EARTHQUAKE RESISTANT DESIGN OF BUILDINGS ON SOFT GROUND

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ABSTRACT: In response to urgent need in Japan to establish earthquake resistant design method of buildings on the soft ground, a committee worked for the Tokyo Metropolitan Government by conducting case studies on the seismic safety of high-rise buildings to be constructed in the Tokyo waterfront subcenter. This paper summarizes the dynamic analysis of soft ground including liquefaction analysis, and response analysis of buildings with various types of foundation and various analytical models, including effect of ground nonlinearity and liquefaction. Important design parameters for the superstructures and foundations, such as peak acceleration, peak shear stress, peak displacement and so on, were analytically determined, and compared with the ones following the ordinary design procedure. This investigation provided important knowledge applicable in establishing earthquake resistant design method of buildings on the soft ground.

1. Introduction

The recent trend toward internationalization and the growing role of information in Japan have created needs for new buildings and urban environment. This trend is particularly evident along the shoreline of Japan's major cities, where high-rise and large scale buildings are being planned in order to provide a rich environment and functions required to turn these areas into new centers of urban activity. At the Tokyo waterfront subcenter, shown in Figure 1, high density developments centering upon multiple function facilities are planned, calling for a new form of architectural and urban space, in which atriums, skyways, artificial ground, and large underground space will be organically integrated with clusters of new buildings.

The ground of these areas is, in general, fill land beneath which thick alluvium soil deposited. There have been few examples of development of high-rise and large scale buildings on such soft ground, and no development of this kind has been subjected to an earthquake. The behavior of buildings on the soft ground, which is supposed to be quite different from the one on the relatively hard deposit, is not clearly known at present, mainly because of the lack of construction experience in these areas. Therefore, it is the one of the most important issues in

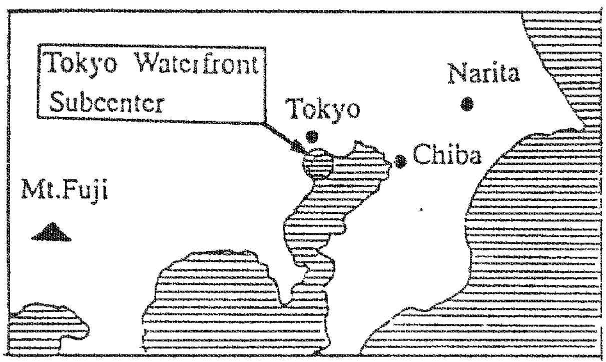

Figure 1. Tokyo waterfront subcenter

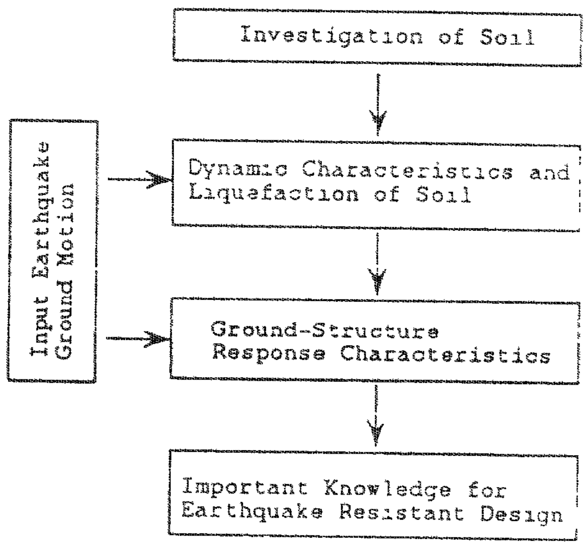

Figure 2. Flow chart

Japan to establish earthquake resistant design method of buildings on the soft ground, including nonlinear dynamic behavior of the ground and the soil liquefaction as well as their effect on the behavior of buildings.

Under these backgrounds, a committee on structural safety of buildings at waterfront areas was established in the Japan Building Disaster Prevention Association, under the auspices of the Tokyo Metropolitan Government, in 1989 for a three-year study of related problems. Under the chairmanship of the author, members of the committee conducted case studies on the seismic safety of buildings proposed to be constructed in the Tokyo waterfront subcenter. This paper summarizes results of the study of this committee, which was conducted as shown in the flow chart in Figure 2.

2. The Ground and Input Earthquake Motion

In the Tokyo waterfront subcenter area, explorations of the subsoil down to the top stratum of the so-called Kazusa Stratum have been performed at three locations shown in Figure 3: one each in Aomi district, Daiba district, and Ariake Minami district. They will be called in this paper location A, location D, and location AM, respectively. An outline of the strata formation based upon these subsoil explorations is shown in Figure 4, and the soil properties are shown in Table 1. Diluvial deposit starts from the Tokyo Gravel Stratum (Tog) which appears at depth 25 m to 40 m, and Tertiary deposit starts from the Kazusa Stratum (Ka) appearing at depth 70 m to 80 m.

As a part of the study of the above mentioned committee on structural safety of buildings at waterfront areas, a provisional input earthquake motion has been proposed. It was developed as the one corresponding to the level two earthquake motion for structural design (a possible maximum motion), considering the most effective earthquakes for the area in the past or in future.

A reference response spectrum was proposed, as shown in Figure 5, in the form of a pseudo velocity response spectrum with damping coefficient h = 0.05. This reference response spectrum corresponds to the earthquake motion of a free surface of engineering bedrock. The bed-

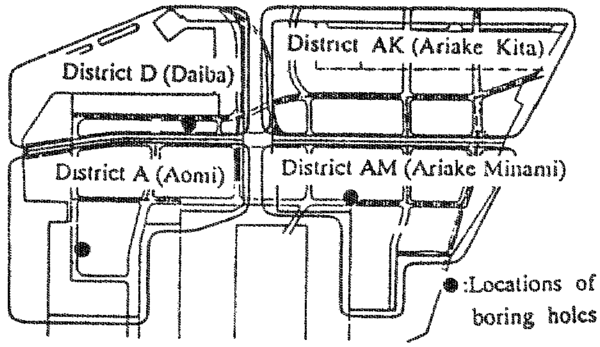

Figure 3. Districts of Tokyo waterfront subcenter

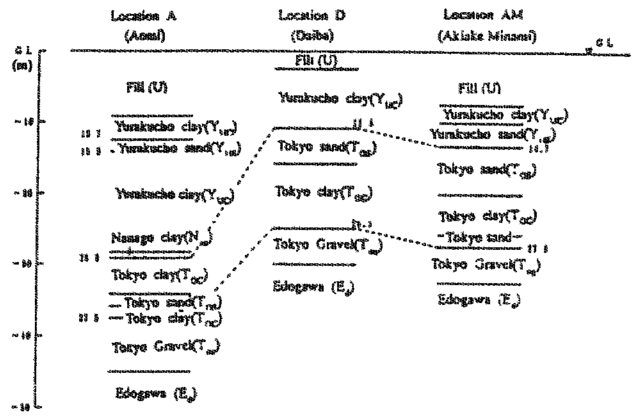

Figure 4. Outline of soil properties of Tokyo waterfront subcenter

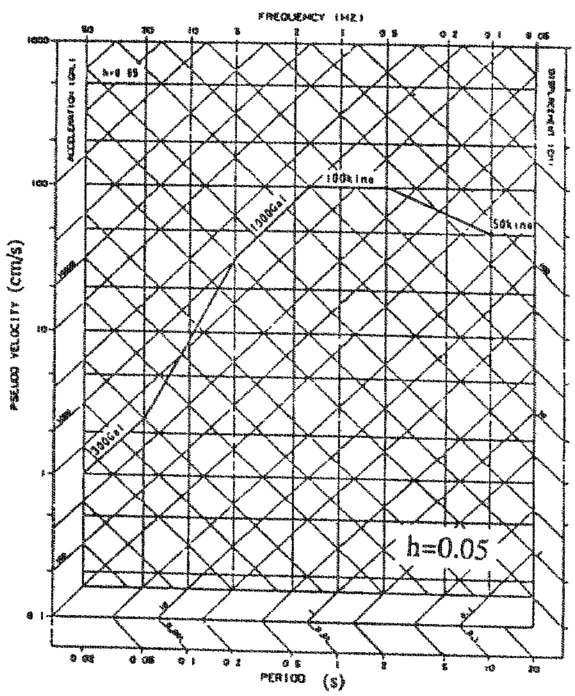

Figure 5. Pseudo velocity response spectrum

rock is assumed in the stratum with the secondary wave (S wave) velocity of 300 to 500 m/s, and in the Tokyo waterfront subcenter area it corresponds to the Tokyo gravel stratum or the Edogawa stratum.

A simulated earthquake motion for the free surface of the engineering bedrock was generated by superimposing sinusoidal waves with the phase characteristics of 1968 Hachinohe record EW component. In order to adjust the overall shape of the wave form, an envelope curve was applied which is similar to the Hachinohe record. Figure 6 shows the time history wave form of the simulated earthquake motion.

3. Dynamic Characteristics of the Ground

Response of the ground surface varies according to the vibration characteristics of surface strata at the site. Response analysis was performed of the surface strata at the three representative locations in the Tokyo waterfront subcenter area, for the proposed bedrock motion. The ground composition at the three locations is shown in Figure 4 and Table 1. The thickness of the alluvial deposit is 28.6 m at location A, where it is the thickest, and 11.5 m and 14.5 m at location D and location AM respectively.

The analysis was performed with a model consisting of masses for strata above the Edogawa stratum, while installing a dash pot at the base taking account of the effect of semi-infinite characteristics below the Edogawa stratum, the assumed engineering bedrock. The constants for the ground at location A are shown in Table 2. The stress-strain relationship of the ground is assumed to be a Ramberg-Osgood model conforming to the non-linear characteristics shown in Figure 7.

Figure 8 shows the transfer function of the ground at location A, and Figures 9 and 10 illustrate the maximum acceleration distribution in the surface strata and the pseudo velocity response spectrum for the ground surface at all three locations.

At location A, where the alluvial soil is the thickest, the first, second and third natural frequencies were 0.90 Hz (1.1 s), 2.73 Hz (0.37 s), and 4.55 Hz (0.22 s) respectively in the small strain range, but the predominant frequencies found from the transfer function of the response

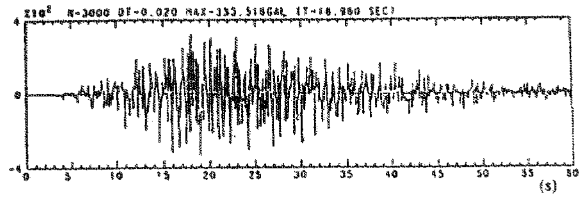

Figure 6. Time history wave form

Table 1. Soil properties of Tokyo waterfront subcenter

Location A(Aomi)

Soil Type	P Wave km/S	S Wave km/s	Unit Weight t/m³	Depth GL.-m
B	1.34	0.11	1.85	4.5
	1.34	0.11	2.08	6.7
Yuc	1.28	0.10	1.73	8.7
	1.48	0.13	1.62	13.7
Yus	1.54	0.18	1.81	15.8
Yuc	1.38	0.11	1.60	25.5
	1.40	0.17	1.72	27.7
Nac	1.54	0.28	1.65	28.8
Toc	1.53	0.23	1.75	31.5
	1.53	0.30	1.85	33.5
Tos	1.59	0.33	1.98	35.7
Toc	1.59	0.34	1.85	37.5
Tog	1.83	0.48	2.20	41.5
Eds	1.58	0.37	2.00	44.0
	1.37	0.38	1.92	47.5
	1.58	0.37	2.05	53.0
	1.70	0.51	2.09	54.5
	1.58	0.43	2.03	56.8
Edc	1.88	0.52	1.85	58.5
Edg	2.17	0.67	2.28	63.9
Ka	1.84	0.45	1.90	77.0
	1.80	0.35	1.83	83.0
	1.85	0.49	1.92	89.0
	1.74	0.54	2.08	109.0
	1.78	0.37	1.80	167.0
	1.83	0.60	1.92	200.0

Location D(Daiba)

Soil Type	P Wave km/S	S Wave km/s	Unit Weight t/m³	Depth GL.-m
B	1.54	0.21	1.52	2.5
Yuc	1.44	0.08	1.52	4.5
	1.55	0.13	1.50	11.5
Yus	1.81	0.17	1.70	14.5
	1.83	0.26	1.70	17.5
Toc	1.43	0.18	1.52	25.1
Tog	1.83	0.37	2.05	29.5
Eds	1.65	0.37	1.84	43.5
	1.65	0.37	1.92	51.0
	1.73	0.53	1.87	53.5
Edg	2.37	0.69	2.08	61.0
	1.71	0.43	2.08	65.0
Ka	1.73	0.49	1.87	78.0
			1.85	84.5
	1.85	0.80	1.86	89.5
			2.00	92.0
			1.87	104.0
			1.99	109.0
			1.87	149.0
			1.93	155.0
			1.87	160.0
			1.98	168.0
			1.87	187.0
			2.04	193.5
			1.95	200.0

Location AM(Ariake Minami)

Soil Type	P Wave km/S	S Wave km/s	Unit Weight t/m³	Depth GL.-m
B	1.37	0.10	1.55	2.5
	1.52	0.09	1.55	4.0
Yuc	1.52	0.09	1.55	8.5
	1.52	0.13	1.70	9.5
	1.52	0.12	1.75	10.9
Yus	1.57	0.15	1.85	12.5
	1.62	0.21	1.85	14.7
Tos	1.59	0.33	1.78	15.7
	1.65	0.30	1.88	18.6
	1.65	0.30	2.05	21.2
Toc	1.50	0.18	1.80	23.5
	1.47	0.25	1.85	25.3
	1.52	0.44	1.90	26.0
Tos	1.52	0.44	1.80	26.8
	1.73	0.49	2.07	27.9
Tog	1.91	0.46	2.20	32.4
Edc	1.34	0.39	2.00	33.8
	1.53	0.29	2.00	35.4
Eds	1.53	0.29	2.00	37.3
	1.72	0.38	2.10	43.5
	1.57	0.35	2.00	51.5
Edc	1.44	0.29	1.81	55.5
Eds	1.60	0.31	1.90	61.3
	1.98	0.47	2.22	64.5
Edc	1.67	0.38	1.35	66.5
Edg	2.24	0.63	2.25	73.5
Ka	1.58	0.31	2.00	74.7
	1.60	0.48	1.90	92.5
	1.68	0.52	1.93	121.3
	1.56	0.54	1.93	135.0
	1.71	0.58	1.93	159.0
	1.75	0.59	1.95	175.0
	1.69	0.57	1.90	200.0

Table 2. Property of soil (Location-A)

Layer category	Depth (m) GL.-	Thick-ness (m)	S-wave velocity (m/s)	P-wave velocity (m/s)	Density (t/m³)
Banking	3.0	3.0	110	1340	1.55
U	7.5	4.5	110	1340	1.55
	9.7	2.2	110	1340	2.06
	12.7	3.0	100	1250	1.73
Yuc	16.7	4.0	130	1480	1.62
Yus	18.9	2.2	160	1540	1.81
Yuc	28.5	9.6	110	1320	1.6
	30.7	2.2	170	1490	1.72
Nac	31.6	0.9	280	1540	1.55
Toc	34.5	2.9	230	1530	1.75
	36.5	2.0	300	1530	1.85
Tos	38.7	2.2	330	1590	1.98
Toc	40.5	1.8	340	1590	1.85
Tog	44.5	4.0	480	1830	2.20
Eds	59.9	15.4	600	1600	2.07

to the simulated earthquake motion were 0.48 Hz (2.22 s), 1.66 Hz (0.60 s), and 2.80 Hz (0.36 s). Thus, the predominant periods lengthen significantly with the plastic deformation of soils during a severe earthquake.

The maximum acceleration increased consistently from GL−44.5 m to GL−20 m, where it exceeded 300 cm/s^2. At shallower levels, however, it tended to decrease, and it was only 222 cm/s^2 at the ground surface, which was about the same as at the Edogawa stratum. The shear strain of the ground was large between GL−29 m and GL−20 m, where it ranged between 1.0 percent and 1.5 percent. In this way, the plastic deformation of the alluvial deposit prevented the increase of acceleration in the shallower strata. The maximum velocity at the ground surface was 58.3 cm/s, and the maximum displacement was 20.9 cm. In terms of the pseudo velocity response spectrum, the maximum response value exceeded 150 cm/s in the long period range between 1.9 s and 3.3 s, and the maximum value at 2.2 s exceeded 200 cm/s. It is anticipated that the response of high-rise buildings with natural periods of 2 to 3 s will become very large.

At the other two locations, location D and location AM, the alluvial layer is not as thick as at location A. The maximum acceleration and maximum velocity at the ground surface were 321.2 cm/s^2, 55.2 cm/s and 317.8 cm/s^2, 59.1 cm/s respectively. The maximum accelerations were greater than at location A, while the maximum velocities were about the same. The natural period range for large response tended to be shorter than that of location A, and the maximum response was reached at the natural period of 1.4 s in both cases.

Thus the difference in surface strata of the ground was shown to give significant effect on the response characteristics of the ground surface and of buildings.

4. Liquefaction of the Ground

The liquefaction of model ground was studied for the earthquake motion at locations A, D, and AM. Two methods were applied to the study. One was the total stress method in which the maximum shear stress was analyzed by a total stress analysis using the program SHAKE developed by Schnabel et al(1972), an equiva-

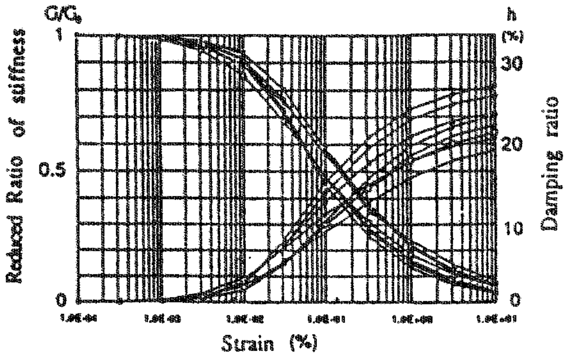

Figure 7. Non-linear property of soil

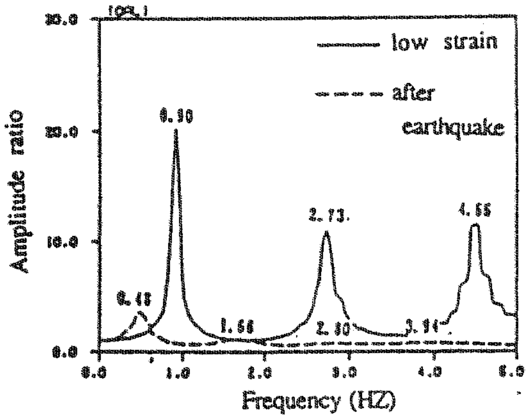

Figure 8. Transfer function of soil (ground surface/GL-44.5m)

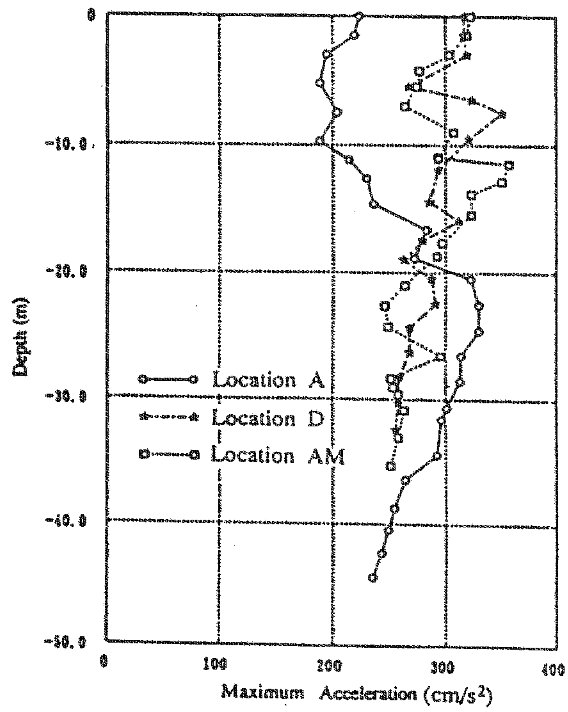

Figure 9. Maximum acceleration of soil

lent linear unidimensional earthquake response analysis program, and the liquefaction was judged by Ishihara's method (1982). The other was the effective stress method using the program YUSAYUSA developed by Ishihara and Towhata (1982), a unidimensional effective stress analysis program. The earthquake motion was set at two levels, level 1 and level 2. The level 1 earthquake motion was created by reducing the simulated earthquake motion by one-half, and the level 2 earthquake motion was the simulated earthquake motion as defined.

The ground model and the constants used in the analysis were the same as the previous section. The ground water level used for the liquefaction analysis was set at GL−3m to account for the fact that the water level is raised by the land filling operation. The liquefaction strength was determined from the result of liquefaction strength testing performed during the two boring explorations at location A. Figure 11 compares values obtained by the liquefaction strength test and the analytical simulation.

Figure 12 compares the maximum response values, while Figure 13 compares the time history response values at the ground surface at location D for two levels of earthquake motions, obtained from the total stress analysis and the effective stress analysis. Table 3 summarizes the liquefaction judgment for four cases. The symbol "X" in the table indicates that liquefaction occurred, while the symbol "0" represents cases in which liquefaction did not take place. The "triangle" means that liquefaction was judged to have not occurred, but the condition was imminent. Table 4 shows maximum response values of ground surface. These results lead us to the following conclusions about the behavior of the ground and the occurrence of liquefaction.

- Liquefaction is possible in three strata: the land fill stratum below the ground water level, the Yurakucho upper sandy stratum, and the Tokyo sandy stratum.
- Almost all locations partially liquefied, even during the level 1 earthquake. The level 2 earthquake liquefied almost all strata.
- The response of the land fill stratum and the ground surface were greatly influenced by the behavior of the soft viscous soil layer of the Yurakucho stratum. In other words, plastic deformation in this stratum reduces the trans-

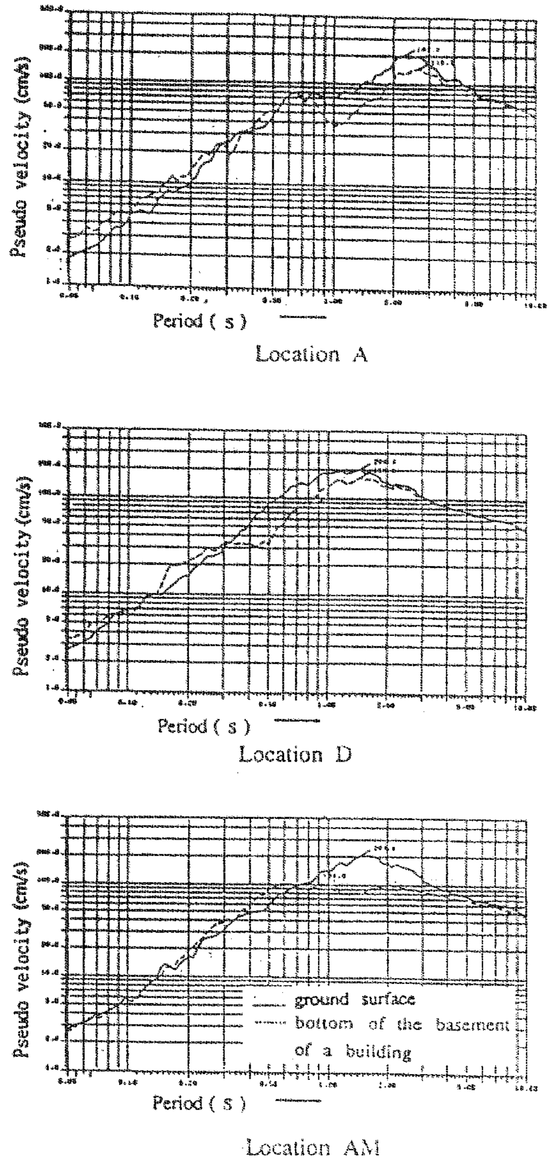

Figure 10. Pseudo velocity respo... spectra

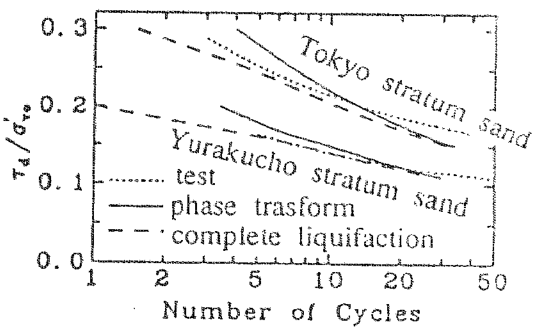

Figure 11. Simulation on liquefaction strength test