Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.VIII)

SD-11

A PROPOSAL FOR SEISMIC DESIGN PROCEDURE OF APARTMENT HOUSES INCLUDING SOIL-STRUCTURE INTERACTION EFFECT

Yoshio INOUE[1), Yutaka OSAWA[2)], Yutaka MATUSHIMA[3)],
Yoshikazu KITAGAWA[4)], Yutaka YAMAZAKI[4)] and Soichi KAWAMURA[5)]

1) Housing and Urban Development Corporation(HUDC), Japan
2) Earthquake Research Institute, University of Tokyo, Japan
3) Institute of Engineering Mechanics, University of Tsukuba, Japan
4) Building Research Institute, Ministry of Construction, Japan
5) Technology Research Center, Taisei Corporation, Japan

SUMMARY

The objective of this paper is to present a proposal where design values of buildings are estimated by taking into account the dynamic soil-structure interaction produced during earthquakes. The building structure is represented by the mass-spring system having swaying and rocking springs and dashpots located at the foundation. The subsoil layers are transformed to the uniform medium with an equivalent shear wave velocity and Poisson's ratio. This is applied to the reinforced concrete and steel framed reinforced concrete apartment houses. The numerical results indicate the reasonable feature of the soil-structure interaction effect.

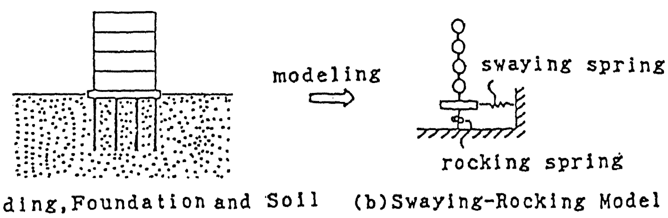
INTRODUCTION

In Japan, along with efficient uses of the land, buildings have been constructed on rather soft unstable soils. For that reason, it becomes all the more necessary to evaluate the seismic design for the building, taking into consideration the characteristics of the soft-soil ground motion and the soil-pile-structure interactions. Taking into account these aspects above, we carried out this research for apartment houses of HUDC while considering dynamic soil-structure interaction effects theoretically, analytically and experimentally. The main purpose was to set up the standards for evaluating seismic inputs for design in order to obtain more rational structures.

This paper presents a proposal where seismic design values of apartment houses are estimated by taking into account the soil-sturucture interaction and an example of numerical results obtained by applying the proposal to a real building.

MODELING OF BUILDING AND DESIGN PROCEDURE

The building structure is represented by the mass-spring system having swaying and rocking and dashpots located at the foundation as seen in Fig.1.



(a)Building,Foundation and Soil (b)Swaying-Rocking Model (SR model)

Fig.1 Interaction System Model

At that time, the subsoil layers are transformed to the uniform medium with an equivalent shear wave velocity and Poisson's ratio. Design procedure in the proposal is shown in Fig.2.

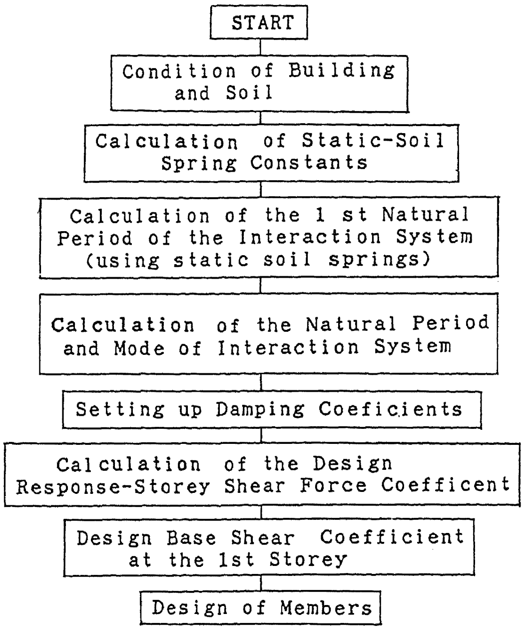


Fig.2 Design Procedure

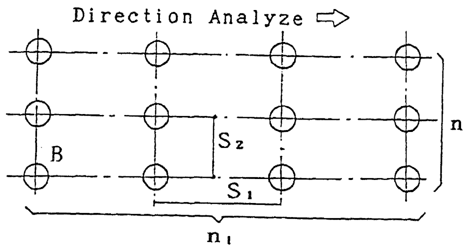


Fig.3 Total Number of Piles n_1, n_2

EVALUTION OF SPRING CONSTANTS

The static swaying and rocking spring constants of the soil, K_S, K_R are calculated according to the following equations:

$$K_S = \mu_S \cdot ({}_F K_S + {}_E K_S + {}_P K_S) \quad , \quad K_R = \mu_R \cdot ({}_F K_R + {}_E K_R + {}_P K_R) \qquad (1)$$

where, K_S, K_R are coefficients for modification regarding cumulation of swaying and rocking constants of the soil and the pile. ${}_F K_S$, ${}_F K_R$ are calculated according to the equations below:

$${}_F K_S = \{8/(2-\nu_e)\} \cdot (r_e/g) \cdot V_e^2 \cdot r_S, \quad {}_F K_R = [8/\{3(1-\nu_e)\}] \cdot (r_e/g) \cdot V_e^2 \cdot r_R^3 \qquad (2)$$

where, r_e, ν_e, g and V_e are, respectively, effective unit of the soil, effective Poisson's ratio of the soil, acceleration of gravity and shear wave velocity of the soil. r_S, r_R are effective radii of the foundation swaying and rocking motions, respectively. ψ_S, ψ_R are coefficients for modification of the effective radii and calculated according to the equations below:

$$r_S = \Psi_S \cdot \sqrt{A/\pi}, \quad r_R = \Psi_R \cdot \sqrt[4]{4I/\pi}, \quad , \Psi_S = 0.05(\mathrm{Log}_2 \lambda + 1.0)^2 + 0.95, \quad \Psi_R = 1.0 \qquad (3)$$

where, λ is ratio between the length and the width of the building (=2c/(2b)). 2c is the width of the building perpendicular to the direction of vibration and 2b is the width of the building of the direction of vibration. ${}_E K_S$, ${}_E K_R$ are swaying and rocking spring constants of the embedded part of the foundation and calculated according to the equations below:

$${}_E K_S = {}_F K_S \cdot (G_0/G_e) \cdot ({}_E H/r_S) \qquad {}_E K_R = 2.5\,{}_F K_R \cdot (G_0/G_e) \cdot ({}_E H/r_R) \qquad (4)$$

where, G_0, G_e are the average shear rigidity at the soil touching the side wall, and effective shear coefficients of the soil. $G_0/G_e = 1$, ${}_E H$ is the depth of the base foundation (bottom of the base beam) from the ground surface. However, when compression/settlement of the soil is expected, the settlement shall be subtracted. ${}_P K_S$, ${}_P K_R$ are swaying and rocking spring constants of the pile and caluclated accoding to the equations below:

$$ {}_pK_S = \alpha_p \cdot N_p \cdot {}_pk_S \quad , \quad {}_pK_R = \sum_j {}_pk_{vj} \, y_j^2 \tag{5}$$

where, j is the serial number of the pile and y_j is the distance between the center line of the foundation and the center of the j-th pile. α_p, the reduction coefficient of the swaying constant of piles due to the group-pile effects, is calculated according to the following equations:

$$ \alpha_p = \exp\{-(\alpha_{p1}\sqrt{n_1-1}+\alpha_{p2}\sqrt{n_2-1})\} \quad , \quad \alpha_{p1}=0.5/\sqrt{S_1/B} \ , \ \alpha_{p2}=0.3/\sqrt{S_2/B} \tag{6}$$

where, S_1 is the interval of piles in the vibration direction, S_2 is interval of piles perpendicular to the direction of vibration, B is the diameter of the pile and N_p is the total number of piles (Fig.3). $_pk_s$ is the swaying spring constant of a single pile and in case pile-head is fixed, it is calculated as follows:

$$ {}_pk_S = 4\,E_p \cdot I_p \cdot \beta_p^3 \quad , \quad \beta_p = \sqrt[4]{k_h \cdot B/(4 \cdot E_p \cdot I_p)} \tag{7}$$

where, E_p is Young's modulus of the pile. I_p is the 2nd inertial moment of the pile and k_h is horizontal reaction of the soil. $_pk_{vj}$ is the spring constant of the j-th single pile in the vertical direction and calculated according to the equation below:

$$ {}_pk_{vj} = a \cdot A_p \cdot E_p/\ell \tag{8}$$

where, A_p is the net area of the cross section of the pile, ℓ is the length of the pile and a is the coefficient for each kind of pile. In case of a supported pile which is reinfoced concrete pile in site, it is caluclated as follows:

$$ a = 0.022(\ell/B) - 0.05 \tag{9}$$

where, μ_S, μ_R are caluclated as follows:

$$ \mu_S = (1-\alpha_S)^{1.5} + \alpha_S^{1.5} \quad , \quad \mu_R = 1.0 \tag{10}$$

where, α_S is the ratio between the swaying spring constants of the pile and the total of swaying spring constants of the soil and pile and calculated as follows:

$$ \alpha_S = {}_pK_S/({}_FK_S + {}_EK_S + {}_pK_S) \tag{11}$$

The natural period of the interaction-system is calculated by the use of weight of each storey, spring constants, weight of the foundation and static soil swaying and rocking spring constants calculated in that step. The dynamic swaying and rocking spring constants of the soil, $\widetilde{K_S}$, $\widetilde{K_R}$ are respectively calculated according to the following equations:

$$\begin{aligned}
&\widetilde{K_S} = \widetilde{\mu_S} \cdot ({}_F\widetilde{K_S} + {}_E\widetilde{K_S} + {}_p\widetilde{K_S}) && , \ \widetilde{K_R} = \widetilde{\mu_R} \cdot ({}_F\widetilde{K_R} + {}_E\widetilde{K_R} + {}_p\widetilde{K_R}) \\
&\widetilde{\mu_S} = \mu_S \ , \ \widetilde{\mu_R} = \mu_R \ (=1.0) && , \ {}_F\widetilde{K_S} = {}_sd_S \cdot {}_FK_S \ , \ {}_E\widetilde{K_S} = {}_sd_S \cdot {}_EK_S \qquad (12) \\
&{}_p\widetilde{K_S} = {}_pd_S \cdot {}_pK_S \ , \ {}_F\widetilde{K_R} = {}_sd_R \cdot {}_FK_R && , \ {}_E\widetilde{K_R} = {}_sd_R \cdot {}_EK_R \ , \ {}_p\widetilde{K_R} = {}_pd_R \cdot {}_pK_R
\end{aligned}$$

where, $_sd_S$, $_pd_S$, $_sd_R$, $_pd_R$ are the ratio of dynamic rigidity reduction and calculated as follows:

$$\begin{aligned}
&{}_sd_R = (1-0.05 \cdot a_{oR})^2 \ ; \ a_{oR} < 10 \quad , \quad {}_sd_R = 0.25 \quad ; \ a_{oR} \geq 10 \qquad (13) \\
&{}_sd_S = {}_pd_S = {}_pd_R = 1.0
\end{aligned}$$

where, a_{oR} is a non-dimensional frequency regarding the rocking spring and equal to $\Omega \cdot r_R/V_e$. Ω is the 1st natural circular frequency of the interaction system based on the static spring constant($=2\pi/T_1$). The j-th natural period ($\widetilde{T_j}$) and the mode of the interaction system is calculated by the use of weight of each storey, spring constants, weight of the foundation, and dynamic swaying and rocking spring constants.

EVALUATION OF DAMPING FACTOR

The damping factor of the j-th mode ($h_{eq,j}$) for calculating the response storey base shear coefficient(${}_EC_i$), is calculated by the following equation:

$$ h_{eq,j} = {}_B\gamma_j \cdot {}_Bh + {}_s\gamma_{S,j} \cdot {}_sh'_S + {}_s\gamma_{R,j} \cdot {}_sh'_R + {}_p\gamma_{S,j} \cdot {}_ph'_S + {}_p\gamma_{R,j} \cdot {}_ph'_R \tag{14}$$

where, the damping factor of each part is weighted according to the strain energy. γ is the ratio between the associated strain energy and the whole strain energy of the vibration system at the j-th vibration mode. ${}_{B}h$ is the damping coefficient of the building and is normally 0.02. ${}_{s}h'_{S}, {}_{s}h'_{R}$ are damping coefficients of the soil for the swaying spring and rocking spring, respectively, modified according to the layered soil and calculated as follows:

$$ {}_{s}h'_{S} = {}_{s}\delta_{S}\cdot{}_{s}\varepsilon_{S}\cdot{}_{s}\kappa_{S}\cdot{}_{s}h_{S} + {}_{s}h_{I} \quad , \quad {}_{s}h'_{R} = {}_{s}\delta_{R}\cdot{}_{s}\varepsilon_{R}\cdot{}_{s}\kappa_{R}\cdot{}_{s}h_{R} + {}_{s}h_{I} \qquad (15) $$

where, δ is the coefficient for modification of the damping of the soil due to the layered soil. ε is the coefficient for modification of the soil due to the embedment of the foundation. κ is the coefficient for modification of the soil due to the opening of the foundation and h is the damping coefficient of the half-space elastic soil replaced with the equivalent. ${}_{s}h_{I}$ is the constant of visco-damping of the soil and is normally 0.03. ${}_{s}\delta_{S}, {}_{s}\delta_{R}$ are coefficients for modification of the swaying spring and rocking spring of the soil, respectively, due to the embedment of the foundation and calculated as follows:

$$ {}_{s}\delta_{S} = \{0.1(V_{e2}/V_{e1}-1)^3+0.36\}/\{(V_{e2}/V_{e1}-1)^3+0.36\} \qquad ; \widetilde{a_{OS}} \le {}_{c}a_{OS} $$

$$ {}_{s}\delta_{S} = 1-[(1.2\,{}_{g}a_{OS}-\widetilde{a_{OS}})\cdot 0.9(V_{e2}/V_{e1}-1)^3]/[(1.2\,{}_{g}a_{OS}-{}_{c}a_{OS})\cdot\{(V_{e2}/V_{e1}-1)^3+0.36\}] $$

$$; {}_{c}a_{OS} < \widetilde{a_{OS}} \le 1.2\,{}_{g}a_{OS} \qquad (16) $$

$$ {}_{s}\delta_{S} = 1.0 \qquad ; 1.2\,{}_{g}a_{OS} < \widetilde{a_{OS}} \quad , \quad {}_{s}\delta_{R} = 0.05 \quad ; \widetilde{a_{OR}} \le {}_{c}a_{OR}. $$

$$ {}_{s}\delta_{R} = 0.05+0.95(\widetilde{a_{OR}}-{}_{c}a_{OR})/(1.8\,{}_{g}a_{OR}-{}_{c}a_{OR}) \quad ; {}_{c}a_{OR} < \widetilde{a_{OR}} \le 1.8\,{}_{g}a_{OR} \quad , \quad {}_{s}\delta_{R} = 1.0 \quad ; 1.8\,{}_{g}a_{OR} < \widetilde{a_{OR}} $$

where,

$$ {}_{c}a_{OS} = {}_{g}a_{OS}(1-1.8^{-(V_{e2}/V_{e1}-1)}) \quad , \quad {}_{c}a_{OR} = 1.8\,{}_{g}a_{OR}(1-2.8^{\sqrt{V_{e2}/V_{e1}-1}}) \qquad (17) $$

$$ \widetilde{a_{OS}} = \widetilde{\Omega}\cdot r_S/V_e , \quad \widetilde{a_{OR}} = \widetilde{\Omega}\cdot r_R/V_e \quad ; \quad {}_{g}a_{OS} = \pi\cdot r_S/(2H_e), \quad {}_{g}a_{OR} = \pi\cdot r_R/(2H_e) $$

$\widetilde{\Omega}$ is the 1st natural circular frequency of the interaction system based on the dynamic soil spring constant and H_e is the thickness of the equivalent two layered soil's 1st layer. ${}_{s}\varepsilon_{S}$, ${}_{s}\varepsilon_{R}$, ${}_{s}\kappa_{S}$, ${}_{s}\kappa_{R}$ are calculated ,respectively, as follows:

$$ {}_{s}\varepsilon_{S} = 1.0+(G_o/G_e)\cdot({}_{E}H/r_S) \; , \; {}_{s}\varepsilon_{R} = 1.0 \quad , \quad {}_{s}\kappa_{S} = \sqrt{1-A'/(2A)} \; , \; {}_{s}\kappa_{R} = 1.0 \qquad (18) $$

where, A' is area of the opening at the foundation and A is the area of the foundation (=2b*2c). ${}_{s}h_{S}, {}_{s}h_{R}$ are calculated respectively as follows:

$$ {}_{s}h_{S} = 0.30\cdot\widetilde{a_{OS}} \quad , \quad {}_{s}h_{R} = 0.1\cdot\widetilde{a_{OR}}^3 \quad ; \widetilde{a_{OR}} < 1 $$

$$ {}_{s}h_{R} = 0.15\cdot\widetilde{a_{OR}}-0.05 \quad ; 1 \le a_{OR} < 5 \quad , \quad {}_{s}h_{R} = 0.70 \quad ; a_{OR} \ge 5 \qquad (19) $$

The damping coefficients of pile for the rocking spring, respectively, modified to the layered soil, ${}_{p}h'_{S}, {}_{p}h'_{R}$ are calculated as follows:

$$ {}_{p}h'_{S} = {}_{p}\delta_{S}\cdot{}_{p}h_{S}+{}_{p}h_{I} \quad , \quad {}_{p}h'_{R} = {}_{p}\delta_{R}\cdot{}_{p}h_{R}+{}_{p}h_{I} \qquad (20) $$

where, ${}_{p}h_{S}$, ${}_{p}h_{R}$ are respectively the damping coefficients for the swaying and rocking of pile located at the equivalent half-space elastic soil and are normary 0.03. ${}_{p}h_{I}$ is damping coefficient due to the visco-damping of the pile and is normally 0. ${}_{p}\delta_{S}$, ${}_{p}\delta_{R}$ are coefficients for modification of the damping coefficient of the pile for the swaying and rocking due to the layered soil is 1, except in the case of special investigations.

RESPONSE STOREY SHEAR FORCE COEFFICIENT FOR DESIGN

The response storey shear force coefficient for the design for the i-th storey is calculated as follows:

$$ {}_{E}C_i = Z\cdot\lambda_1\cdot R_t(\widetilde{T_1})\cdot\phi_i\cdot C_o \qquad (21) $$

where, Z , $R_t(\widetilde{T_1})$, Co are seismic hazard zonong coefficient, vibration property at the 1st natural period ($\widetilde{T_1}$), standard layer shear force coefficient as given in the Building Standards Act, respectively. ϕ_i is the coefficient at the i-th storey showing the vertical distribution of the response storey shear force coefficient(= ϕ'_i/ϕ'_1). λ_1 is the coefficient for modification of the spectrum at the 1st natural period and calculated as follows:

$$\lambda_1 = 1 - \{1 - 2.25/(1.75 + 10\,h_{eq.1})\} \cdot t_1 \qquad ;\ h_{eq.1} \geq 0.05$$
$$\lambda_1 = 1 + \{1.5/(1.0 + 10\,h_{eq.1}) - 1\} \cdot t_1 \qquad ;\ h_{eq.1} < 0.05 \tag{22}$$

where, t_1 is unity in the usual range of the natural period ($\widetilde{T}_1$) and is calculated by the use of $\widetilde{T}_1$ in accordance with the equations below:

$$t_1 = 0 \quad ;\ \widetilde{T}_1 \leq 0.05\ ,\ \widetilde{T}_1 \geq 10.0\ , \qquad t_1 = (\log \widetilde{T}_1 + 1.30)/0.3 \quad ;\ 0.05 < \widetilde{T}_1 < 0.1$$
$$t_1 = 1.0 \quad ;\ 0.1 \leq \widetilde{T}_1 \leq 2.5\ , \qquad t_1 = (1 - \log \widetilde{T}_1)/0.6 \quad ;\ 2.5 < \widetilde{T}_1 < 10.0 \tag{23}$$

where, ϕ'_i is the storeyed shear force coefficient for calculating at the i-th storey of the building and is calculated as follows:

$$\phi'_i = \sqrt{\sum_{j=1}^{K} [\sum_{m=i}^{{}_BN} (W_m \cdot \beta_j \cdot u_{mj} \cdot \lambda_j \cdot R_t(\widetilde{T}_j))]^2} / \sum_{m=i}^{{}_BN} W_m \tag{24}$$

where, ${}_BN$ is the total number of storeys above the foundation and W_m is the weight of the m-th storey. $\beta_j \cdot U_{mj}$ is j-th participation function of the m-th storey. λ_j is the coefficient for spectrum modification due to damping at the j-th natural period and is calculated similarly by the equations for λ_1. $R_t(\widetilde{T}_j)$ is the design spectrum coefficient at the j-th natural period ($\widetilde{T}_j$) as given in the Building Standerd Act. k is the highest mode number to be considered to be more than 2. However, when the base shear force coefficient of the 1st storey falls below the base shear force coefficient Z·Rt·Co given in the Building Standard Act, its lower limit is 75% of Z·Rt·Co , and the response storey shear force coefficient for each storey is modified at the same rate.

EXAMPLE OF APPLICATION FOR PROPOSAL

Various types of apartment house founded on different grounds are analysed by following this procedure. The building has fourteen stories and are made of reinforced concrete(Figs 4 and 5). The underlying ground consists mainly of silty soil down to depth 18m from the ground surface (Fig.6). The constants of the soil are shown in Table.1. The building is supported by reinforced concrete piles, 21m in length placed in site. The diameter of the piles is from 1.6m to 1.9m. The constants for analysis are shown in Table.1. In Table.1, Ki is the spring constant of each storey of the building and $\widetilde{K}_s$, $\widetilde{K}_R$ are dynamic soil spring constants of the swaying and the rocking, respectively. The design storey shear force coefficients in a

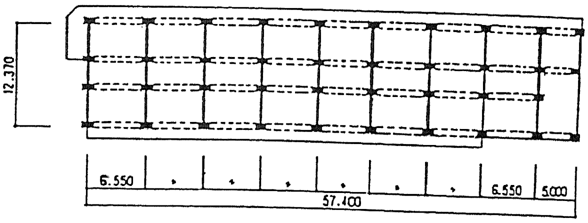
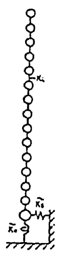


Fig.4 Plan of Building

Tab.1 Constants K_i , $\widetilde{K}_S$, $\widetilde{K}_R$



		longitudial	transverse
K_i (t/cm)	14	5.014	3.557
	13	6.298	5.320
	12	7.329	6.801
	11	7.949	8.299
	10	8.780	9.707
	9	9.708	11.385
	8	10.156	13.107
	7	10.897	15.368
	6	12.199	17.801
	5	13.132	20.679
	4	14.105	24.976
	3	15.503	30.513
	2	18.195	40.495
	1	28.177	43.865
$\widetilde{K}_S$ (t/cm)		1.889	3.066
$\widetilde{K}_R$ (t cm/r)		8.156×10^{10}	0.685×10^{10}

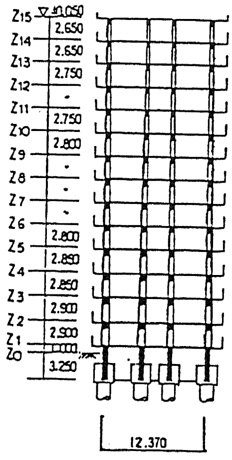


Fig.5 Section of Building

depth from surface (m)	soils	Gi (t/m²)	Vs (m/s)
0 – 2.0	silt	2.980	135
2.0 – 5.5	silt	730	70
5.5 – 9.0		2.590	130
9.0 – 13.0		1.630	100
13.0 – 18.0		1.800	105
18.0 – 25.0	sandy clay	10.840	250
25.0 – 39.0	gravel	39.260	450
39.0 – 50.0	sand	16.530	300

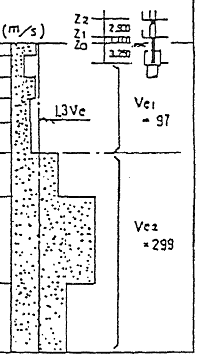


Fig.6 Constants of Soil

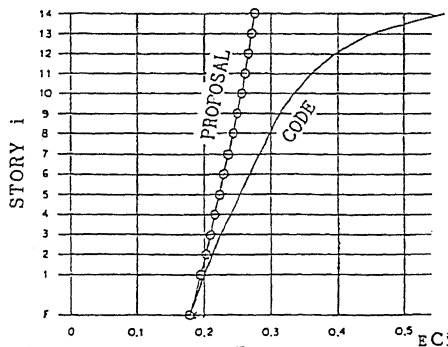


Fig.7 Design Story Shear Force Coefficients, ECi

longitudinal direction of the building evaluated by this proposal is shown in Fig7. It is less than that required by the code owing to the effect of soil-structure interaction.

CONCLUDING REMARKS

A proposal where seismic design values of apartment houses are estimated by taking into account the soil-structure interaction is presented. The numerical results obtained by applying the proposal to real buildings indicate the reasonable features of the soil-structure interaction effect.

ACKNOWLEGEMENTS

In order to excute this reserch, a reserch committee (chairman,Y.Osawa, professor emeritus, University of Tokyo) was organized in the KENCHIKU KENKYU SYINKO KYOKAI (Sosciety for Promoting Building Reserch) and the scheme of the reserch and studying results were carried out. The authors wish to express there sincere thanks to menbers of the committee and persons concerned.

REFERENCES

1)Inoue,Y. and Osawa,Y. et al.,"Study on Seismic Input to Apartment houses of HUDC (part-6,7,8)", Proceeding,Annual Meeting of AIJ,Oct.1987