Fig. 3 presents a plot of fundamental periods against the number of storeys, for horizontal vibrations in both main planes, as well as for torsional vibrations. Periods of vibrations are obviously smaller for the longitudinal plane than for the transverse one. Torsional periods are currently located between the two previous kinds of periods, excepted for tower-like buildings with almost square horizontal section and stiff external walls, for which they are smaller than periods corresponding to translatory vibrations. Long buildings, with parts separated by joints, present systematically two dominant periods for torsional vibrations. This fact points out a dynamic interaction between the parts of the buildings, separated by joints.

The normalized fundamental shapes derived from experimental data have shown, for all types of vibration (bending-shearing, torsional, vertical), a practically linear variation over the whole building height, as it can be seen in fig. 4. Significant deviation from the linear variation becomes apparent only for flexible structures with height-to-width ratio greater than 2.5, for which pure bending distortions are especially important. Natural torsional shapes are related to significant slab deplanations, in most cases. This fact shows that the assumption of closed cross section does not hold for current buildings (exception, tower-like structures with strong external walls) and that, for more refined analysis, buildings should be reduced to vertical bars with thin walls and open cross section, especially for cases of weak, fragmented, external walls.

The amplitudes of torsional vibrations presented comparatively important values, although almost all buildings were symmetrical. The amplitudes of horizontal displacements on transverse direction, due to torsional vibrations, reaches, at the front walls of long buildings, up to 4o or 5o% of the amplitudes of horizontal displacements on the same direction, due to bending-shearing vibrations. The importance of torsional vibrations is obviously increased for buildings with weak front walls.

The contributions of several types of distortions, for bending-shearing vibrations, evaluated by means of the relations (7)-(18), are plotted in fig. 5, for longitudinal (left) and transverse vibration planes of some buildings. It can be remarked that, in each case, the contributions of pure bending, pure shearing and foundation tilting are comparable. Pure bending distortion becomes important especially for tall, flexible buildings, while pure shearing distortion is important especially in the longitudinal vibration plane. Foundation compliance cannot be neglected in any case.

The stiffness factor for tilting ground distortion, C_φ, has been evaluated by assuming that the whole area enclosed by the building borderings contributes to the tilting stiffness. The results obtained in this way, pointed out a strong variation of the conventional values C_φ, for different building dimensions, even in cases of practically invariable ground conditions. Fig. 6 presents the values derived for C_φ, as a function of the foundation dimension B (which corresponds with the vibration plane). It must be remarked that experimental results agree with scale conditions given by similarity criteria applied to the half-space deformation.

6. Conclusions for Aseismic Design

Results obtained during the research program are sufficiently accurate and systematic to be considered as representative for the dynamic behaviour of multi-storey buildings subjected to moderate stresses[I]. Some conclusions can be pointed out for practical aseismic design on this basis.

a. Fundamental vibration periods for usual types of buildings with R.C. shear walls can be rapidly evaluated as a function of the total number of storeys, n, by means of the simplified relations (for transverse and longitudinal planes)

$$T_{tr} = (0.045 \ldots 0.055)n \quad (19)$$

$$T_{lg} = (0.035 \ldots 0.040)n \quad (20)$$

which agree rather well with the results presented in fig. 3. The numerical values of the expressions (19) and (2o) are to be taken at their minimum for structures with relatively frequent shear walls and at their maximum for structures with relatively rare shear walls, which co-operate with more flexible structural elements.

(I) Some full-scale tests of the authors [5] have shown weak changes of structural characteristics within the elastic range.

For tower-like structures with shear walls, another relation is recommendable for each of the main vibration planes,

$$T = 0.065 \frac{H}{\sqrt{B}} \qquad (21)$$

(where H denotes the building height and B its horizontal dimension in the vibration plane, both lengthes being measured in m.).

The formulae for fundamental periods agree rather well with computational evaluations and with experimental results of other authors, [8]. They should be used for rapid checking, even in cases when more refined methods of analysis are adopted.

b. Fundamental natural shapes of buildings up to 15 storeys should be assumed to vary linearly with height, for deriving the distribution of conventional seismic forces. For the aseismic design of these buildings, it is reasonable to consider only the fundamental mode. For structures with a greater total number of storeys, an increased number of modes should be considered in practical design.

c. Torsional effects should be considered in the aseismic design even for symmetric buildings. Experimental data obtained from microtremor records pointed out these effects. If a similarity of spectral compositions of microtremors and strong earthquakes is accepted, the relative importance of torsional effects should be the same, because the wave propagation velocity is practically the same in both cases .

The analysis of experimental results leads to the conclusion that for buildings with front walls of the same stiffness as the inner walls, an eccentricity of 5% of the building horizontal dimension in the longitudinal plane covers practical design needs. This result agrees with code requirements [12]. For buildings with particularly weak front walls, and with rigid inner walls, this conventional eccentricity should be increased to about 7%.

d. Foundation compliance has always an important contribution to the overall displacements of the structure and it must be considered in the analysis of structural characteristics, simultaneously with bending and shearing distortions.

For computation needs, it is reasonable to adopt a simplified scheme, in which the actual contact surface between building and ground should be replaced by the full area enclosed by the exterior borders of foundation. It is also reasonable to adopt, for the conventional factor C_φ, values depending on the ground quality. Scale effects,which are well pointed out in fig. 6, should be considered by means of the simple relation

$$C_\varphi (tf./m.^3) = \frac{A}{B(m.)} \qquad (22)$$

where the factor A should be assigned values in dependence of the soil nature, while B represents the horizontal dimension of the building, in the vibration plane dealt with. A numerical value A = 80,000 is to be recommended for ground conditions similar to those existing at the sites of buildings dealt with (a 3-4 m. deep clay layer, over a 2o-3o m. deep sand and gravel layer). For different ground conditions, the values of A should be changed proportionally to the soil rigidity modulus in uniform compression.

The research program presented in the paper gives an outlook on the dynamic deformation of tall buildings with shear walls. Similar techniques could be applied to other types of structures, in order to get useful information for their aseismic design. The use of possibilities furnished by the stationary small-intensity vibrations due to microtremors may be a recommendable method for extensive research programs concerning any type of structures.

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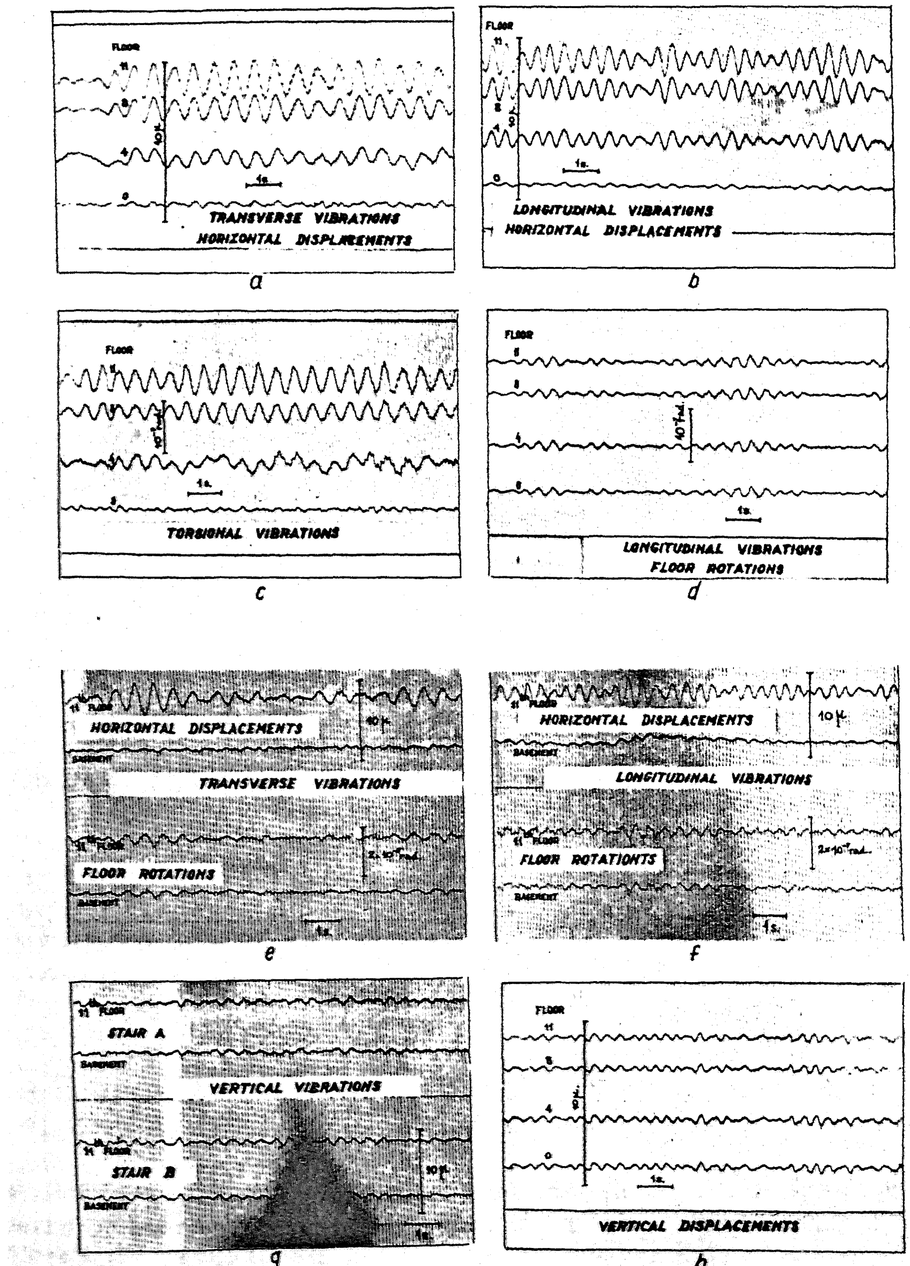


Fig. 1 - TRANSLATORY – ROTATORY AND TORSIONAL VIBRATIONS OF A 12-STOREY R.C. BUILDING PRODUCED BY MICROTREMOR DISTURBANCE

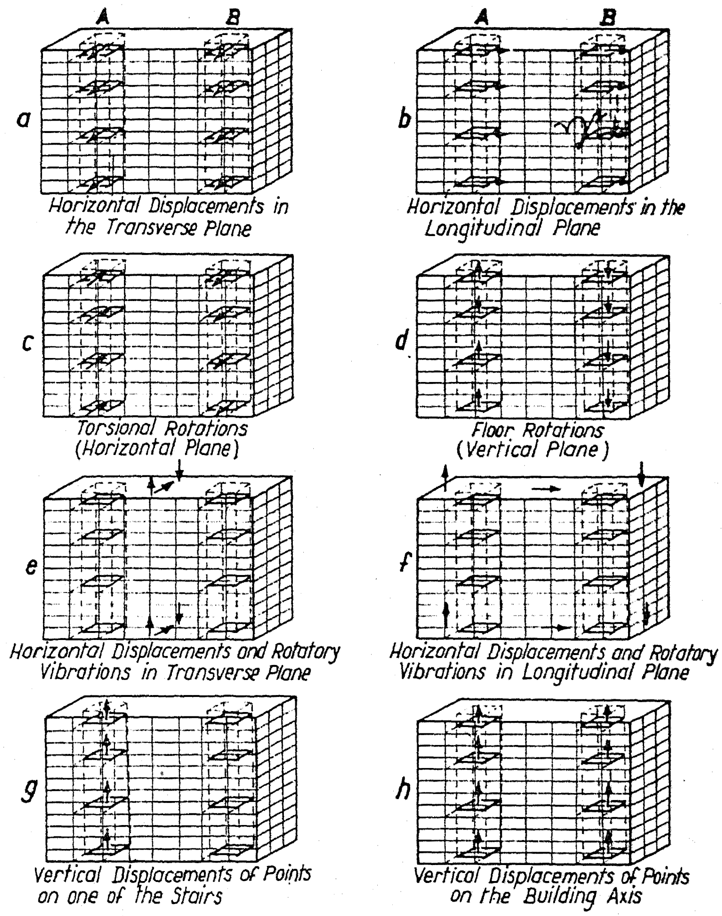
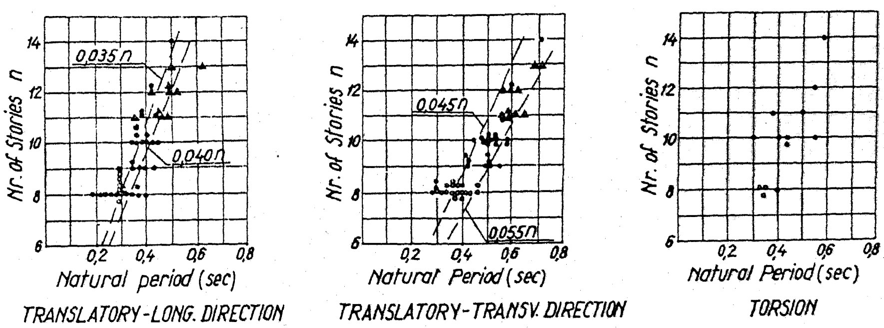


Fig.2 - BASIC CONFIGURATIONS OF DISPLACEMENT MEASUREMENTS AT A 12-STOREY BUILDING



KEY: • -Panel Buildings
▲ -Tower-Like Buildings With Shear Walls
• -Long Buildings With Shear Walls

Fig. 3 - FUNDAMENTAL PERIODS OF VIBRATION MEASURED AT MULTISTOREY R.C. BUILDINGS

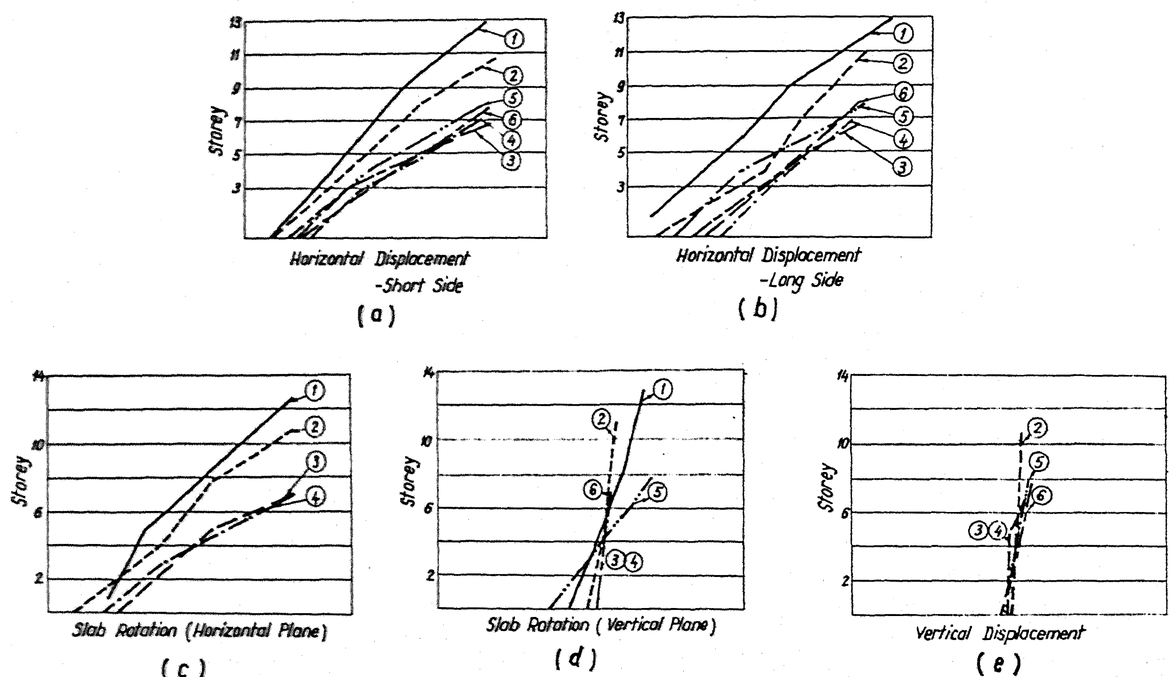


Fig. 4 - CHARACTERISTIC SHAPES FOR SIX REINFORCED CONCRETE MULTISTOREY BUILDINGS
a, b, e - TRANSLATORY VIBRATIONS
c - TORSIONAL VIBRATIONS
d - ROTATORY VIBRATIONS
(Conventional Units)

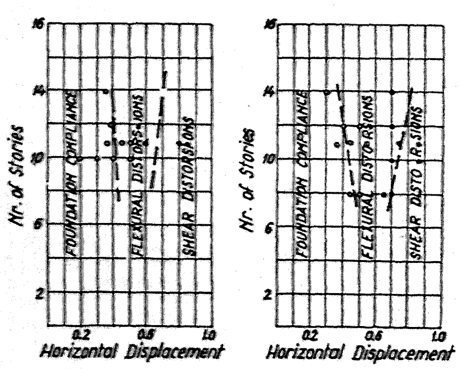


Fig. 5 - RELATIVE INFLUENCE OF DIFFERENT TYPES OF DISTORSIONS ON THE TOP HORIZONTAL DISPLACEMENT FOR SEVERAL R.C. BUILDINGS

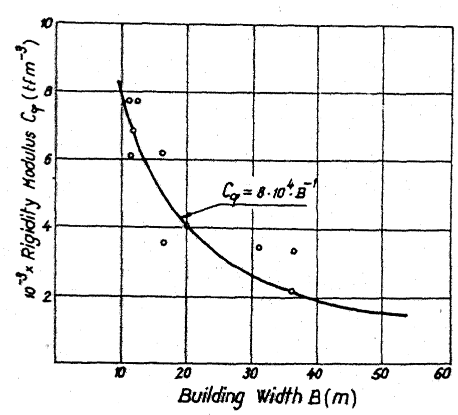


Fig. 6 - SCALE EFFECT FOR THE ROTATORY (TILTING) RIGIDITY OF GROUND