VIBRATION ANALYSIS OF BUILDINGS WITH CONSIDERATION FOR THE IN-PLANE DEFORMATION OF FLOOR SLABS

by

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SYNOPSIS

The vibration characteristics of buildings with long and narrow plans are influenced by the in-plane deformation of floor slabs. In the paper, soil-structure interaction is analyzed by using two-dimensionally distributed multi-mass models in order to obtain the effective factors for in-plane deformation of slabs. Eigenvalues and response values of soil-structure systems are computed and discussed on the cases where a partial basement is laid at different positions in the whole plan of building, where the soil formation under the site has a dislocation or consists of duplicated bias layers, and where the shape of floor plan is complicated. The relations between the maximum response and the direction of ground motion are also investigated.

INTRODUCTION

The vibration problem of buildings is generally analyzed under the assumption that the floor slabs show no deformation in their own plane. In the case of the buildings with long and narrow floor plans, however, the above assumption may not be applied. The authors have ascertained that the floors deform due to ground motion particularly in low-rise buildings through the microtremor tests of buildings(1) and the observation of the behavior of a building during an earthquake.

In previous papers(2∿4) by the authors, the dynamic behaviors of the low-rise buildings with some series of typical long and narrow plans were analyzed under the conditions that the floor slabs were deformable in-plane and the columns were fixed at the bases, and the relations between the characteristics of vibration and the structural conditions such as the distribution of stiffness of the elements (columns,walls and slabs) and the shape of plan or front view of the building were discussed.

In the present paper, the effects of soil conditions on the in-plane deformation of floor slabs are discussed. The analysis of interaction between structure and soil is carried out with the two-dimensionally distributed multi-mass system.

SOIL-STRUCTURE INTERACTION SYSTEM

When the building with a rectangular floor plan has a basement in a part of the plan as shown in Fig.1(a), the soil-structure system can be idealized by replacement with a multi-mass system which is arranged in the vertical and horizontal directions shown in Fig.1(b). In other words, the masses of the building in every floor are replaced by discrete masses at the frames in the direction of short sides 'Y' in Fig.1(a). The lateral stiffness of the horizontal members is calculated from bending-shear stiffness of slabs with beams along the edges of floors. The equivalent stiffness of columns may be given by shear stiffness of frames and walls when the building is relatively low. The masses of the soil prisms are lumped at discrete points distributed in the same conception as the mass system of the building. The rectangular prism of soil presumed for extent of soil where the soil-structure interaction will be effective. Stiffness of the linkages connecting the adjacent masses of soil is obtained from the shear stiffness of soil.

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Each of the masses of the building on the foundation level is connected to the adjacent mass of soil on the same level by spring of sway. Each mass of the basement on the ground level is joined to the adjacent mass of soil with spring by which dynamic soil pressure on basement-walls is replaced. The bases of the columns are supported with rotation springs.

As for vibration system in the direction of 'X', to simplify the analysis of the vibration, it may be assumed that each distance between every two adjacent masses does not vary and that the displacement caused by rotation is extremely small, and thus, the one-dimensionally distributed multi-mass system without rotation spring as shown in Fig.1(c) may be used. The vertical displacement of masses is not taken up in the paper.

MODELS FOR NUMERICAL COMPUTATION

The prototype building for numerical computation is a three-story reinforced concrete structure without a basement and is formed into a rectangular floor plan with one bay by eight bays shown Fig.2. The standard soil condition in this discussion is of two soil layers, where the upper layer is 3.5m deep and of Vs=100m/sec, the lower layer is 20m deep and of Vs=200 m/sec. The variations of the soil-structure-interaction models consist of three models with basements and three models with irregular soil conditions as shown in Fig.3. The spring constant of soil, K, in the multi-mass system is given according to the well-known equation $K=A\cdot\rho\cdot V_S^2/d$, where A = area of the boundary plane between two adjacent soil prisms which are divided to correspond to masses, ρ = density of soil, V_S = velocity of S wave, d = distance between adjacent masses.

Eigenvalues of these models are calculated as undamped systems. Participation factors are calculated for uniform input force in direction of 'X' or 'Y'. Dynamic response is computed with modal analysis by using the eigenvalues, the participation factors and shear-force coefficient response spectrum of single-degree-of-freedom system that is assumed to be constant $q=1$,i.e. white noise, regardless of natural periods of the interaction systems.

RESULTS AND DISCUSSION

(1) Vibration of the buildings with basements

The examples of the normal modes of buildings are shown in Fig.4. In this figure, the modes on the levels of GF, 1F, 2F and 3F (cf. Fig.1) in the buildings are projected on a horizontal plane and the modes along the vertical axis of a frame are shown. The low order modes of the ground surface, G0,and the underground, G1, are quite small.

The effective response displacement, $_e\delta$, of the buildings with the basements is much different from that of the building without basement,"B0", particularly on upper floors. The effective response displacement or $_e\delta$ means the relative response displacement between the top and the bottom of columns with the exclusion of the displacement produced by rocking. As is evident from Fig.5, $_e\delta$ of the model "B8" with the same basement plan as the ground floor plan decreases to about two-thirds at the end columns in the top story, and to about a half at the center column in comparison with those of "B0". In the case of "B2e" with two bays of basement at the end of the building or "B2c" with two bays of basement at the center, the distribution of $_e\delta$ is extremely uneven and the value of $_e\delta$ of a column above the basement is the maximum in every story.

The further analysis was attempted on the response of the building with a basement by varying continuously three parameters : area of basement, position of basement on building plans and in-plane stiffness of slabs in all floors. The dynamic behavior of the building with a partial basement may be concluded as follows. The effective displacement of the columns in these buildings is larger than that of "B8" and smaller than that of "BO". The distribution of the effective displacement in each story of these buildings is more uneven than that of "BO" or "B8". In particular, the effective displacement of a column above the basements is the largest in the same story. This tendency becomes more obvious as the stiffness of floor slabs is smaller and the floor level is more upper. The effect of the area or the position of basement is not quite remarkable.

(2) Vibration of the buildings on duplicated bias layers or dislocation

In the case of the buildings on the duplicated bias layers such as "S1" or "S2", torsional effect is observed on the natural modes and response values. The additional in-plane deformation of floor slabs due to the inclination of layers is scarcely found, because the depth from the ground surface to the boundary surface between two layers are varied continuously and linearly along the 'X' axis. Torsional effect occurs more severely as the stiffness of layers are larger, therefore the response values of the building "S2" on inclined layers with large stiffness are asymmetrically distributed and the maximum effective displacement is larger than that of "BO" with symmetrical soil condition as shown in Fig.6.

In the case of the building "S3" on dislocated soil, the deformation of floor slabs and torsional vibration are brought about owing to discontinuous stiffness of soil as shown in Fig.6. The distribution shapes of response values on all floors are similar. The general validity of this behavior was confirmed from the analysis of the buildings on various soils with the variation of three factors: the stiffness ratio of floor slabs between the variation models and the prototype model, k , the velocity ratio between the soils, v $(=V_2/V_1)$, and the quantified value of position of dislocation, e $(=l/L)$, which are shown in Fig.7(a). This figure shows the relation of r to k and e at v=8.0, where r is the maximum value of the ratio of $_e\bar{\delta}$ to $_e\bar{\delta}_0$ in each soil condition. The value of $_e\bar{\delta}_0$ is the effective displacement calculated under the assumption that floor slabs are fully rigid in-plane. The value of $_e\bar{\delta}$ equals the value subtracted the in-plane deflection of floor slabs of "BO" on the uniform soil from the effective displacement of each model with dislocated soil. The ratio r takes a maximum value when the range of k is from about 0.5 to about 2 in any position of dislocation. The ratio r becomes a maximum by about 1.3 when the dislocation is under the center of the plan (e=0.5) and becomes a minimum by about 0.2 when e=0.25∿0.5. The maximum value or the minimum value of r is found in the end column of each building. The larger the soil velocity ratio v is, the larger the deformation of floor slabs is, as shown Fig.7(b). If v is smaller than 2, it can be permitted to neglect the existence of dislocation for estimating the deformation of floor slabs on design, because r is about 0.9∿1.1 to any value of k or e at v=2. Generally the ditribution curve of response values is convex, and the response values above the dislocation are relatively small in the same story.

(3) Vibration of the buildings with wings

Fig.8 illustrates the several normal modes of the buildings with "L", "U", or "Z" shape of floor plan and with the frames similar to "BO". Although the distribution of stiffness and masses in these buildings are uniform except the vicinity of corners and ends, the in-plane deformations of floor slabs are observed clearly as shown in Fig.9. Those deformations must appear more clearly when wall or basement is located partially.
All the response values, $_e\delta$, of these buildings to the ground motion in the

direction of 'X' or 'Y' are affected by the in-plane deformation of slabs. Even though the center of rigidity and the center of gravity fall into the same point, the response values appear in both the directions parallel and perpendicular to the direction of ground motion.

Taking the incident angle, θ , of ground motion to the axis 'X' as argument, the response displacement of a column in a direction with angle of α to the principal axis 'x' of the column-section against a constant intensity of ground motion, which is taken as radius vector, describes a closed curve in the polar co-ordinates. This curve is given the name of "response influence line to θ " in this paper. In the similar way, taking the angle, α , between the direction of response displacement and the principal axis 'x' as argument and the response displacement of a column in the same direction as radius vector, the obtained curve is given the name of " response influence line to α ".

In Fig.10, the response influence line to θ at $\alpha = 0°$ and $90°$ calculated on the end column of a one-storied building with the L-shaped floor plan are illustrated as the examples. It can be observed that the maximum response values in the direction of the principal axis 'x' or 'y' of column-section is caused by the ground motion in the direction inclined to the axis 'X' (='x'). Fig.10 shows also that the response influence lines are completely different from those in the analysis under the assumption of rigid floor slabs whether or not the torsional effect is taken into consideration.

The envelope curve obtained from the response influence lines to α at $\theta = 0° \sim 180°$ expresses the maximum response values in all the directions in column-section. Fig.11 indicates the envelope curve derived on the same column as in Fig.10. As is evident from Fig.11, as to the end column of the building, the maximum response value appears nearly on the axis 'x', and as to the column at the corner of the plan, the maximum value appears in the direction of 135° to the axis 'x' and is about one and half times the amount of that in the axis 'x' or 'y'.

A four-story school—building of reinforced concrete was heavily destroyed in Hakodate City by TOKACHIOKI earthquake of 1968, though the other reinforced concrete buildings in the same area suffered a little or no damage. The destroyed building had a long and narrow plan of open L-shape. The other school building of three stories which is one of non-damaged buildings, has a rectangular plan and is located nearly perpedicular to that of the destroyed building as shown in Fig.12. The normal modes of the destroyed building are shown in Fig.13. The risk rates, which are obtained as the ratios of the response value to the ultimate resistibility in all the directions of column sections, are compare between the buildings. If the direction of ground motion was in the region of $-5°$ to $40°$ to the axis of the long wing of the destroyed building, this building could be collasped in earlier time than non- dameged building. If the direction of ground motion were in the region of $45°$ to $160°$, however, the risk rate of the latter could be higher than that of the former. According as these results, the cause why only the former building was collasped should be in contingency of the direction of ground motion. This view point seems to be an important facet to investigate the damages of buildings by an earthquake.

CONCLUSIONS

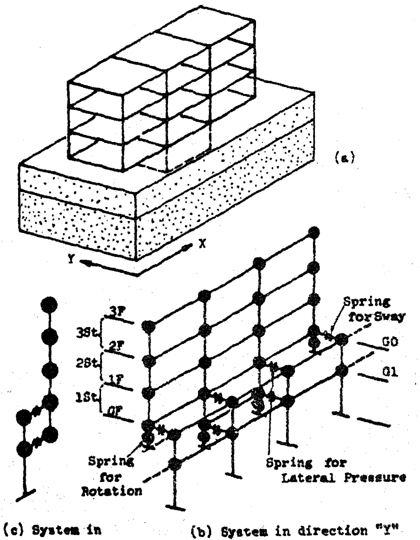
Numerical analysis of soil-structure systems for buildings with long and narrow floor plan were carried out by using two-dimensionally distributed multi-mass models in consideration of the in-plane deformation of floor slabs. From the results of the investigation, the following conclusions may be deduced as to the vibration characteristics of the buildings with long and narrow plans.

1. The existance of basement generally yields the decrease of the response value. When the basement is laid partially in the whole plan, however, the response values of the columns in a floor are not uniformly distributed and the maximum value of them appears in the range above the basement on each floor almost independently of the partial occupation area against the whole floor plan and the layout of the basement.
2. When a building is constructed on the soil with a dislocation or duplicated bias layers, the distribution of the response values of columns on each floor is uneven with torsional effect. The in-plane deformation of slabs is observed more obviously as the distance between the dislocation and the center of the floor plan is smaller, and the defference of stiffness between the soils separated by the dislocation is larger.
3. In general, the maximum response value of columns is rarely produced by the input force in the directin of the principal axes of column section, therefore the response analysis should be performed in all anticipative direction of ground motion so as to obtain the maximum response value.

REFERENCES

(1) O.Joh,K.Minamide,"Dynamic Behavior of a School Building by Measurement of Microtremor",Transaction of A.I.J.,1970 (in Japanese)

(2∿4) O.Joh,K.Ohno,et al.,"Vibration Analysis of Buildings with Consideration for the In-Plane Deformation of Floor Slabs ——
——Effect of Frame Stiffness Distribution on Dynamic Behavior", Trans.of A.I.J.,1969 (in Japanese)
——Effect of Various Distribution Patterns of Stiffness in Slabs and Various Shapes of Front-View of Building on Dynamic Behavior",Trans.of A.I.J.,1971 (in Japanese)
——Dynamic Behavior with Complex Shapes of Floor Plans",Trans. of A.I.J.,1973 (in Japanese)



(c) System in direction "X"   (b) System in direction "Y"

Fig.1 The interaction model of the building and soil with the idealized multi-mass systems.

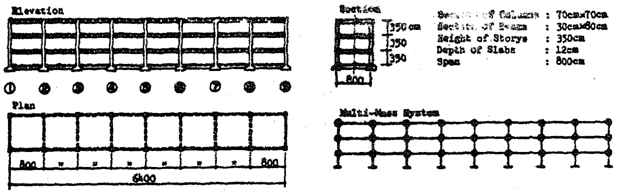


Fig.2 Dimensions of the structure of the prototype building.

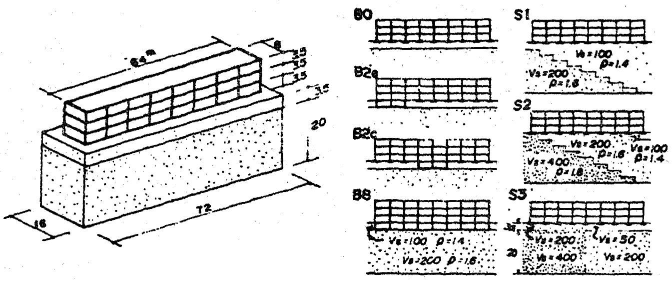


Fig.3 The types of buildings and soils for analysis.

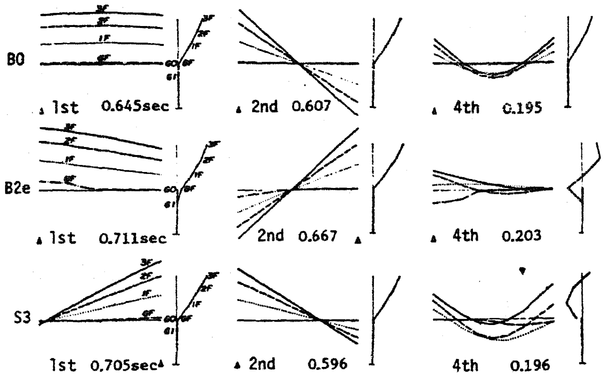


Fig.4 Normal modes.

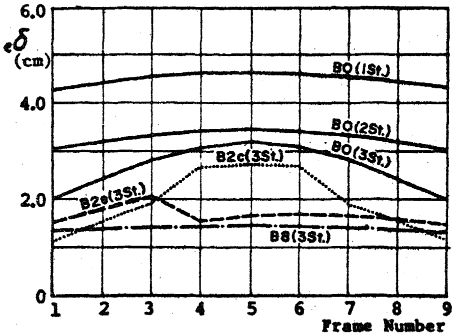


Fig.5 Effect of the location of basements on effective response displacement of columns.

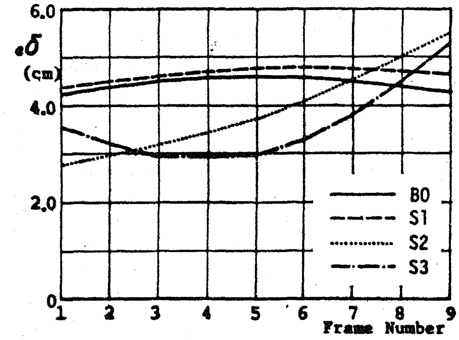


Fig.6 Effect of the soil conditions on effective response displacement of columns.

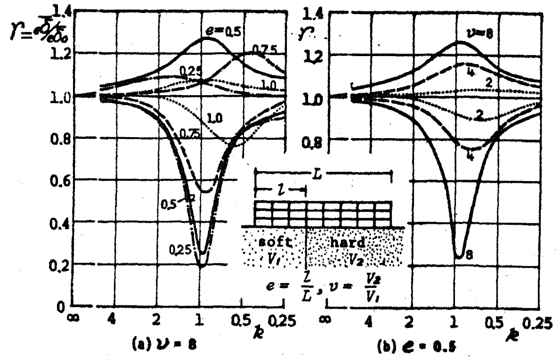


Fig.7 Effect of the dislocation on the in-plane deformation of floor slabs.

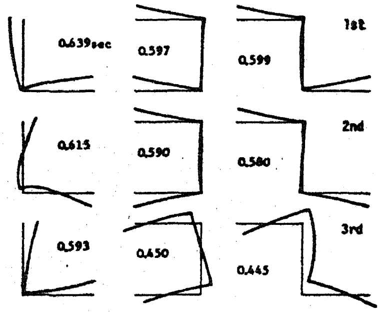


Fig.8 Normal modes of the buildings with wings.

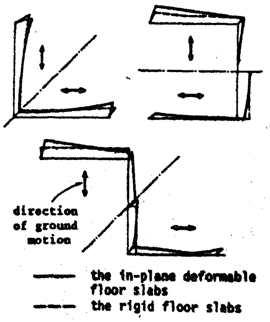


Fig.9 Effective response displacement.

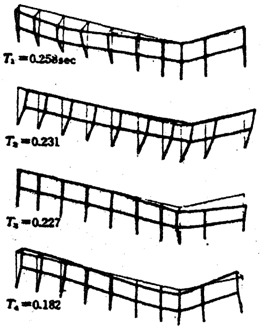
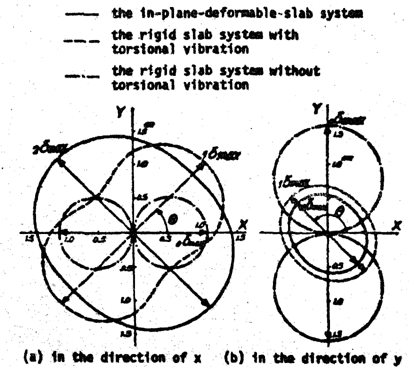


Fig.13 Normal modes of the destroyed building



(a) in the direction of x (b) in the direction of y

Fig.10 Response influence lines to θ in the direction of x and y.

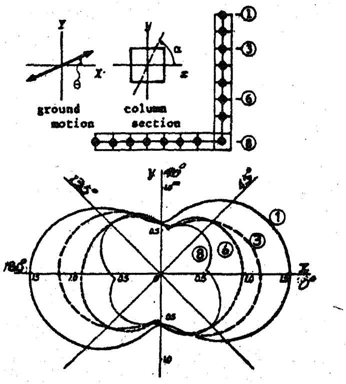


Fig.11 Envelope curves of response influence lines to α.

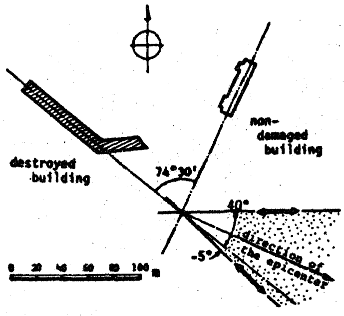


Fig.12 The location of the buildings