A STUDY REGARDING DYNAMIC ANALYSIS OF STRUCTURES SUPPORTED BY WALL FOUNDATION SYSTEM

by WFS STUDY GROUP*

SUMMARY

The effects interaction between superstructure-WALL FOUNDATION SYSTEM ("WFS")-plus-soil has been studied. This report, first of all, describes the analytical model and the theoretical studies of imaginary buildings, in which structural characteristics of the building and the soil were assumed to be elastic. The items studied are the differences in response stresses when unit WF panel sections were varied, the external forces exerted on panels and the influence of inner soil surrounded by WFS. Furthermore, simulation analyses of an existing building supported by this system have been performed.

INTRODUCTION

A WALL FOUNDATION SYSTEM, the underground structure which consists of cast-in-place reinforced concrete walls built by the OWS-SOLETANCHE METHOD, has functions as earth-retaining walls for excavations, as principal structural members of basement and as pile foundations. The underground structure having such a WFS includes the following features: 1 Unit WF panel has a rectangular section, that is, the lateral resistance of a pile, in the direction of in plane or out of plane, makes a difference. 2 In case of the WF panels are constructed around the underground structure as pile foundations, the soil is divided into the inner and outer zones.

A structure supported by this system-soil interaction effects have been studied using a lumped mass method. An analytical model, theoretical studies and simulation analyses are described in the following.

ANALYTICAL MODEL

An elastic multi-lumped mass system, shown in Fig. 1, is considered as the vibration model. In substance, this is about the same idea as Penzien's method (*1). In this analytical model, however, the soft stratum is divided into three different systems, i.e. the inner soil (shown in note C of Fig.1), the surrounding soil (note B) and the free field (note D). Besides, when estimating the stiffness of WFS-soil interaction and the like, the characteristics of WFS are considered. The composition of the mathematical model is as follows:

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Superstructure and WFS (shown in note A of Fig. 1)

a. The stiffnesses are calculated by considering the bending and shearing deformations.

b. Basement and WFS is divided into some stratified segments, shown in Fig. 2, and the WF panels situated at the same segment are assumed to have the same horizontal movement both in plane and out of plane but independent rotations.

c. When estimating the stiffness of WF panels, elastic deformation of hard stratum at the tip of pile is considered.

d. The friction interacting between succeeding panel is not considered.

e. Underground structure is assumed to have a rotational movement as the rigid-body at the bottom, that is, the elastic deformation of WF panel by axial strain is not considered.

Surrounding Soil (note B)

a. The stiffness of WFS-soil interaction is estimated by resistance of soil deposit which produce by giving a unit displacement to an arbitrary segment of the divided underground structure, as shown in Fig. 3. As an analytical approach, displacement and force-points are located on the surface of underground structure, as shown in Fig. 4, and the simultaneous equation is derived, on a basis of Mindlin's equations, with respect to unknown distributed forces, which produce the above-mentioned displacement (Fig. 3). Besides, to solve it numerically, a least square approach is employed (*2). As the stiffness obtained in this way, however, includes both the reactions from the surrounding and inner soil, it is divided into proportion to the amount of strain energy stored in each soil. Fig. 5 shows an example of these proportions to the dimensions of underground structure.

b. The effective mass is based on Penzien's method (*1).

c. Damping coefficient is assumed as the ratio to critical damping as the following: $C = 2h\sqrt{mk}$

Inner Soil (note C)

The inner soil surrounded by WFS is divided into the part (Mm) having the same movement with WF panel and the independent one (Mf), using two-dimensional finite element method. Fig. 6 shows the calculated model and an example of the proportion of Mf and Mm to the total mass of a layer. These two soil columns are jointed by the horizontal spring.

Damping Coefficient

Different damping coefficients are given to superstructure, WFS and inner soil systems. The damping characteristic of total system is assumed to be independent to frequency based on Caughy's damping theory.

DYNAMIC ANALYSES OF IMAGINARY BUILDING

Superstructure, WFS, soil layer formation, damping coefficients and input base motions are imagined as follows:

Superstructure. 20 and five storied shear type buildings having the same total weight, shown in Fig. 7, are imagined. The first natural periods fixed at base are 2.0 sec and 0.5 sec respectively.

Underground Structure. The three types of WFS (Model-A, B and C) with basement, having the dimensions of 50 x 50 x 25 meters, are imagined. At the pile foundation part, the total cross-sectional area of these WFSs is the same, but the cross-sectional shapes of unit WF panel, as shown in Fig. 8, are different. The first natural periods of the WFS itself are 0.42 sec, 0.25 sec and 0.17 sec respectively.

Soil Layer. A soft alluvial subsoil layer above hard stratum is assumed. The material constant of these layers are listed in Fig. 7. The first natural periods is 1.0 sec.

Inner and Surrounding Soil. The inner soil of Model-A, B, C is divided into Mf and Mm. For the purpose of comparison, the following two models called Model-B' and B" with the same WFS as Model-B have also been analyzed. The former is that which the inner soil and WF panels are assumed to have the same movement, and the latter is that which the alluvial layer is neglected.

Damping Coefficient. Damping coefficients for superstructure, WFS and soil are assumed to be 1%, 5% and 10% respectively.

Input Base Motion. The earthquake waves utilized for the dynamic response are El Centro 1940 (NS) and Hachinohe 1968 (EW). The maximum acceleration intensity of each wave was fixed at 0.1g.

RESULTS OF DYNAMIC ANALYSES FOR IMAGINARY BUILDINGS

Damped Natural Periods and Modes. Damped natural periods, modes and modal damping factors of each model having a 20 storied superstructure is compared in Table 1 and Fig. 9. For the first and second modes, the values are almost equal. For the third mode which the underground structure is excited, however, the values are different.

Time History and Acceleration Responses. Fig. 10 shows the comparative acceleration at ground level of Model-A, B and C with a 20 storied superstructure and free field. These waves are more or less different due to the stiffness of WFS. For the comparatively flexible underground structure such as Model-A, the response wave of structure shows a similar tendency to that of free field. While, for the rigid one such as Model-C, the natural vibration of structure is recognized.

Story-Shearing Force. Story-shearing force of preceding models are compared in Fig. 11. As shown in this figure, the values are larger in Model-A, B and C considering the alluvial layer than Model-B" neglecting it.

Maximum Response Stresses. Maximum bending fiber stress ($\sigma = M/Z$), shearing stress ($\tau = Q/A$) which generate in WF panel subjected to earthquake force in plane and base shear coefficient area discussed. These stresses of Model-A, B and C having a 20 storied superstructure are compared in Fig. 12. The values are very different due to the cross-sectional shapes of unit WF panel. Therefore, when a WFS-soil system is imagined, it is possible to find the most suitable cross-sectional shape.

Fig. 13 shows the effects of the inner and the surrounding soil. Response stresses of Model-B and B' is almost equal, it can be considered, in this model, that there is no effect of the inner soil. While, for the values of Model-B", this is smaller than that of Model-B and B'. The stresses in WF panel are affected considerably by the external force from the surrounding soil.

Further, the response values of a 20 and five storied superstructure with Model-B are compared in Fig. 14. As shown in this figure, the values does not change in both models very much. However, the base shear coefficient of five storied building shows a value about three times as much that of 20 storied one.

EARTHQUAKE RECORDS AND THEIR ANALYSES ON A 11 STORIED BUILDING

The proposed method has been applied to the analysis on an existing 11 storied steel framed reinforced concrete building during an earthquake. This building is supported by WFS with a two storied basement constructed in alluvial sand layers 25 meters below ground. A general view of the building, the WFS, the soil layer formation and the location of seismometers are shown in Fig. 15, and 16. The recorded accelerogram and its spectrum are compared with the computed values, as shown in Fig. 17 and 18. In this analysis, the shearing moduli have been decided from the results of the in-situ shear wave velocity measurement at the site. The damping coefficients for the superstructure, WFS and soil are assumed as 1%, 3% and 3% respectively. As shown in Fig. 17, and 18, the theoretical results agree with the observed values.

CONCLUSION

The simplified evaluation method for the superstructure-WFS-plus-soil interaction during an earthquake has been proposed and the examples of theoretical studies were discussed. Although no definitive results on earthquake response of building-soil systems are deduced from the limited number of example studies, it may be possible that the influence of the external force acting to WF panels is larger in soil than in base shear.

Furthermore, the results of simulation analyses proved to be in good agreement with the records observed in the existing building.

ACKNOWLEDGEMENT

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(*1) J. Penzien el al; "Seismic Effect on Structure Supported on Piles extending through Deep Sensitive Clays", Univ. of Calf. Aug., 1964
(*2) Y. Ohsaki; "ON MOVEMENT OF A RIGID BODY IN SEMI-INFINITE ELASTIC MEDIUM", Univ. of Tokyo, Aug., 1973

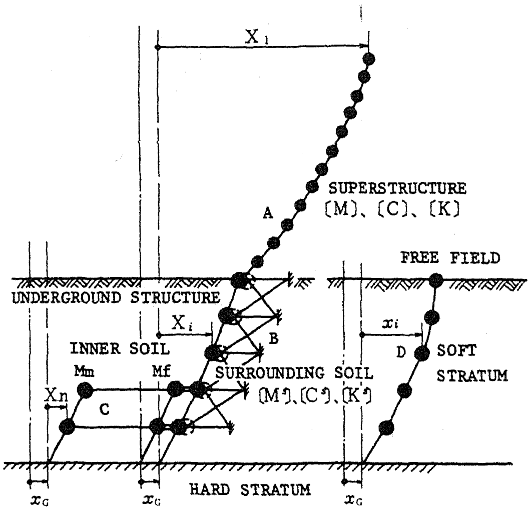


Fig. 1 ANALYTICAL MODEL

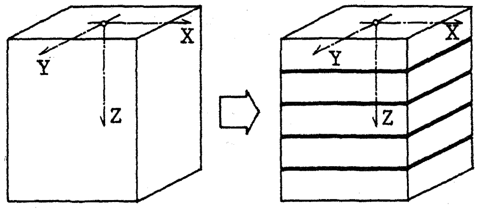
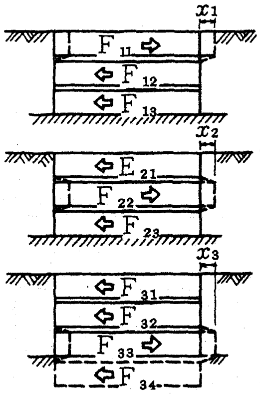


Fig. 2
DIVISION OF UNDERGROUND STRUCTURE

$$\begin{Bmatrix}F_1\\F_2\\F_3\end{Bmatrix} = \begin{bmatrix}a_{11} & a_{12} & a_{13}\\a_{21} & a_{22} & a_{23}\\a_{31} & a_{32} & a_{33}\end{bmatrix}\begin{Bmatrix}x_1\\x_2\\x_3\end{Bmatrix}$$



$x_2=x_3=0$
$a_{11}=F_{11}/x_1$
$a_{12}=F_{12}/x_1$
$a_{13}=F_{13}/x_1$
$x_1=x_3=0$
$a_{21}=F_{21}/x_2$
$a_{22}=F_{22}/x_2$
$a_{23}=F_{23}/x_2$
$x_1=x_2=0$
$a_{31}=F_{31}/x_3$
$a_{32}=F_{32}/x_3$
$a_{33}=F_{33}/x_3$

Fig. 3
STIFFNESS OF WFS-SOIL INTERACTION

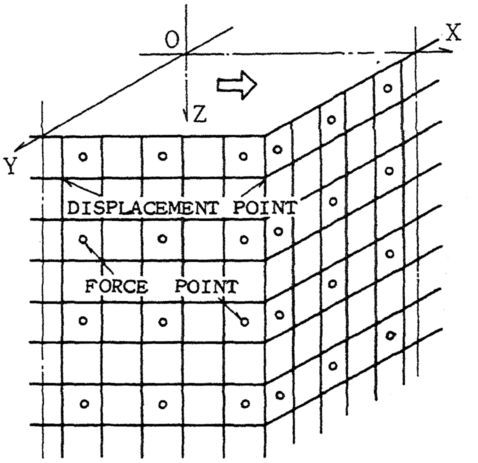
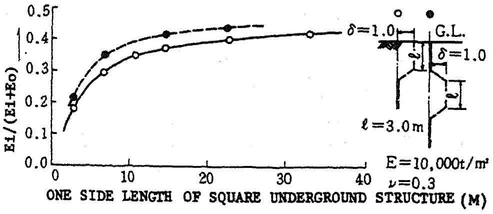


Fig. 4 DISPLACEMENT AND FORCE-POINTS



Ei: STRAIN ENERGY STORED IN INNER SOIL
Eo: STRAIN ENERGY STORED IN SURROUNDING SOIL

Fig. 5
RELATIONSHIP BETWEEN Ei/(Ei+Eo) AND DIMENSIONS OF UNDERGROUND STRUCTURE

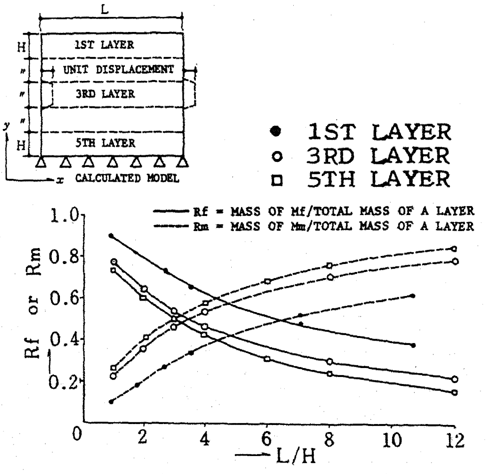
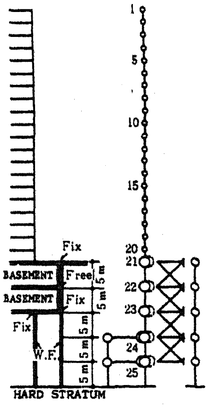


Fig. 6
RELATIONSHIP BETWEEN (L/H) AND Rf OR Rm



● SUPERSTRUCTURE (SHEAR TYPE, TOTAL WEIGHT=10000TON)

20 STORIES

WEIGHT OF EACH FLOOR :	20F ~ 1F const.	Wi=500ton
STIFNESSES :	20F	Ki= 50,000t/m
	19F	Ki= 55,000
	18F ~ 17F	Ki= 60,000
	16F ~ 15F	Ki= 65,000
	14F ~ 13F	Ki= 70,000
	12F ~ 11F	Ki= 75,000
	10F ~ 9 F	Ki= 80,000
	8 F ~ 7 F	Ki= 85,000
	6 F ~ 5 F	Ki= 90,000
	4 F ~ 3 F	Ki= 95,000
	2 F	Ki=100,000
	1 F	Ki=120,000

5 STORIES

WEIGHT OF EACH FLOOR :	5 F ~ 1F const.	Wi=2000ton
STIFFNESSES :	5 F	K_5=200,000t/m
	4 F	K_4=280,000
	3 F	K_3=380,000
	2 F	K_2=430,000
	1 F	K_1=500,000

DAMPING COEFFICIENT : 1%

● UNDERGROUND STRUCTURE (WFS AND BASEMENT)

BASEMENT : GA=50,000,000t

WFS : MODEL-A, B AND C

ELASTIC MODULUS OF CONCRETE : $E=2.1\times10^6 (t/m^2)$

DAMPING COEFFICIENT : 5%

● SOFT STRATUM

V_s=100m/sec P=1.6t/m³、ν=0.45

E =4736t/m²

DAMPING COEFFICIENT OF INNER SOIL : 10%

DAMPING COEFFICIENT OF SURROUNDING SOIL : $C=2h\sqrt{mk}$, h=10%

● HARD STRATUM

V_s=400m/sec ν=0.4

E =82286t/m²

● FREE FIELD

T_1=1.0sec T_2=0.35sec T_3=0.22sec

DAMPING COEFFICIENT : 10%

● INPUT BASE MOTION

EL-CENTRO 1940 NS
HACHINOHE 1968 EW
MAX. ACC. 0.1G

Fig. 7 IMAGINARY BUILDING AND SOIL

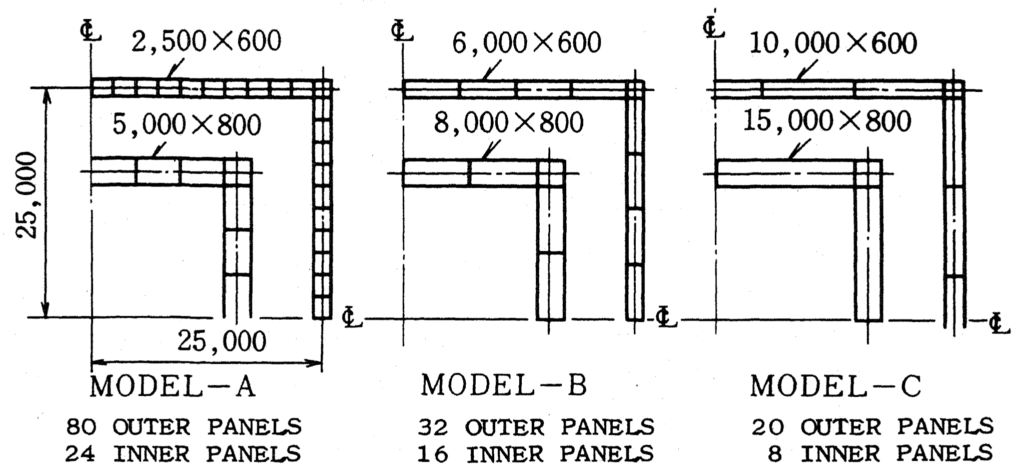
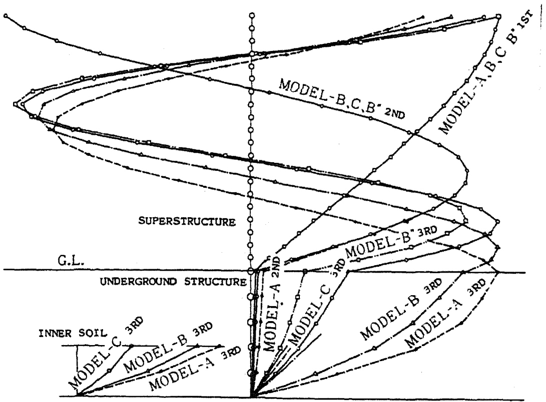


Fig. 8 PILE FOUNDATION PART OF EACH WFS

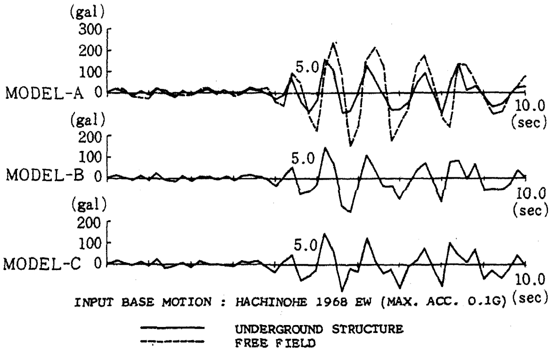
	MODEL−A	MODEL−B	MODEL−C	MODEL−B	MODEL−B'
1ST	2.0717sec(1.30%)	2.0713sec(1.28%)	2.0713sec(1.28%)	2.069sec(1.27%)	2.104sec(1.17%)
2ND	0.7129(1.77)	0.7107(1.30)	0.7904(1.16)	0.711(1.28)	0.713(1.07)
3RD	0.5740(19.0)	0.4985(16.34)	0.4564(13.84)	0.498(16.34)	0.444(1.85)
4TH	0.4259(1.52)	0.4241(2.17)	0.4241(3.35)	0.424(2.20)	0.354(4.83)
5TH	0.3080(1.23)	0.3078(1.21)	0.3077(1.22)	0.307(1.10)	0.302(1.63)
6TH	0.2930(9.94)	0.2891(10.08)	0.2886(10.14)	0.242(1.08)	0.297(10.05)
7TH	0.2419(1.20)	0.2416(1.14)	0.2414(1.13)	0.200(1.06)	0.240(1.14)

Table 1. DAMPED NATURAL PERIODS AND MODAL DAMPING FACTORS



Model-B' is a almost the same mode as model-B.

Fig. 9
DAMPED NATURAL VIBRATION MODES
(A 20 STORIED SUPERSTRUCTURE)



INPUT BASE MOTION : HACHINOHE 1968 EW (MAX. ACC. 0.1G)

Fig. 10 TIME HISTORY OF ACCELERATION OF MODEL-A, B AND C WITH A 20 STORIED SUPERSTRUCTURE AT GROUND LEVEL

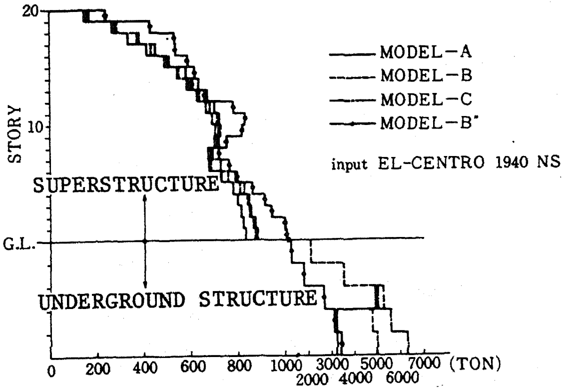


Fig. 11 STORY-SHEARING FORCE

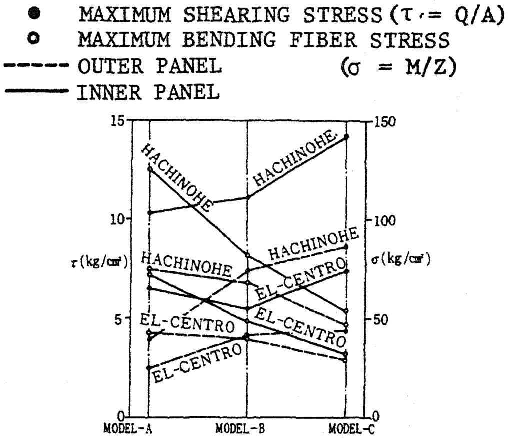


Fig. 12 EFFECT OF CROSS-SECTIONAL SHAPES OF UNIT WF PANEL

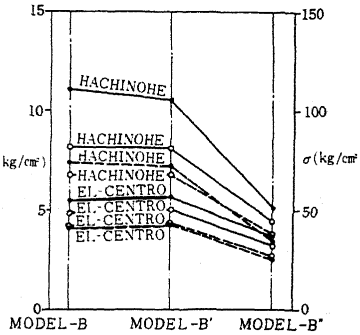
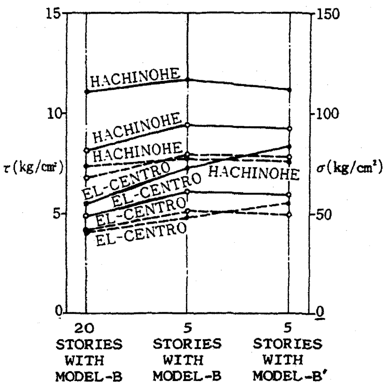


Fig. 13 EFFECT OF INNER AND SURROUNDING SOIL



BASE SHEAR COEFFICIENT
FOR EL CENTRO 1940 NS
C_B=0.088 C_B=0.23 C_B=0.24
FOR HACHINOHE 1968 EW
C_B=0.098 C_B=0.28 C_B=0.28

Fig. 14 EFFECT OF SUPERSTRUCTURE

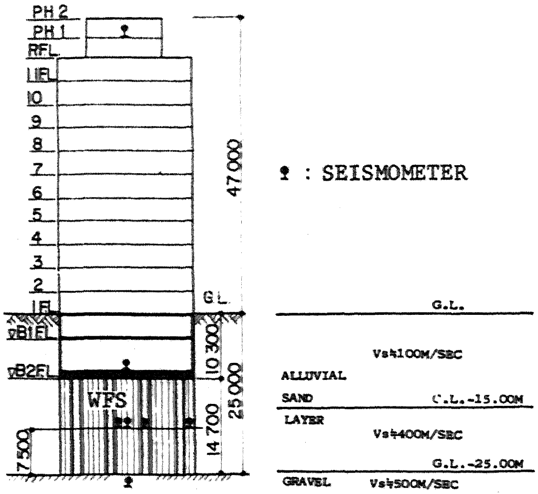


Fig. 15 GENERAL VIEW OF THE BUILDING UTILIZED FOR THE SIMULATION ANALYSIS

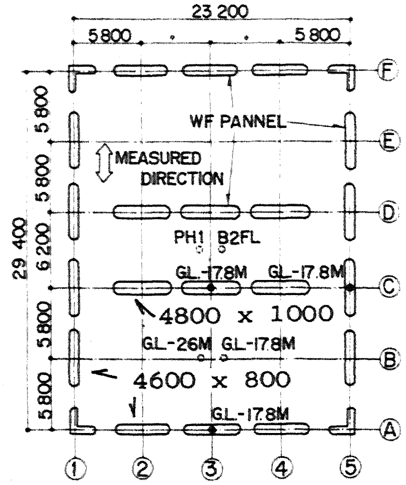


Fig. 16 PLAN OF WFS

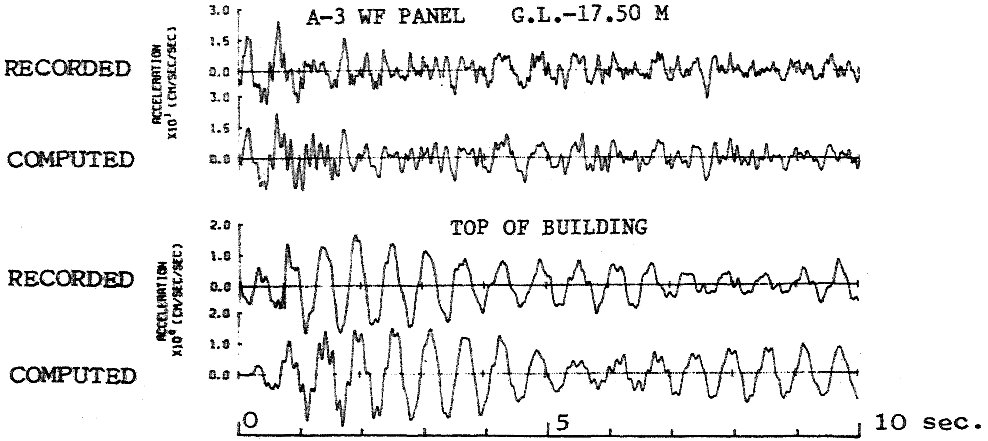


Fig. 17 TIME HISTORIES OF ACCEL. OF 11 STORIED BLDG. DURING AN EARTHQUAKE

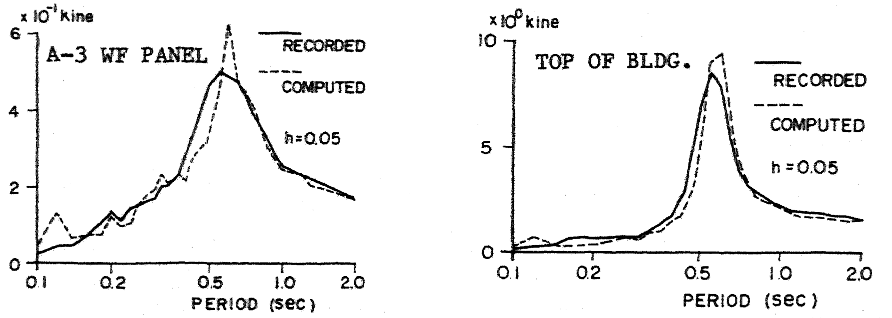


Fig. 18 COMPARISON BETWEEN RESPONSE SPECTRA OBTAINED BY RECORDED AND COMPUTED ACCELEROGRAMS