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A STUDY ON THE EFFECT OF SOIL - STRUCTURE INTERACTION ON THE DYNAMIC PROPERTIES OF RC STRUCTURES BASED ON THE MICROTREMOR RECORDS

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In order to evaluate the effect of the size of building and the site soil condition on the first mode's natural period and damping ratio, the results of the microtremor measurements of 14 buildings located in the Higashiyama campus of Nagoya University are analysed. The selected buildings have different number of stories and foundation size. Also, they have been constructed on different parts of the campus with different soil conditions. So, it is possible to estimate the effect of height and aspect ratio on the dynamic properties of structures as well as the effect of Soil-Structure Interaction (SSI). As the evaluation method, the curve fitting method for the observed transfer functions (Hv estimation) as well as the Random Decrement (RD) method for the generation of free vibration motion are used. Also investigated is the variation of the dynamic characteristics of a 10-story building in the different stages of construction.

Key Words: Natural Period , Damping Ratio , Soil-Structure Interaction , Microtremor Test , Hv Estimation Method , RD Method

Introduction :

It is well known that the natural periods and damping ratios are the key parameters in the seismic design of structures. As the conventional method in the different seismic design codes, these parameters are approximately evaluated by using some empirical formulations.[1,2] Therefore, the accuracy of these empirical formulas can influence the whole seismic design, necessitating the need to improve the reliability of such formulas by increasing the quality and quantity of the experimental studies. Since the seismometers became available, several tests have been conducted in order to discover the relationship between the dynamic characteristics of buildings, i.e. the natural period and damping ratio, and the number of stories, size of foundation and structural system.[3~7] Recently, more reliable results have been achieved through the use of high precision measurement devices, more accurate techniques and high speed computers. Also, the effect of soil condition on these key parameters have been studied by some researchers, analytically[8,9], and experimentally.[10,11] In this regard, the ambient vibration measurements have always been a fast and efficient way of determining the dynamic properties of buildings. However, it should be mentioned that because of low amplitude of vibrations, microtremor records are easily affected by existing noises. Additionally, the final analysis of results can be subjective and may render different results, depending on the techniques used and the personal judgement applied. There is even a greater degree of subjectivity involved in cases where no clear peak exists in the transfer function or where more than one peak exist. In this regard, short and stiff buildings warrant special attention because in these cases a well shaped and suitable transfer

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function can not be achieved except under very well controlled conditions. Therefore, it is not sufficient to only deal with the final numerical results without taking all effective parameters into account.

In this paper the results of the microtremor tests on fourteen Reinforced Concrete (RC) buildings located in the Higashiyama campus of Nagoya University are presented and discussed considering the above mentioned aspects. It should be mentioned that because of heavy earthworks during the years, the topography of the campus has been drastically changed from the original situation. Therefore, the different parts of the campus have different soil conditions. On the other hand, most of the selected buildings have almost a typical plan of educational type buildings, i.e. a slender rectangular with almost the same width. So, the effect of soil condition on the eigenproperties of buildings can be studied well.

Description of the Buildings and Soil Conditions:

Figure 1 shows the Higashiyama campus and the location of the selected buildings. The numbers on the figure refer to the order number of buildings in the first column of table 1. The change of topography of the campus due to heavy earthworks from 1936 to 1991 is shown in the background. Although only the groundfilled parts are shown in the figure, it is interesting to say that the difference between the level of the excavated and filled areas reaches up to 50 meters in some parts. Darker shades in the background indicate an increase in filling depth. Generally speaking, the northwestern and northeastern parts of the campus are the earthfilled areas and consequently have looser soil. The other areas, especially the central part of the campus have been mainly excavated and better soil condition is expected in these areas. The buildings were selected among the existing RC buildings considering some parameters which are of interest, e.g. the number of stories, plan's shape and size, soil condition and also the availability of boring data. It should be mentioned that totally, there are 202 boring data available in the campus which are mainly related to the northern and central parts of the campus as it can be seen in Fig.1. The information related to each of the selected buildings including the number of stories, age, height, type of foundation and the soil condition are summarized in table 1. As the criteria for the soil stiffness, two alternatives were considered: 1) the average of shear wave velocities and 2) the average of N-values over the first 10 meters from the ground surface. Since the number of directly measured data for the shear wave velocity is very limited in the campus, the empirical formulations[12] are used in the first alternative for computing the shear wave velocities as a function of N-value, soil type, geological age and depth of soil layers. Although it seems that the first method should be more reliable, the lack of soil related information as well as the dispersion of the results due to the empirical nature

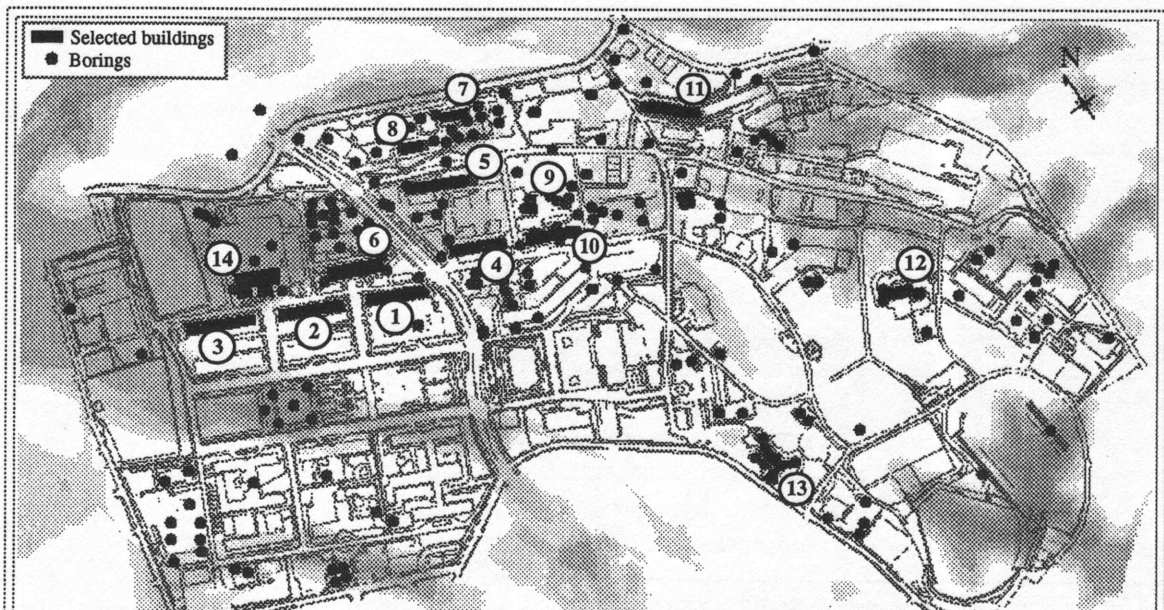


Fig.1_ The location of the borings and selected buildings and the groundfilled area in the campus

Table1_ Selected buildings' information

No.	Building	Ref. name	No. of Stories	Height (m)	Struc. System	Pile length (m)	Embedment (m)	Construc. Year	Average N-value
1	Faculty of Eng. No.1	Eng1	3+1	15.3	RC	-	1.2	1951-70	14.6
2	Faculty of Eng. No.2	Eng2	3+1	15	RC	-	1.1	1954-65	10.8
3	Faculty of Eng. No.3	Eng3	4	15.8	RC	5 - 16	1.5	1962-70	12.5
4	Faculty of Eng. No.4	Eng4	4	14.75	RC	6	1.25	1964-70	17.2
5	Faculty of Eng. No.5	Eng5	6	22.17	RC	5 - 33	1.7	1967-69	14.4
6	Faculty of Eng. No.7	Eng7	4	15.2	RC	20	1.2	1971-89	16
7	Faculty of Eng. No.8	Eng8	4	16	RC	9 - 10	2.8	1987	28.9
8	Faculty of Eng. No.9	Eng9	6	22.2	RC	12	2.3	1982-93	22.9
9	Faculty of Science_A2	Sc.A2	5	18.1	RC	9	1.5	1979	17.2
10	Faculty of Science_E	Sc.E	5+1	19.7	RC	8	1.7	1967-85	21.6
11	Faculty of Agriculture	Agr.	6	21	RC	-	2	1966	23.1
12	Inst. for Hydrospher.	Hyd.	5	18.8	RC	9	1.6	1971	30.2
13	International Residence	Res.	8	33.2	RC	15	2	1981-88	27.8
14	Faculty of Eng. No.1(new)	Eng1_N	10	39.3	SRC	45	8.05	1995	11.6

of the formulations led to some contradictory results in some cases. On the other hand, the N-values are available in one meter intervals of depth at each boring point. It means that in relation to the second alternative, the effect of layers' depth will be taken into account by using a simple linear averaging of N-values over a specific depth. Also, for the case of pile foundations with piles shorter than 10 meters, the average value over the length of piles is used in order to avoid the distortion of data due to significant difference between soil layers.[10] So, in comparison to the reliability of the first alternative and considering that most of the selected buildings have pile foundations, the second one is used here as an approximation for the soil stiffness.

Microtremor Tests and the Parameter Estimation Methods :

The microtremor measurements were performed for NS and EW directions which are related to the transverse and longitudinal dimensions of buildings, respectively. The responses were measured at the first floor and top of the buildings as well as on the ground surface. The measurements on the ground surface were done at a distance from the building which are not affected by the building's vibration. In the case of the Eng1_N building, the test was repeated for different stages of construction, i.e. after completion of each story.

The moving coil type seismometers with natural period of 1.0 second were used to measure the responses simultaneously at the above mentioned locations and the velocity was measured in all cases. The signals, after amplification and low pass filtering (f_c =30 Hz) are digitized at the rate of 100 samples per second. In all cases, the measurements were conducted three times in ten-minute intervals, providing the total length of 30 minutes. The Fast Fourier Transform was computed for every 2048 points leading to a total of 87 specimens which were used for ensemble averaging. The testing condition information including the wind velocity and root mean square (rms) of responses at the ground and top of buildings are listed in table 2.

For the parameter estimation methods, two techniques are used:

Transfer function fitting : In this method, the dynamic properties of the building are estimated by finding a known system whose transfer function can be matched well with the observed one. The observed transfer function can be calculated by using H1,H2 or Hv estimations depending on the existence of noise in the output, input or both. Here only the results of the Hv estimation are presented while all three estimations have been tried in the main research. For calculating the transfer functions, the response of the top of the building is considered the output where the input is either the response at the first floor or at the ground surface. As the known system, a single degree of freedom system or the first mode of a multi-degree of freedom system may be used. The latter has been used in this research. In this regard, although the natural frequencies (or periods) can be estimated properly, the damping ratios can be influenced by the participation factor (β) of the first mode in the total response of structure. In order to alleviate this problem, the ratio of the estimated damping ratio to the related participation factor is used as the representative of damping factor when the different cases are compared with each other. Also, it should be mentioned that the fittings were performed by using the amplitude of the transfer

Table2_ Testing condition information

Ref. Name	Weather Condition	Wind Direction	Wind Vel. (m/sec.)	Average rms @ ground		Average rms @ top	
				NS	EW	NS	EW
Eng1	fair	SSE	4.0	0.213	0.219	0.397	0.260
Eng2	fair	ESE	2.7	0.170	0.256	0.244	0.196
Eng3	cloudy	SSE	5.2	0.098	0.099	0.196	0.147
Eng4	fair	N	2.2	0.380	0.280	0.486	0.460
Eng5	fair	N	1.9	0.638	0.694	1.347	0.691
Eng7	fair	SE	2.2	0.374	0.367	0.273	0.251
Eng8	fair	SSE	3.4	0.264	0.218	0.278	0.228
Eng9	fair	N	2.4	0.277	0.261	0.406	0.393
Sc.A2	fair	SSE	5.0	0.339	0.502	0.897	0.616
Sc.E	fair	SSE	3.7	0.212	0.994	0.697	0.568
Agr.	slight rain	SE	1.5	0.362	0.229	0.814	0.938
Hyd.	fair	SSE	3.2	0.152	0.175	0.251	0.242
Res.	fair	NW	7.0	0.235	0.828	0.809	0.719
Eng1_N (3)	-	-	-	0.190	0.201	0.240	0.204
Eng1_N (4)	-	-	-	0.196	0.200	0.305	0.231
Eng1_N (5)	-	-	-	0.200	0.203	0.414	0.311
Eng1_N (6)	-	-	-	0.208	0.231	0.483	0.414
Eng1_N (7)	-	-	-	0.166	0.192	0.484	0.393
Eng1_N (8)	-	-	-	0.167	0.198	0.528	0.494
Eng1_N (9)	-	-	-	0.190	0.213	0.628	0.558
Eng1_N (10)	fair	NNE	3.2	0.204	0.221	0.715	0.685

functions and no complex curve fitting has been used. The reason will be discussed in detail in the next section.

Random Decrement (RD) technique : This method is based on the extraction of the free vibration motion from the recorded data by superimposing a sequence of intervals with the same phase.[13] This is done in a range of frequencies including the dominant frequency of the system. Hence, the data should be passed through a band pass filter before applying the technique. After extraction of the free vibration motion, the system's parameters can be estimated by conventional methods. It has been shown that this technique is applicable for the system identification of actual buildings.[14]

The selection of the frequency band for the curve fitting in the first method and for the band pass filtering in the second method plays an important role in these methods and sufficient attention should be paid to this point, especially in the case of short and stiff buildings where usually no sharp and clear peak exists in the transfer function or Fourier spectrum curves.

Results and Discussion :

Table 3 shows the estimated values for the natural periods and damping ratios for all the buildings. Three sets of results presented for each building are related to the following cases respectively: 1) Using the transfer function fitting method by considering the responses at the ground as the input for calculating the observed transfer functions, 2) The same as case #1 but using the responses of the first floor as input, 3) Using the RD method. It is believed that the results of the second case can be considered as a quasi-fixed base case because the sway effect is not included. So, it was expected to obtain longer periods and higher damping ratios for case #1 compared to the case #2. However, the resulted damping ratios are not generally compatible with this idea.

It should be noted of course that, the reliability of all the presented results is not equal. That is true even through the results of each specific case. For the case of using the transfer function fitting method (with using either the responses of the first floor or the ground as the input) a fitting error index related to the area under the observed and fitted transfer functions is introduced in order to estimate the accuracy of the results. However, the fitting error index only shows the suitability of the curve fitting process and the reliability of the final results should be examined by considering some other parameters such as the shape of the observed transfer function. For instance, the transfer function for three cases are presented in Fig. 2. All parts in the figure are related to the case of using the ground motion as the input of the system. Figure 2-a related to the NS direction of the Eng5 building is presented as a representative of the measurements which have been taken under a well controlled condition. A clear peak exits and the curve fitting can be performed well. However, there are a few other cases where more than one peak exists

Table 3_The estimated parameters for NS direction

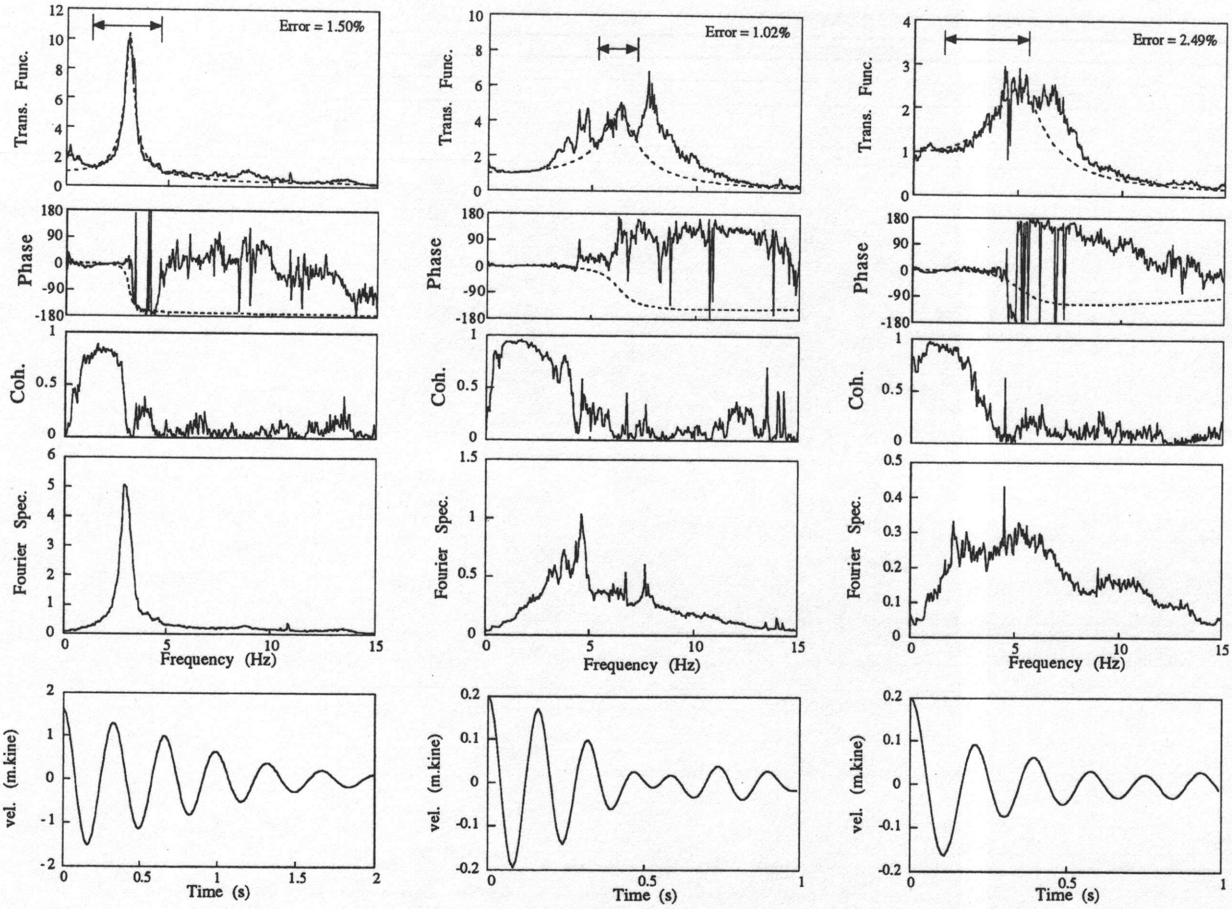
Ref. name	Transfer Function Fitting Method										RD Method		
	Top / 1st floor					Top / Ground							
	freq (Hz)	Period (S)	h	h/β	Error	freq (Hz)	Period (S)	h	h/β	Error	freq (Hz)	Period (S)	h
Eng1	5.13	0.195	0.134	0.102	1.82%	4.82	0.207	0.146	0.081	2.57%	5.08	0.197	0.117
Eng2	5.82	0.172	0.137	0.094	0.67%	5.51	0.181	0.134	0.093	0.86%	5.47	0.183	0.128
Eng3	-	-	-	-	-	5.25	0.190	0.310	0.142	2.29%	5.08	0.197	0.137
Eng4	6.93	0.144	0.243	0.113	3.42%	6.34	0.158	0.113	0.115	1.02%	6.64	0.151	0.132
Eng5	3.30	0.303	0.119	0.089	0.85%	3.06	0.327	0.057	0.048	1.50%	2.93	0.341	0.075
Eng7	6.64	0.151	0.184	0.115	0.45%	5.22	0.192	0.204	0.225	2.49%	5.08	0.197	0.161
Eng8	5.54	0.181	0.107	0.051	0.85%	5.15	0.194	0.093	0.057	1.46%	5.08	0.197	0.095
Eng9	4.72	0.212	0.156	0.076	1.43%	4.05	0.247	0.103	0.066	1.37%	3.71	0.269	0.089
Sc.A2	5.04	0.198	0.220	0.068	0.80%	4.48	0.223	0.096	0.040	2.70%	4.49	0.223	0.088
Sc.E	4.08	0.245	0.272	0.158	0.27%	3.48	0.287	0.055	0.031	1.43%	3.52	0.284	0.096
Hyd.	5.93	0.169	0.177	0.077	0.87%	5.36	0.187	0.122	0.060	3.57%	5.47	0.183	0.093
Agr.	3.70	0.271	0.189	0.080	3.70%	3.59	0.279	0.117	0.038	5.22%	3.32	0.301	0.114
Res.	3.37	0.297	0.054	0.018	1.41%	3.33	0.300	0.022	0.021	3.08%	3.32	0.301	0.056
Eng_N (3)	7.56	0.132	0.224	0.137	0.94%	9.10	0.110	0.150	0.261	0.96%	9.38	0.107	0.120
Eng_N (4)	5.67	0.176	0.194	0.093	0.66%	5.71	0.175	0.450	0.270	0.93%	4.30	0.233	0.203
Eng_N (5)	4.78	0.209	0.126	0.074	2.30%	4.60	0.217	0.217	0.177	1.61%	5.08	0.197	0.084
Eng_N (6)	3.05	0.328	0.086	0.076	5.55%	2.90	0.345	0.107	0.097	4.64%	2.73	0.366	0.101
Eng_N (7)	2.93	0.341	0.070	0.045	0.98%	2.74	0.365	0.065	0.056	11.60%	2.73	0.366	0.079
Eng_N (8)	2.67	0.374	0.071	0.039	0.56%	2.46	0.406	0.072	0.053	1.72%	2.54	0.394	0.104
Eng_N (9)	2.35	0.425	0.057	0.034	0.71%	2.23	0.449	0.059	0.043	1.00%	2.15	0.466	0.079
Eng_N (10)	2.09	0.478	0.051	0.030	0.54%	2.00	0.499	0.031	0.018	1.82%	2.06	0.485	0.042

β : Participation factor

Table3(cont.)_The estimated parameters for EW direction

Ref. name	Transfer Function Fitting Method										RD Method		
	Top / 1st floor					Top / Ground							
	freq (Hz)	Period (S)	h	h/β	Error	freq (Hz)	Period (S)	h	h/β	Error	freq (Hz)	Period (S)	h
Eng1	6.25	0.160	0.130	0.098	0.53%	6.12	0.163	0.121	0.130	1.99%	5.47	0.183	0.103
Eng2	5.95	0.168	0.118	0.102	0.58%	5.46	0.183	0.180	0.208	1.16%	5.08	0.197	0.140
Eng3	5.41	0.185	0.242	0.301	1.24%	5.99	0.167	0.216	0.229	2.50%	5.08	0.197	0.167
Eng4	4.81	0.208	0.114	0.080	0.54%	4.76	0.210	0.105	0.085	0.96%	4.69	0.213	0.101
Eng5	3.84	0.260	0.102	0.085	0.32%	3.42	0.293	0.117	0.127	1.14%	3.13	0.320	0.135
Eng7	5.55	0.180	0.060	0.049	1.22%	5.22	0.192	0.155	0.196	5.08%	5.47	0.183	0.107
Eng8	6.95	0.144	0.098	0.054	1.81%	6.03	0.166	0.085	0.049	1.29%	5.86	0.171	0.083
Eng9	5.06	0.198	0.207	0.097	2.25%	4.63	0.216	0.155	0.109	0.66%	4.10	0.244	0.152
Sc.A2	5.00	0.200	0.151	0.078	1.52%	4.67	0.214	0.104	0.046	2.45%	4.49	0.223	0.075
Sc.E	3.96	0.252	0.156	0.125	1.12%	3.66	0.274	0.083	0.067	1.77%	3.52	0.284	0.113
Hyd.	4.98	0.201	0.113	0.066	0.58%	4.57	0.219	0.084	0.050	2.03%	4.69	0.213	0.133
Agr.	3.85	0.260	0.119	0.041	2.93%	3.97	0.252	0.043	0.029	2.32%	4.10	0.244	0.047
Res.	3.17	0.315	0.036	0.029	1.11%	3.10	0.322	0.019	0.037	0.73%	3.13	0.320	0.030
Eng_N (3)	9.19	0.109	0.104	0.093	1.30%	11.62	0.086	0.153	0.421	1.08%	12.11	0.083	0.134
Eng_N (4)	7.17	0.139	0.175	0.080	1.32%	7.58	0.132	0.136	0.440	0.96%	7.42	0.135	0.121
Eng_N (5)	5.37	0.186	0.148	0.101	1.13%	5.17	0.193	0.244	0.263	6.57%	4.10	0.244	0.133
Eng_N (6)	4.55	0.220	0.138	0.082	3.58%	3.93	0.254	0.322	0.248	1.45%	-	-	-
Eng_N (7)	3.32	0.301	0.098	0.067	1.15%	2.90	0.345	0.100	0.098	1.26%	2.93	0.341	0.131
Eng_N (8)	3.01	0.333	0.111	0.059	1.05%	2.62	0.381	0.072	0.064	1.72%	2.54	0.394	0.095
Eng_N (9)	2.63	0.380	0.066	0.048	0.45%	2.42	0.414	0.076	0.061	1.09%	2.54	0.394	0.100
Eng_N (10)	2.32	0.431	0.070	0.039	0.75%	2.13	0.469	0.040	0.032	0.78%	2.15	0.466	0.067

or no clear peak can be distinguished. The examples for these cases are shown in Figs. 2-b,c which are related to the NS direction of the Eng4 and Eng7 buildings, respectively. In such cases, the band width for curve fitting should be selected according to the phase delay characteristics and possibility of torsion or interaction with the other direction. But even in the case of a suitable band width selection, although the natural frequency can be estimated properly, the damping ratio may not be a suitable estimation. For example in cases such as Fig.2-b, where a short band width is selected, although the fitting error is a low value, the reliability of the results for the damping ratio is unknown. Therefore, a qualitative judgement about the reliability of the results should be combined with the quantitative comparison of the results for a suitable conclusion. As already mentioned, the results of the RD method can be also affected by the shape of the transfer function. The problem rises for the cases with no clear peak or multiple peaks. Specially in the latter case, one may has to choose very narrow band pass filter which leads to generation of unsuitable free vibration motion and consequently, unreliable results (Fig.2-b). It should be mentioned that the whole record length (30 minutes) have been used in RD method for all cases in this research. It provides more than 15000 superimpositions in average which is quite adequate[15] and no problem exists in this regard. Also, a worth mentioning point about the RD method is its capability to consider the amplitude dependency of the results which can be done by employing the Ranked RD method (RRD).[16] The ambiguous cases were investigated in more detail by using this capability. However, its effect was



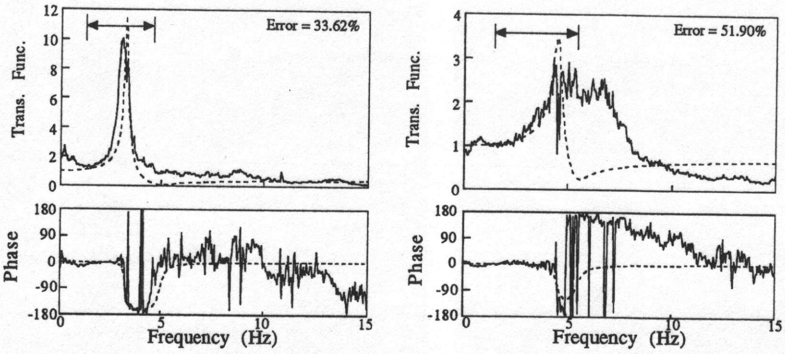
(a) Eng5 (NS) (b) Eng4 (NS) (c) Eng7 (NS)

Fig.2_ Representative examples, from top to bottom for each case:
Transfer function (top/ground + fitted curve), Phase delay (observed + fitted),
Coherence, Fourier spec. at top, Free vibration motion generated by RD method

negligible in comparison with the results' error related to the unsuitability of the generated free vibration motions. It is also used for some other cases and no remarkable change in the results is observed and even in some cases higher damping ratios are achieved for low amplitudes. So, only the traditional RD method results are used and presented here.

In relation to the transfer function fitting method, only the results of the transfer functions which are calculated by using the responses at the ground as input are presented. It is because no generally meaningful results are achieved in relation to the above mentioned quasi-fixed base idea . However, there are some cases where this idea works well. For example, the effect of SSI can be studied well in the case of Eng1_N building by comparing the 5th and 10th columns of table 3. The higher effect for the lower number of stories and larger foundations can be seen clearly. These results are compatible with the previous analytical studies[9] as well as the results in the next sections of the present paper.

Sensitivity of the results on the fitting methods : It was already mentioned that only the amplitudes of the transfer functions have been used for curve fitting and no complex curve fitting has been used. Here, it is discussed in more detail. Since the phase delay function can be easily affected by probable existence of noise on the system, it is evident that the results of the complex fitting are more sensitive to the testing conditions. Although under the well controlled conditions the complex curve fitting for transfer function can lead to good results, generally it is difficult to use the complex curve fitting method for all the cases. For example, the results of the complex curve fitting for cases "a" and "c" of Fig.2 are shown in Figs.3-a,b, respectively. It can be seen that even for the case of the Eng5 building which we had already put in the well controlled condition category, the complex curve fitting leads to a large error of about 34 percent. Of course, a better fitting for the phase delay function is achieved, but the transfer function fitting can not be acceptable. Also, the change in the estimated values can be distinguished by comparing the related figures. The change in the estimated system parameters is more evident in the case of the Eng7 building (Fig.3-b) where an error of higher than 50 percent is calculated for the complex curve fitting.



(a) Eng5 (NS) (b) Eng7 (NS)

Fig.3_Results of complex curve fitting for transfer function (top/ground)

<u>The effect of height of building on the results :</u> All the resulted natural periods for the curve fitting method, including the results of the different stages of the Eng1_N building are plotted in Fig. 4. A linear regression for the results leads to the following relationships for the NS and EW directions, respectively:

$$T = 0.01233\,H - 0.0037 \quad (1)$$

$$T = 0.01166\,H - 0.0074 \quad (2)$$

where T is the natural period of the building and H shows its height. The above results show a big difference in comparison to the empirical formulations which are proposed by different seismic codes. This can be mainly explained by the effect of non-structural members[17] and the fact that the structure behaves stiffer during the ambient vibration in comparison to their behavior during earthquakes.[18,19] The Building Standard Law of Japan[1] and ATC-03[2] give the following equations for Reinforced Concrete moment frame buildings, respectively, which are also plotted in Fig.4.

$$T = 0.02\,H \quad (3)$$

$$T = .061\,H^{3/4} \quad (4)$$

ATC-03 also offers the following formula for buildings with any structural system against the lateral loads except moment resisting frames:

$$T = \frac{0.09\,H}{\sqrt{D}} \quad (5)$$

where D is the dimension of the foundation in the direction of interest. Equation 5 which is more usable for the NS direction of selected buildings, gives the relationship of $T = 0.023\,H$ for the common width of D=15 meters in the selected buildings. This relationship leads to values higher than the Japanese standard and is not drawn in the figure. Figure 5 show the same results but using the RD method and the results are consistent. Here it should be mentioned that the results related to the Eng1_N building up to the 4-story stage don't lead to suitable transfer functions and different results can be

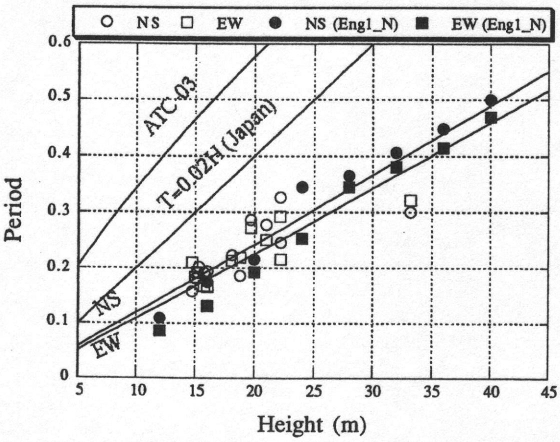


Fig.4_Distribution of period with the height of buildings (Trans. func. fit.)

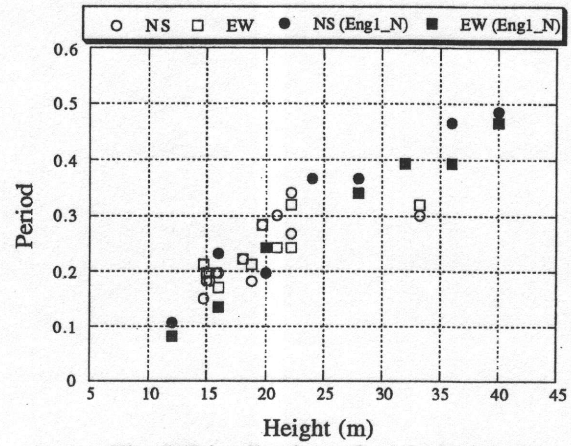


Fig.5_Distribution of period with the height of buildings (RD)

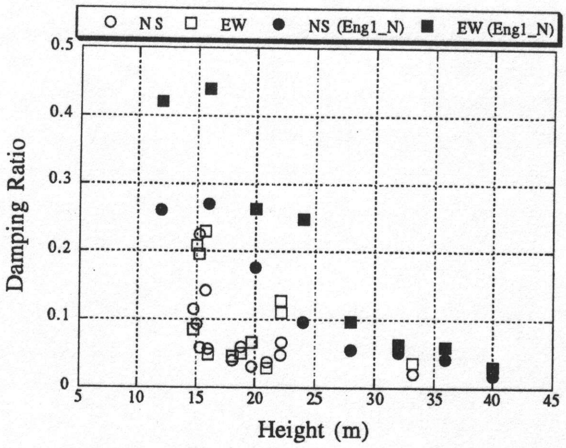


Fig.6_Distribution of the damping ratio with the height of buildings (Trans. func. fit.)

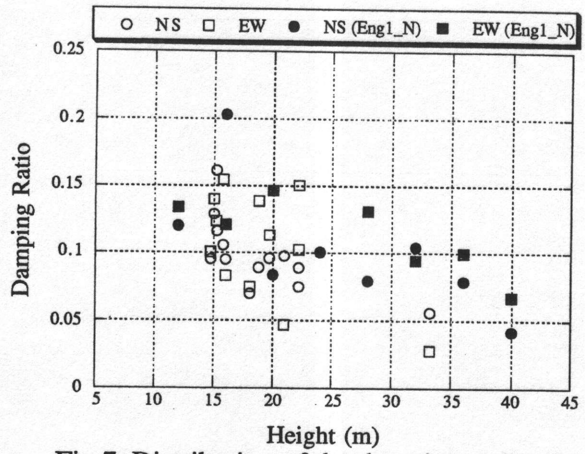


Fig.7_Distribution of the damping ratio with the height of buildings (RD)

achieved by choosing different band widths for fitting or filtering. The presented results are for band widths which are compatible with the general tendency for the higher number of stories. However, only the results related to the 4-story and taller stages have been used for regression. Also, the resulted damping ratios for the transfer function fitting method are drawn versus the height of the buildings in Fig.6. It represents a general tendency of lower damping ratios for taller buildings which may be interpreted as the effect of SSI. Although the site's soil condition is not the same for all buildings, generally one may conclude that the SSI effect is higher for short buildings. More specifically, the results of the Engl_N building, which are related to the different number of stories but the same soil condition, clearly lead to the same conclusion. From another point of view, the results show higher dispersion in the left hand side of the graph, i.e. for shorter buildings. This can be partly explained by SSI effect. There is an apparent difference between the results of the Engl_N building and the other buildings. This difference also may be explained by the effect of SSI because the Engl_N building has been located in the worst soil condition area in the campus where higher damping ratios can be expected. Also two of other high damped samples in the graph with damping ratios close to the Engl_N building belong to the Eng2 and Eng3 buildings which are located in the same area as the Engl_N building. Again, the results of the RD method are presented for comparison (Fig. 7). Two methods show the same tendency. However, the RD method generally results in higher estimations for taller buildings and lower estimation for shorter ones which consequently leads to a slighter change in the damping ratios (Note the different scale of vertical axes).

The effect of soil condition on the results : For evaluation of the effect of soil condition on the dynamic properties of the building, the natural periods and damping ratios are plotted versus the average N-value of the soil. Since the height of the building affects the SSI effect, the buildings are divided into two categories according to their height:
1) Short buildings including 3 and 4-story buildings
2) Moderate height buildings including 5 and 6-story buildings. The results of the transfer function fitting method for these two categories are shown in Figs. 8 and 9, respectively. The results of the 6-story stage of the Engl_N building is also included. A clear tendency of lower periods for stiffer soils can be seen for both NS and EW directions of moderate height buildings (Fig. 9-a). This can be demonstrated more strongly by considering the following about the EW direction of the Engl_N and both directions of the Sc.A2 buildings. The transfer function of the EW direction of the Engl_N building doesn't show any specific peak and the period may be increased by changing the selected band width. This unreliability can also be extended for the damping ratio. In relation to the Sc.A2 building, two points are significant. First, it is a 5-story building while the others, except the Hyd. building, are 6-story buildings. Secondly, the boring data investigation shows a sudden change in the stiffness of the soil at the depth of 4 meters, providing a layer on an almost rigid base case. So, given that the soil condition for the other cases can be approximately considered as

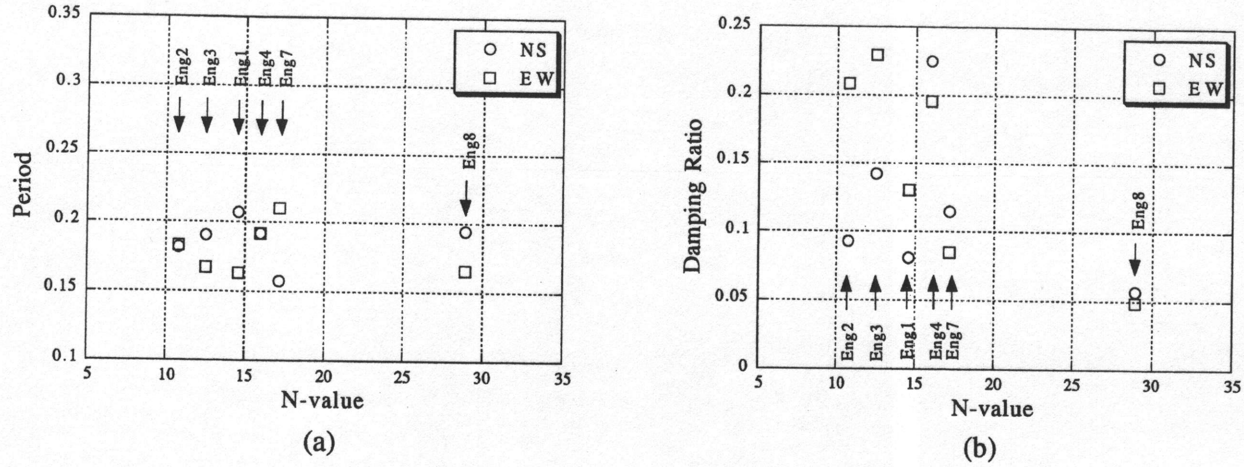


Fig.8_ Results of transfer function fitting method for short buildings

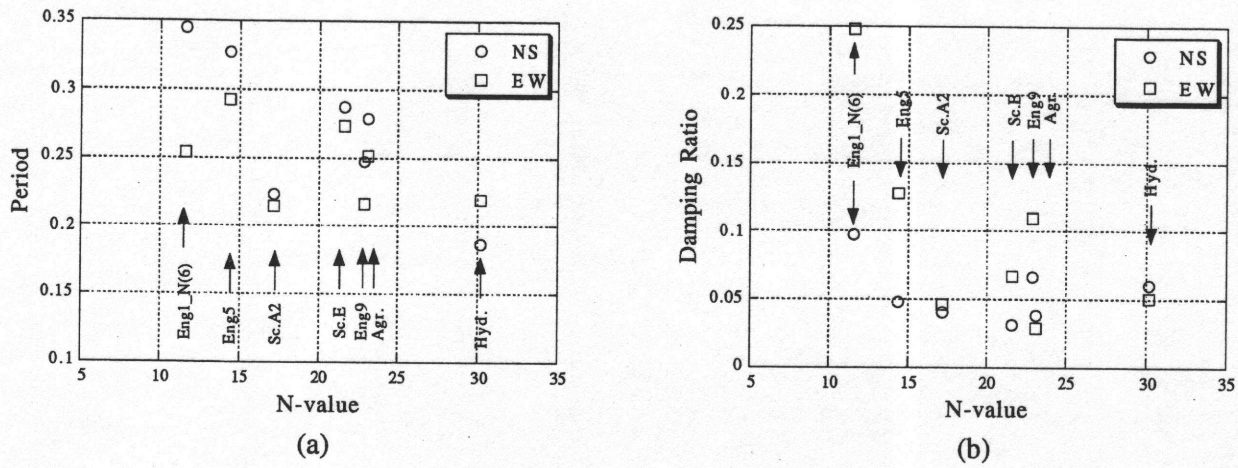


Fig.9_ Results of transfer function fitting method for moderate height buildings

a half-space, a lower effect of SSI will be reasonable for the case of Sc.A2 building. Figure 8-a shows the results for the case of short buildings, but no specific conclusion can be reached. The effect of SSI on the damping of buildings can be studied by Figs. 8-b and 9-b. By considering the above mentioned points about the Sc.A2 building, a general tendency of lower damping ratios for stiffer soils can be concluded, although it is not so clear for the case of NS direction. It should be noticed that the Hyd. building is a 5-story building and in comparison to the general tendency of the other 6-story buildings, a higher SSI effect can be reasonable for it. Considering this fact may help to clarify the figure, specially for the NS direction. Figure 8-b shows the same tendency for the EW direction of short buildings, but the data concerning the NS direction is inconclusive, especially given the unreliability of some results such as Eng4 and Eng7 buildings. By comparing Figs. 8-b and 9-b two conclusions can be reached. First, the effect of SSI can be seen more clearly in the EW direction, i.e. the longitudinal direction. Also, the rate of change of damping ratio with the change in the N-values is faster for short buildings. It means that buildings with lower aspect ratios (squat buildings) are affected by SSI more than slender buildings. Secondly, the short buildings generally show higher damping ratios which supports the conclusion of high SSI effect for shorter buildings. All the above mentioned conclusions are consistent with the results of analytical studies.[9]

Conclusion :

The microtremor tests were conducted on fourteen buildings located in the Higashiyama campus of Nagoya University and the results were used in order to evaluate the effect of the size of building and the site soil condition on the dynamic properties of buildings. The transfer function fitting and RD methods were used in order to analyse the recorded data. The sensitivity of the final results on the fitting methods such as using the amplitude or the complex value for fitting, shape of the transfer function and selected band width for fitting or band pass filtering are discussed. It was emphasized that a qualitative judgement about the level of reliability of the results should be combined with the quantitative comparison of the numerical results for a suitable conclusion. One should be more careful in cases where no clear transfer function exists, e.g. for the case of short buildings. The relationships 1 and 2 between the natural period and height of buildings were observed for the directions related to the short and long dimensions of the plan, respectively. These relationships produce much lower values in comparison to the conventional empirical formulas in the seismic design codes. Also, a high damping ratio, exceeding 25 percent in some cases, was observed in the buildings. These high damping ratios may be explained by the SSI effect by studying the effect of site soil stiffness on the results. Comparing the results of the same size buildings located on the sites with different soil conditions reveals that damping ratio can drastically vary for different soil conditions. It was seen that this SSI effect is higher for the case of larger foundations and shorter buildings, i.e. for squat buildings. The conclusion was confirmed by studying the change in dynamic properties of a 10-story building in different construction stages.

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