EFFECT OF PHASE DIFFERENCES ON THE DYNAMIC BEHAVIOR OF LARGE-SCALE APARTMENT HOUSES

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SUMMARY

In Japan, large-scale apartment houses are as long as 100m. For such large buildings, during earthquakes the characteristics of the input ground motion at the foundation may vary along the length of the building. The resulting phase differences in the ground motion may case torsional motion of the structures. Conventional structural design methods usually only consider vertical ground motion, and not torsional motion. Therefore, the effect of phase differences on the dynamic behavior of structures must be considered and new structural design methods developed.

To obtain a more rational structural design method, we modeled the behavior of apartment buildings built by the Japanese Housing and Urban Development Corporation (HUDC), accounting for the phase difference effect. We modeled large-scale apartment buildings by using a two-dimensional frame model with swaying and rocking springs and with dash pots connected to the foundation. We varied two main parameters: (i) the length of the building and (ii) the associated springs and dash pots used to represent the ground response. We assumed that the SH-waves input ground motion propagated with constant velocity along the longitudinal direction (i.e., oblique incidence of SH-waves). We then compared numerical results with and without the phase differences.

The numerical comparisons show that the phase difference effect becomes increasingly significant as the length of the building increases, especially for buildings on soft ground. The numerical results also provide insight into the phase-difference effects that can be incorporated in the structural design of large-scale apartment buildings.

INTRODUCTION

In Japan, multi-dimensional earthquake ground motion and multi-dimensional building response is studied extensively in the field of earthquake engineering [4]. To date, earthquake-resistant designs have included this effect. Because the coupling between the ground motion and the building response is very complicated for buildings whose length exceeds 100m, however, conventional structural design methods have not considered torsional motion of structures.

For seismic design of apartment buildings built by HUDC, bending & shearing or equivalent shearing vibration models shown in Fig.1(a) are used. These models therefore to not account for torsional motion of structures, and include the following assumptions:

i) In-plane floor is very rigid.

ii) Ground input along the length of the foundation is vertically incident and independent of location.

However, HUDC has built many long apartment buildings, for which more appropriate assumptions are as follows:

i) In-plane floor deformation is not negligible.

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ii) Ground input is not independent of location.

For large-scale buildings without eccentricity, the flexibility of long slabs increases as the length increases, thus increasing the floor deformation, which in turn amplifies the in-plane floor vibration. The purpose of this study was to simulate the dynamic behavior of large-scale apartment building considering in-plane floor vibration.

IN-PLANE FLOOR VIBRATION AND INPUT PHASE DIFFERENCE

The vibratory mode shapes in large-scale buildings are shown in Fig. 2. These shapes are called the i^{th} translation mode along the vertical direction of the building and the j^{th} slab mode along the in-plane floor direction. As shown in the right column of Fig. 3, the main in-plane floor vibration for the dynamic behavior of large-scale buildings is thought to be an arch-shaped vibration mode when the response at the center of building increases, and is thought to be a torsional vibration mode with in-plane floor deformation (referred to as "1^{st} slab vibration mode") when the response at the end of building increases. To properly represent these vibration modes, either a 2-D frame model similar to that shown in Fig. 1(b) or a 3-D model is required.
The cause of torsional vibration with in-plane floor deformation in buildings with no eccentricity is thought to result from phase differences in the input ground motion. In a broad sense, the input phase difference is related to the difference in input to the foundation and that to the rest of the building. To quantitatively evaluate the effect of torsional vibrations combined with in-plane floor deformation, for an input wave of constant magnitude and frequency (see Fig. 4), in this study we assumed a time difference of the input motion along the length of the foundation. The relation between the angle of incidence, θ, and the apparent velocity, C, can be expressed as:

$$C = Ve/\sin\theta \tag{1}$$

where Ve is equivalent shear wave velocity in the soil. The antisymmetric vibration mode of the buildings shown in Fig. 5 corresponds to the effect of phase differences in the input (referred to as "antisymmetric phase input"). It is thought that for the large-scale buildings, the wave length of the input ground motion, λ, is about twice the length of the building [1]. Therefore, the apparent velocity that affects the 1^{st} slab vibration mode can be written as:

$$C = \lambda/T_{11} = 2L/T_{11} \tag{2}$$

where T_{11} is the period of the antisymmetric vibration mode of the building. On the other hand, an arch-shaped vibration mode occurs even if buildings without eccentricity are subjected to a vertically incident wave (referred to as "synchronized phase input"). Therefore, these effects are not negligible for evaluating the seismic characteristics of the large-scale buildings.

NUMERICAL SIMULATIONS

Numerical Method

The numerical model we developed is a 2-D frame model with swaying and rocking springs and with dash pots connected to the foundation (see Fig. 1(b)). A linear stiffness response model is used. We developed two different analytical models. The first model assumes a rigid floor and is thus referred to as "rigid floor model", and the second model assumes in-plane floor deformation and is thus referred to as "non-rigid floor model". The constraints of the nodal point are that translation of the transverse direction and rotation along the longitudinal and vertical axes are free; other degrees of freedom are fixed.
The BCJ-L2 waveform (earthquake ground motion proposed by the Building Center of Japan) was used for the input motion (Fig. 6). The acceleration response spectrum of this wave is flat in the principal zone of the wave period. Using the BCJ-L2 waveform, we did a response analysis for both synchronized and antisymmetric phase input.
We evaluated the effect of the 1^{st} slab vibration by calculating the ratio of the shear force at the end of building during antisymmetric phase input determined by using the non-rigid floor model to the shear force in the center of building during synchronized phase input determined by using the rigid floor model. In this study, this shear force ratio closely corresponds to the maximum possible shear ratio, because the simulations were made under conditions where the 1^{st} slab vibration showed maximum increase. That is, we used a phase difference input such that the antisymmetric vibration mode excited both the building and the soil.

For synchronized input, we evaluated the effect of the arch-shaped vibration by calculating the ratio of the shear force at the center of the building for a non-rigid floor model to the shear force for a rigid floor model.

Numerical Conditions

For the numerical simulations we modeled a typical HUDC apartment building that was 88.0m long, 30.0m high, and 8.0m deep. This building was 11 stories high, had side corridors, had a core at the center, and showed no eccentricity in the transverse direction. We used the three different subsoil models shown in Table 1. According to the "Guidelines for Design Procedure of Apartment Houses of HUDC," we simulated swaying and rocking springs and dash pots in the foundation [2]. Associated with the soil springs, we considered an average degrading ratio of the shear modulus, shown in Table 1. We simulated 14 case studies, summarized in Table 2, for various building lengths, widths, longitudinal spans, and soil conditions.

RESULTS

Numerical results for the eigenvalue analysis

The comparison of the natural period determined from the eigenvalue analysis (Table 3) shows that the differences between the natural period (T_{10}) at the 1st translation and the 0th slab modes (referred to as the "1st translation mode") are relatively small, and that the differences between the natural period (T_{11}) at the 1st translation mode and the 1st slab mode (referred to as the "1st slab mode") increased as the length of the building increased. The relation between the length of the building and T_{11}/T_{10} (Fig. 7) shows that T_{11}/T_{10} is only weakly affected by the condition of the building and the soil.

Numerical results for the study of 1st slab vibration

Figure 8 shows the relationship between the non-dimensional frequency and the ratio of the first-floor shear force at the end of the building for rigid and non-rigid floor models. The significant results of this study can be summarized as follows.

a) Adjacency of the translational and the torsional modes

The natural period at the torsional vibration mode increases as the length of the building increases, and the natural period at the translational and the torsional modes adjoins. Therefore, the predominant frequency zone significantly overlaps each of these modes, and the effect of the phase difference input increases as the length of the building become increases (Fig. 9).

b) Soil structure interaction existing rigid foundation

For a rigid foundation on soft ground, the effect of phase differences input is suppressed due to the resistance effect of the rigid foundation. But the effect of phase differences input increases in large-scale buildings because the in-plane floor stiffness of the foundation is small relative to the standard buildings.

c) Compulsory displacement for the foundation

If the ground is relatively hard, the stiffness of the foundation becomes small relative to the ground. In this case, the resistance of the foundation is small compared with that of the soil. If the 1st slab vibration mode is amplified, the effect of the phase-difference input increases as the length of the building decreases because the input of the torsional component increases (Fig. 10). This is classified as the type 2 pattern shown in Fig. 8, accounting for the condition of the soil and the length of the building.

1st tendency: Subsoil is soft and/or the building is long

The effect of the 1st slab vibration mode increases as the subsoil becomes soft and/or the length of the building become large because effects a) and b) become important.

2nd tendency: Subsoil is hard and/or length of the building is short

The effect of the 1st slab vibration mode increases as the subsoil becomes hard and/or the length of the building becomes short because effect c) becomes important. In addition, the angle of incidence used to excite the 1st slab vibration must be relatively large compared with the angle of incidence required to excite the 1st slab vibration when the subsoil is soft and the building is long. Therefore, the probability of the 2nd tendency occurring is relatively small.

Numerical results for the arch-shaped vibration

Figure 11 shows the relationship between the length of the building and the ratio of the first floor shear force at the center of the building for rigid and non-rigid floor models. The figure shows that the ratio of the shear force is about 1.25, independent of the length of the building.

PROPOSED EVALUATION PROCEDURE

Proposed evaluation procedure

We propose the following procedure for evaluating the seismic characteristics of large-scale buildings, considering in-plane floor vibrations.

(1) Create an evaluation flow chart

Seismic design of large-scale buildings is made according to the evaluation flow chart shown in Fig. 12, and the ultimate horizontal resistance force in each story must not be lower than a maximum allowed horizontal resistance force shown in the figure. When length of the building is less than 80 m and the length:width aspect ratio is less than 5:1, then the effect of in-plane floor vibration can be neglected because the rigidity of in-plane floor is assumed to very large.

(2) Evaluate the predominant period at the 1st slab vibration mode

The period of the 1st slab vibration mode is calculated from Fig. 2, which is determined from eignvalue analysis (Fig. 7). Usually the period of the 1st translation mode is calculated by using eigenvalue analysis with a reduction model as the single mass-spring model (see Fig. 1(a)).

(3) Evaluate the equivalent shear wave velocity

The equivalent shear wave velocity is evaluated for the average of the weighted mean thickness of the layer to the base rock. In addition, the effect of degrading shear modulus subjected to strong earthquake motion is evaluated for multiple initial shear wave velocities by degrading ratio of shear modulus according to the level of soil strain.

(4) Evaluate the angle of incidence exciting the 1st slab vibration mode

The angle of incidence exciting the 1st slab vibration mode is calculated as:

$$C = 2L/T_{11} \qquad (3)$$
$$\theta = \sin^{-1}(Ve/C) \qquad (4)$$

where C is the apparent velocity exciting the 1st slab vibration mode, θ is the angle of incidence exciting the 1st slab vibration mode, L is the length of the building, T_{11} is the natural period of 1st slab vibration mode, and Ve is the equivalent shear wave velocity of the soil. The possibility of the occurrence of the 1st slab vibration mode is determined from the calculated angle of incidence.

Generally, the angle of incidence of earthquakes is about 5 to 10 degrees. Takenaka et al. [6] showed that for earthquakes propagated horizontally along the surface of rocks at Vs=3km/s in the Kanto area of Japan, the angle of incidence at Vs=0.7km/s was about 14 degrees. Accordingly, the procedure described only needs to be applicable to angles of incidence less than 20 degrees.

(5) Determine the increment in the necessary ultimate horizontal resistant force for the 1st slab vibration mode

We propose that the necessary ultimate horizontal resistant force in the transverse direction increases for the 1st slab vibration and/or arch-shaped vibration modes when the angle of incidence is less than 20 degrees. Figure14 is established that relaxing to ratio of shear force shown in Fig.8 is exchanged to increment of ultimate horizontal resistant force. Furthermore, the 2nd tendency shown in Fig. 8 is negligible because it corresponds to an angle of incidence larger than 20 degrees, and this probably only occurs on bedrock. In this case, the minimum increment of the necessary ultimate horizontal resistant force determined from step 6 is 1.1, because the effect of the arch-shaped vibration mode is not negligible.

(6) Increment of the necessary ultimate horizontal resistant force for the arch-shaped vibration mode

It is unlikely that an angle of incidence exciting the 1st slab vibration mode is greater then 20 degrees. But, the arch-shaped vibration mode probably is excited for all angles of incidence. Therefore, we propose that the necessary ultimate horizontal resistance force in the transverse direction be increased by 10% to account for the arch-shaped vibration mode.

Sample application of the proposed procedure

Here is an example of how the procedure is used. Here, we consider two subsoils shown in Fig. 15 for a building whose plan view is shown in Fig.16. The period of the 1st translation mode is 0.6 sec.

(1) $T_{11}/T_{10} = 0.82$ for L = 100 m for the building shown in Fig. 2. Accordingly, the natural period of the 1st slab vibration mode is 0.492 sec.

(2) The degrading ratio of the shear modulus (G/Go) is 0.7, so that the equivalent shear wave velocity of the soil is calculated as

Subsoil A) $Ve = \sqrt{0.7} \times (100\times15 + 150\times25)/40 = 109.8$ m/s

Subsoil B) $Ve = \sqrt{0.7} \times (150\times10 + 250\times20)/30 = 181.3$ m/s

(3) The apparent velocity exciting the 1st slab vibration mode is calculated from equation (3) as

$C = 2L/T_{11} = 2\times100/0.492 = 406.5$ m/s

The angle of incidence exciting the 1st slab mode is calculated from equation (4) as

Subsoil A) $\theta = \sin^{-1}(Ve/C) = \sin^{-1}(109.8/406.5) = 15.67°$

Subsoil B) $\theta = \sin^{-1}(Ve/C) = \sin^{-1}(181.3/406.5) = 26.49°$

As mentioned above, the necessity of considering the effect of the 1st slab vibration mode increases as the equivalent shear wave velocity of the soil decreases, because the angle of incidence exciting the 1st slab vibration mode decreases.

(4) In subsoil A, the necessary ultimate horizontal resistant force increases for the 1st slab vibration mode because the angle of incidence is smaller than 20 degrees. The necessary ultimate horizontal resistant force is increased by 19% (see Fig. 17), and thus the non-dimensional frequency is calculated as

$(\Omega_{11}\times L/Ve)\times(L_1/B) = (12.77\times100/109/8)\times5/8 = 7.27$

(5) In subsoil B, the necessary ultimate horizontal resistant force increases by 10% for the 1st slab vibration mode, because the angle of incidence is greater than 20 degrees.

CONCLUSIONS

1. We developed a numerical model for quantitatively evaluating the effect of in-plane floor vibrations on the dynamic behavior of large-scale buildings.
2. We made a numerical study of the behavior of large-scale apartment buildings subjected to oblique incident waves. From our simulations we conclude that:
   a) The natural periods of in-plane floor vibrations increase as the length of the building increases.
   b) The effect of the 1st slab vibration increases as the length of the building increases, especially for buildings on soft ground.
   c) The effects of arch-shaped vibration are not negligible.
3. We propose that the evaluation procedure for determining the seismic characteristics of large-scale buildings include in-plane floor vibration. This proposal provides insight into the effects of in-plane floor vibrations that can be incorporated into the structural design practice for large buildings.

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3) "*Structural Performances under Multi-Dimensional Earthquake Ground Motions"*, Architectural institute of Japan, 1998 (in Japanese).
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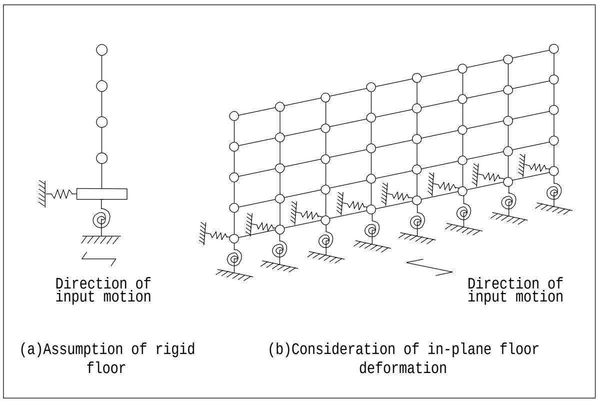

Figure1: Models for apartment houses of HUDC

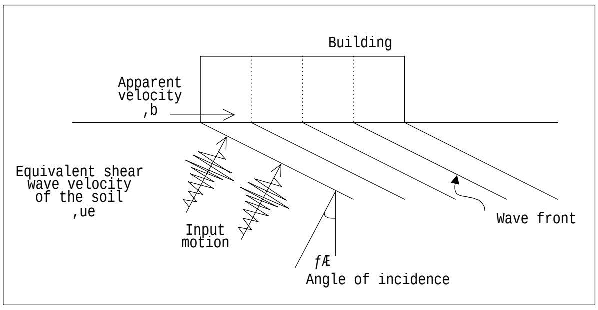

Figure4: Oblique incidence of SH waves

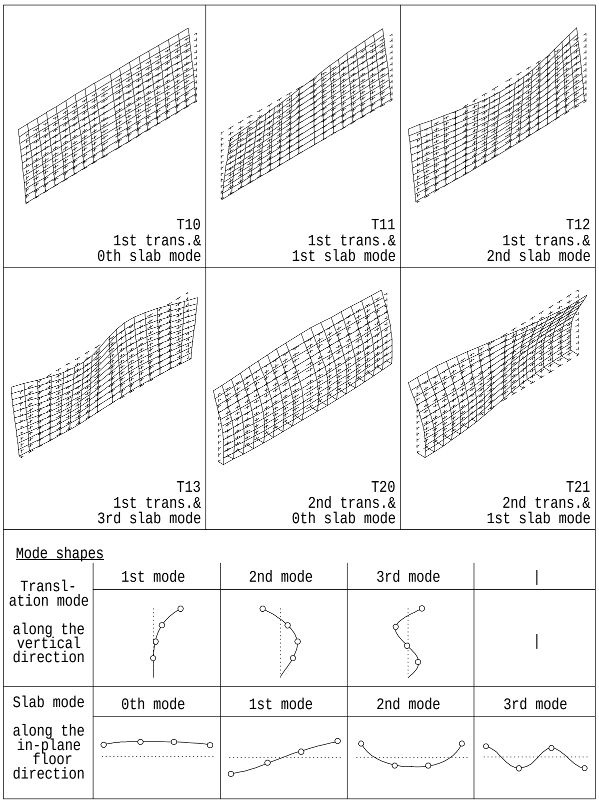

Figure2: Vibratory mode shapes

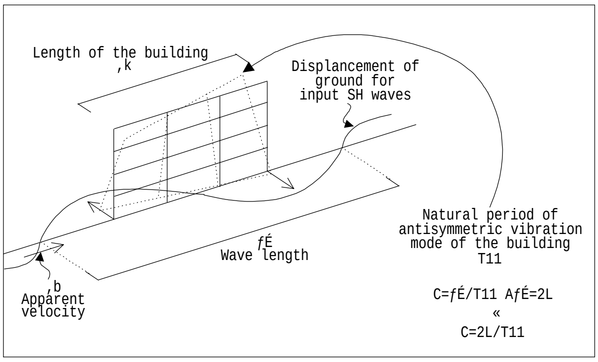

Figure5: Conditions for Excitation of 1st slab vibration mode

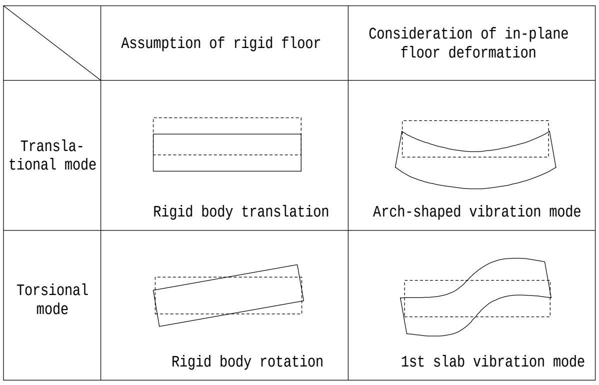

Figure3: Mode shapes of in-plane floor deformation

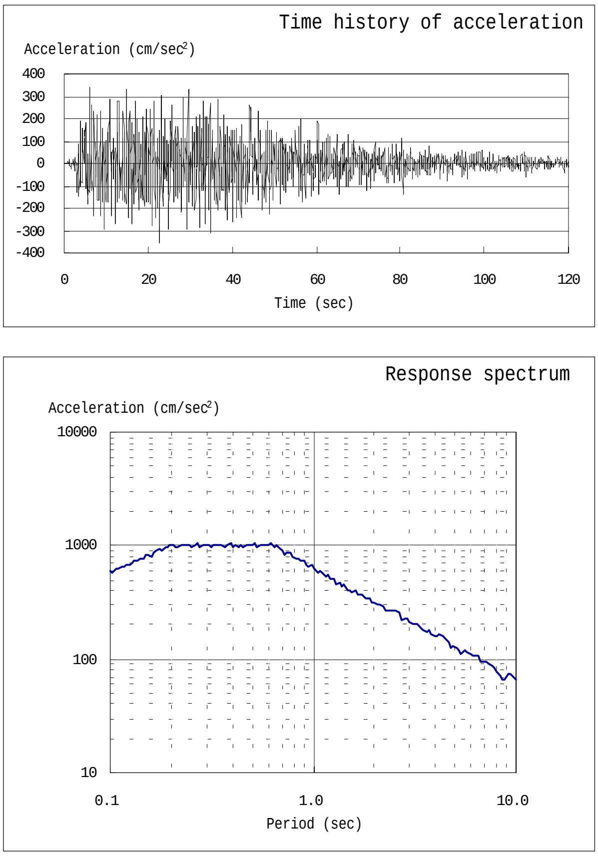

Figure6: Time history of acceleration and response spectrum of BCJ-L2 wave

Table1: Models for subsoil

(a) Model for subsoil-1

Depth (m)	Thickness of layer (m)	Soil type	Density ρ (t/m3)	Initial shear wave velocity Vso (m/sec)	Degrading ratio of shear modulus G/G0
0.0	1.0	Surface	1.6	100	0.8
-1.0	2.0	Loam	1.8	150	
-3.0	6.0	Loam	1.8	150	
-9.0	3.0	Gravel	1.8	300	
-12.0	13.0	Fine sand	1.8	200	
-25.0	—	Base rock	1.8	500	—

(b) Model for subsoil-2

0.0	2.0	Back fill	1.6	100	0.7
-3.0	3.0	Back fill	1.6	100	
-6.0	10.0	Clay	1.8	130	
-16.0	6.0	Fine sand with silt	1.8	150	
-22.0	18.0	Fine sand	1.8	200	
-30.0	—	Base rock	1.8	400	—

(c) Model for subsoil-3

0.0	2.0	Back fill	1.6	100	0.7
-2.0	1.0	Back fill	1.6	100	
-3.0	2.0	Back fill	1.6	100	
-5.0	5.0	Silty fine sand	1.8	100	
-10.0	10.0	Silt	1.8	120	
-20.0	15.0	Sandy silt	1.8	180	
-35.0	5.0	Sandy clay	1.8	250	
-40.0	—	Base rock	1.8	400	—

Table2: Combination of Parameters for the Numerical Analysis

Case number	Length of the building (m)	Width of the building (m)	Longitudinal span of the building (m)	Condition of the subsoil
0	88	8.0	5.0	2
	108			
	128			
	158			
1	88	8.0	5.0	3
	158			
2	88	8.0	5.0	1
	158			
3	88	6.5	5.0	2
	158			
4	86	8.0	6.5	2
	164			
5	86	6.5	6.5	2
	164			

Table3: Comparison of natural period (unit: sec)

Case number	Length of the building (m)	Translation mode (0th slab mode) 1st T10	2nd	Slab mode (1st translation mode) 1st T11	2nd
0	88	0.74	0.18	0.57	0.34
	108	0.74	0.18	0.61	0.40
	128	0.74	0.18	0.64	0.46
	158	0.74	0.18	0.66	0.52
1	88	0.77	0.18	0.58	0.34
	158	0.77	0.18	0.69	0.53
2	88	0.68	0.16	0.53	0.32
	158	0.68	0.15	0.62	0.49
3	88	0.82	0.18	0.62	0.37
	158	0.82	0.18	0.74	0.58
4	86	0.81	0.19	0.60	0.34
	164	0.82	0.19	0.73	0.56
5	86	0.90	0.19	0.67	0.38
	164	0.91	0.19	0.82	0.63

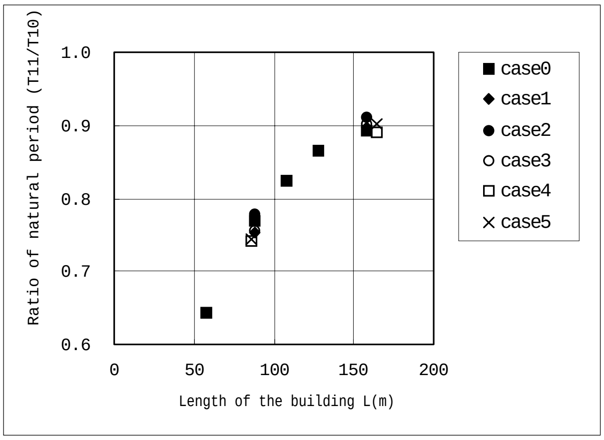

Figure7: Ratios of natural period

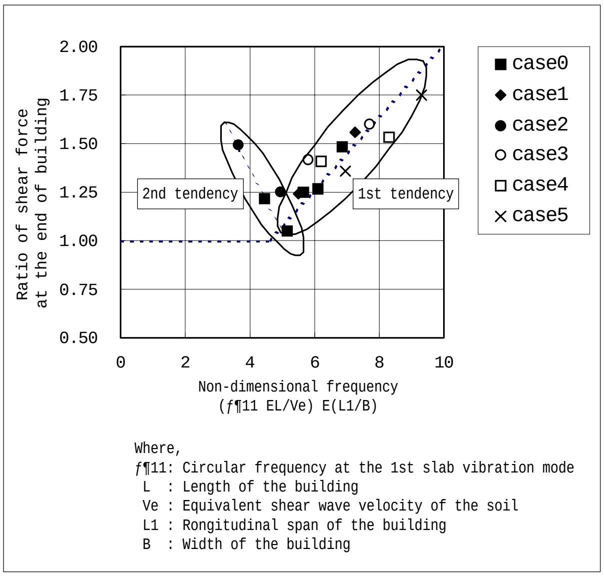

Figure8: Ratios of shear force for the 1st slab vibration

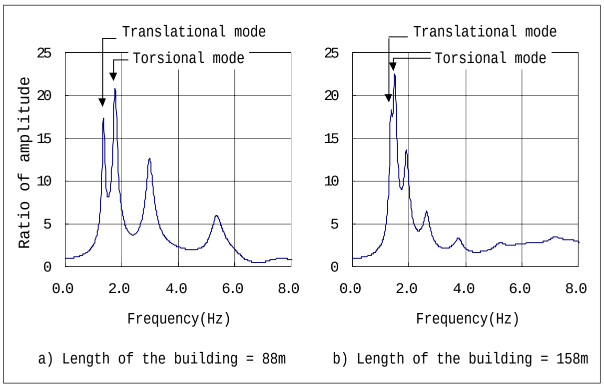

Figure9: Transfer functions at the end of building subjected to oblique incidence of SH waves (ƒÉ=2L)

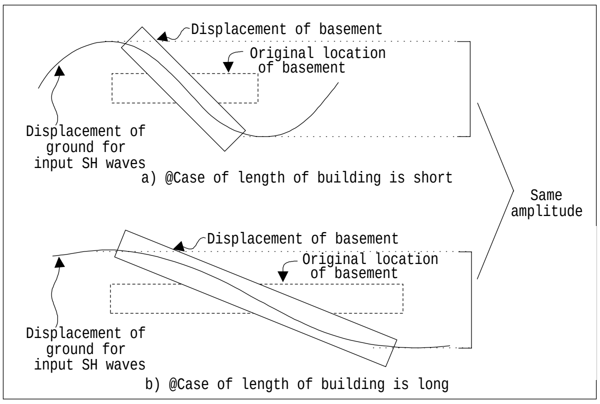

Figure10: Relations between length of the building and input motion at the plan

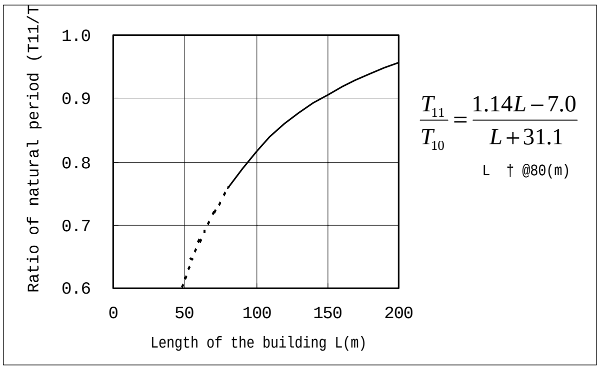

Figure13: Ratio of natural period

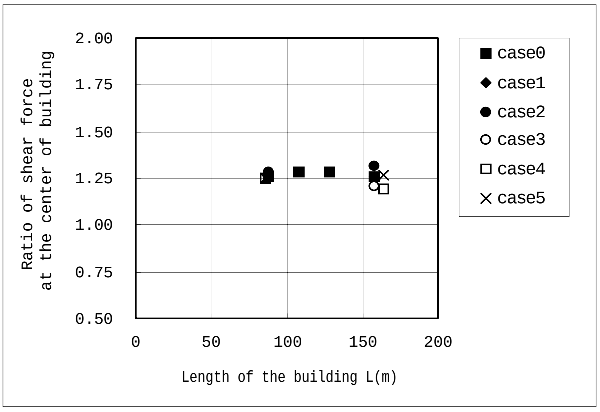

Figure11: Ratios of shear force for the arch-shaped floor vibration

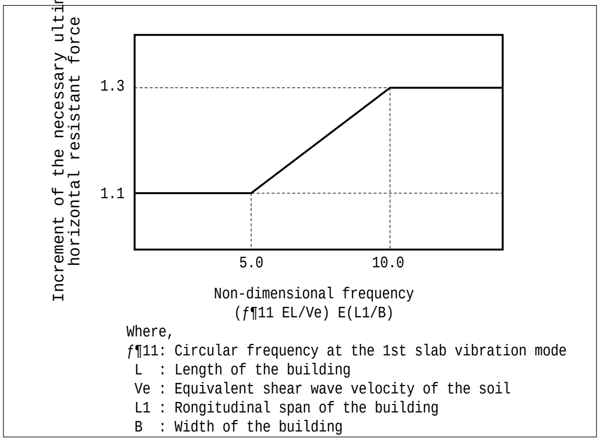

Figure14: Increment of the necessary ultimate horizontal resistant force

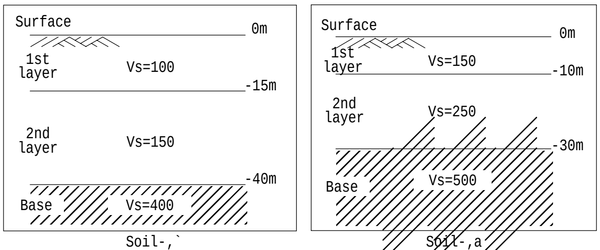

Figure15: Models for subsoil

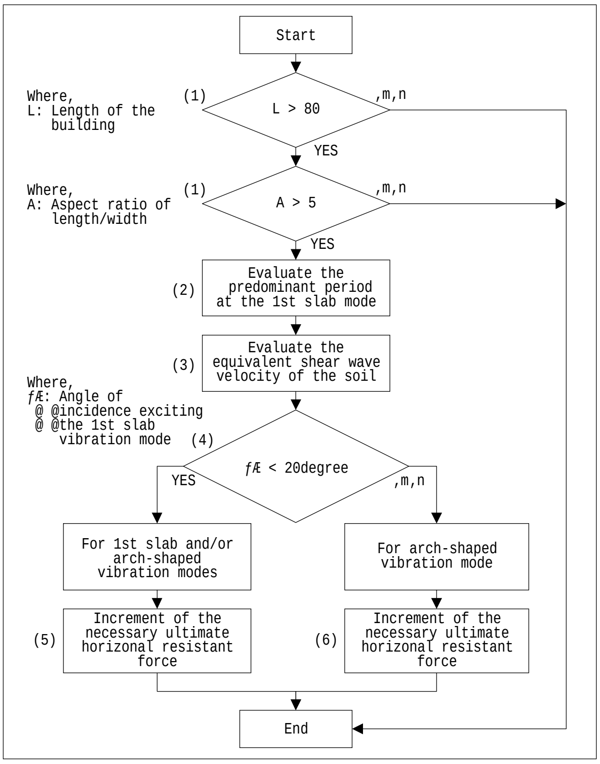

Figure12: Proposed evaluation procedure in view of seismic characteristics

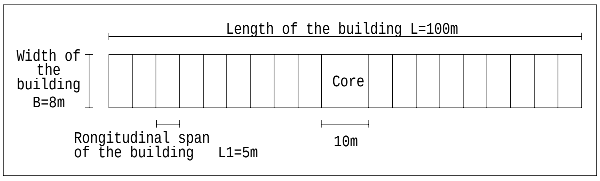

Figure16: Plan viwe of the building

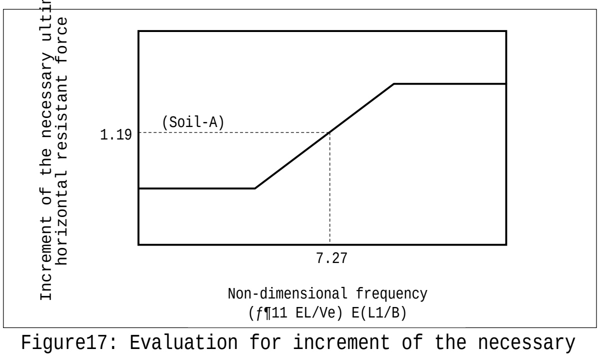

Figure17: Evaluation for increment of the necessary ultimate horizontal resistant force at the soil-A