STRUCTURAL DAMAGE AND STIFFNESS DEGRADATION OF BUILDINGS CAUSED BY SEVERE EARTHQUAKES

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In order to check the effect of the severe earthquake on actual buildings, like the equivalent stiffness degradation, the natural periods of 205 buildings were investigated both before and after a 0.25∼0.4 G ground acceleration earthquake through the microtremor measurement. The average value of the natural periods ratios was 1.31. The shear crack damage could be found by visual observation in the buildings of which the natural periods ratio was more than 1.3. In the case of buildings which had the precast pile foundation on soft alluvial ground, the natural periods ratio was very large.

INTRODUCTION

The Sendai area was hit twice by strong earthquakes in 1978. Sendai city is a middle-sized city of 650,000 inhabitants and located about 350 km northeast of Tokyo. The first one occurred on February 20, 1978. The maximum value of the recorded ground acceleration was 0.15 G in Sendai. The second one occurred on June 12, 1978. The Richter magnitude was 7.4. The epicenter was located about 120 km east of Sendai. The maximum value of the recorded ground acceleration was 0.25∼0.4 G in Sendai. The quake caused a loss of 27 lives and the collapse of six reinforced concrete buildings and five steel frame buildings. But the collapse of buildings did not cause any loss of life. Some other reinforced concrete buildings and steel frame buildings were seriously damaged.

Before those two quakes, the natural periods of more than 200 buildings in Sendai had been investigated through the microtremor measurement. Immediately after the June earthquake mentioned above, the natural periods of those buildings were remeasured with the same method, in order to check the change of the natural periods and to estimate the equivalent stiffness degradation of them, mainly caused by the shocks of strong earthquakes.

INVESTIGATED BUILDINGS

The total number of the buildings investigated was 205. With respect to the construction, the number of the buildings was 96 for reinforced concrete construction, 93 for steel framed reinforced concrete construction and 16 for steel frame construction. There were five buildings which had only the transverse component data. Therefore, the total number of the whole components data was 405. The number of buildings with pile foundation was 61 and that with spread foundation was 144. There were thirteen precast pile foundation buildings out of fifteen buildings in Zone IV, which had very soft alluvial soil.

The schematic location plan of the Sendai area is shown in Fig. 1 with the positions of the buildings mentioned above. The four kinds of Zones are also given in Fig. 1 with Roman numerals. The definition of them in regard to the ground properties is given in Table 1. According to the construction

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Table 1 The zoning of the Sendai area and its geological properties

ZONE	NAME OF SECTION	USAGE OF AREA	GEOLOGICAL PROPERTIES
I	Yagiyama Aobayama Hachimanmachi (Tohoku Univ.)	residential area school zone	hill area of diluvial upland
II	(Center of City) (Sendai Station)	business area commercial area residential area	river terrace area of diluvial upland
III	Nagamachi Minaminome Minamikoizumi	commercial area residential area	alluvial plain
IV	Nigatake Rokuchonome	manufacturing area commercial area	soft ground (peat soils) of alluvial plain

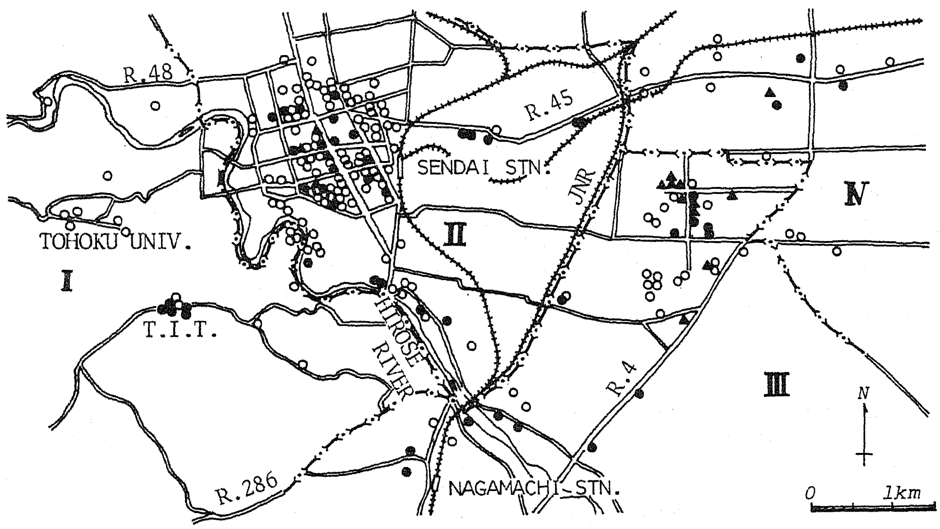

Fig.1 The schematic location plan of the Sendai area with the positions of the buildings, of which the natural periods were investigated both before and after strong earthquakes.

▲ : more than 50% stiffness degradation in the two components.
● : more than 50% stiffness degradation in the either component of the two.
○ : less than 50% stiffness degradation in any component.

types and the Zones, the numbers of buildings and the numbers of stories of the buildings are given in Table 2. Almost all of the buildings were from four to eleven stories buildings above the ground level.

MEASUREMENT OF NATURAL PERIODS

The moving coil type electro-magnetic seismometer with an inverted pendulum, of which the natural period was 1.0 second, was used as a micro-seismometer. The electrical output signals from two microseismometers of the longitudinal and the transverse components were simultaneously recorded on an analogue magnetic tape recorder. The eight milliseconds interval digitization of the records was done efficiently with the A-D converter. The power spectrum was computed from the sample record of ten seconds length which was selected from the three minutes original record.

RESULTS

In Fig. 1, the solid triangle marks indicate the buildings, of which the stiffness degradation was more than 50% in both the longitudinal and the transverse components. In other words, the natural periods ratio was more than 1.41 in the two components. The solid circle marks indicate the buildings, of which the stiffness degradation was more than 50% in one component only. There are 65 buildings (65/205=32%), of which the natural periods ratio was more than 1.41. It is remarkable that the more than 50% stiffness degradation occurred in half of the buildings in Zone III. The change of the natural periods, in other words the damage extent of the building, is dependent on the geological ground condition.

All components of 205 buildings were plotted in Fig. 2. All points are above the 45° dash line. This means that the shocks of the strong quakes made the natural period longer in all buildings. The average values of the natural periods ratio on whole components are given in Table 3, according to the Zone and the construction. The average value of the entire data is 1.31, i.e. the value of the equivalent stiffness degradation ratio is 0.42.

Table 2 The numbers of stories of the buildings above the ground level.

STORY	2	3	4	5	6	7	8	9	10	11	12	14	17	18	T L
R C	-	7	31	22	17	12	3	4	-	-	-	-	-	-	96
S R C	-	-	1	2	1	5	19	26	15	20	1	1	1	1	93
S	2	1	2	-	4	1	1	1	2	-	1	-	1	-	16
I	2	1	8	2	2	2	1	2	-	1	-	-	-	-	21
II	-	-	7	4	13	15	19	28	17	15	2	1	2	1	124
III	-	3	14	15	4	1	3	1	-	4	-	-	-	-	45
IV	-	4	5	3	3	-	-	-	-	-	-	-	-	-	15
T L	2	8	34	24	22	18	23	31	17	20	2	1	2	1	205

RC : reinforced concrete construction
SRC : steel framed reinforced concrete construction
S : steel frame construction

Table 3 The average value of the natural periods ratio.

ZONE	I	II	III	IV	AV
R C	1.18	1.25	1.36	1.32	1.29
S R C	1.25	1.32	1.42	1.34	1.33
S	1.40	1.20	1.27	1.48	1.25
A V	1.21	1.30	1.37	1.34	1.31

Table 4 The definition of the damage rank according to visual observation.

RANK	THE EXTENT OF DAMAGE
1	non-damage or almost non-damage like very fine cracks in structural and non-structural elements
2	almost non-damage in columns and beams and many fine cracks in RC shear walls or non-structural RC walls
3	slightly damage in columns and beams and many shear cracks in RC shear walls or non-structural RC walls
4	shear cracks in columns and beams or shear failure in RC shear walls or non-structural RC walls, and in steel construction braces buckled
5	shear failure in columns or severe shear failure with concrete spall-off in RC shear walls or non-structural RC walls

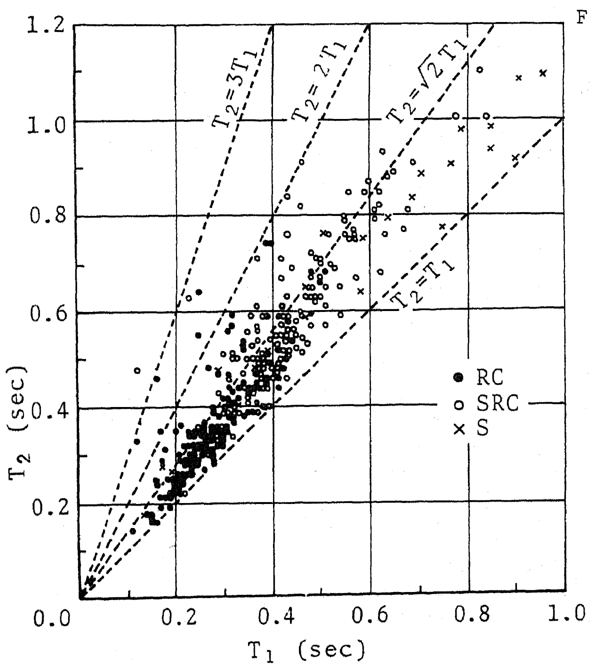

Fig. 2 The relation between the natural period measured before these two quakes (T1) and that measured after the quakes (T2).

$$T2/T1 = \sqrt{K1/K2}$$

$$(K1-K2)/K1 = 1-(T1/T2)^2$$

When the stiffness degradation ratio is 50%,

$$K2 = K1/2$$

$$T2 = \sqrt{2}\ T1$$

Wherein K : the eqivalent stiffness of the building.

The definition of the five damage ranks is given in Table 4, according to the extent of the damage on the buildings, observed immediately after the June quake. The more heavily the building had been damaged, the higher rank the building was given. The relation between the natural period before the quakes and the natural periods ratio is shown in Fig. 3 with special rank marks. In the case of the natural periods ratio was more than 1.4, the pile foundation buildings were indicated with rank marks in a big circle. The periods ratios of the relatively short natural period buildings were large, but those of the relatively long natural period buildings were small. The bigger the value of the natural periods ratio of the building was, the more severely the building was damaged. When the value of the natural periods ratio of the buildings exceeded 1.3, the shear crack damage could be found in the building by visual observation. The damage rank and the average value of the periods ratio are given in Table 5.

The relation between the natural periods ratio and the damage rank is shown in Fig. 4 (a)-(c). It could be roughly said from these diagrams that the relation between these two parameters was almost linear, except the case of Zone IV in Fig. 4 (b) and that of the precast pile foundation in Zone IV in Fig. 4 (c). In the case of the pile foundation in Zone IV, soft alluvial soil, the value of the natural periods ratio was much larger in the damage ranks 3 and 4 than other cases. This suggests that the damage might occur in the precast pile foundation.

Table 5 The damage rank and the average value of the natural periods ratio.

RANK	1	2	3	4	5	TOTAL
R C	1.15(70)	1.30(74)	1.44(28)	1.52(11)	1.74(5)	1.29(188)
SRC	1.13(16)	1.24(86)	1.44(60)	1.50(16)	1.53(7)	1.33(185)
S	1.17(10)	1.21(7)	1.30(13)	1.53(2)	-	1.25(32)
ZONE I	1.10(19)	1.21(8)	1.39(8)	-	1.54(2)	1.21(37)
ZONE II	1.15(48)	1.26(116)	1.41(66)	1.50(15)	1.58(3)	1.30(248)
ZONE III	1.21(23)	1.30(23)	1.42(24)	1.51(13)	1.65(7)	1.37(90)
ZONE IV	1.13(6)	1.32(20)	1.76(3)	1.66(1)	-	1.34(30)
SPREAD F.	1.15(58)	1.25(120)	1.43(78)	1.48(19)	1.61(8)	1.31(283)
PILE FOUNDATION	1.15(38)	1.31(47)	1.41(23)	1.57(10)	1.63(4)	1.31(122)
PILE F. IN IV	1.13(6)	1.35(16)	1.76(3)	1.66(1)	-	1.35(26)
TOTAL	1.15(96)	1.27(167)	1.42(101)	1.51(29)	1.61(12)	1.31(405)

Table 6 The average value of the natural periods ratio for the natural period before these quakes (T1).

	DILUVIAL UPLAND			ALLUVIAL PLAIN		
PERIOD : T1 (sec)	T1 < 0.3	T1 ≧ 0.3	TOTAL	T1 < 0.3	T1 ≧ 0.3	TOTAL
SPREAD F.	1.33(51)	1.29(190)	1.30(241)	1.29(30)	1.54(12)	1.36(42)
PILE FOUNDATION	1.17(20)	1.26(22)	1.22(42)	1.36(51)	1.34(29)	1.36(80)
TOTAL	1.28(71)	1.29(212)	1.29(283)	1.34(81)	1.40(41)	1.36(122)

The average value of the natural periods ratio of the buildings on alluvial soil was larger than that on diluvial soil. On the diluvial soil, the natural periods ratio of the pile foundation buildings was smaller than that of the spread foundation buildings. On the alluvial soil, the natural periods ratios were just the same in both the pile and the spread foundation. The largest value of the natural periods ratio was the case of the spread foundation buildings with the longer natural period than 0.3 seconds on the alluvial soil. The smallest value of the natural periods ratio was the case of the pile foundation buildings with the shorter natural period ratio than 0.3 seconds on the diluvial soil. These tendencies are shown in Table 6.

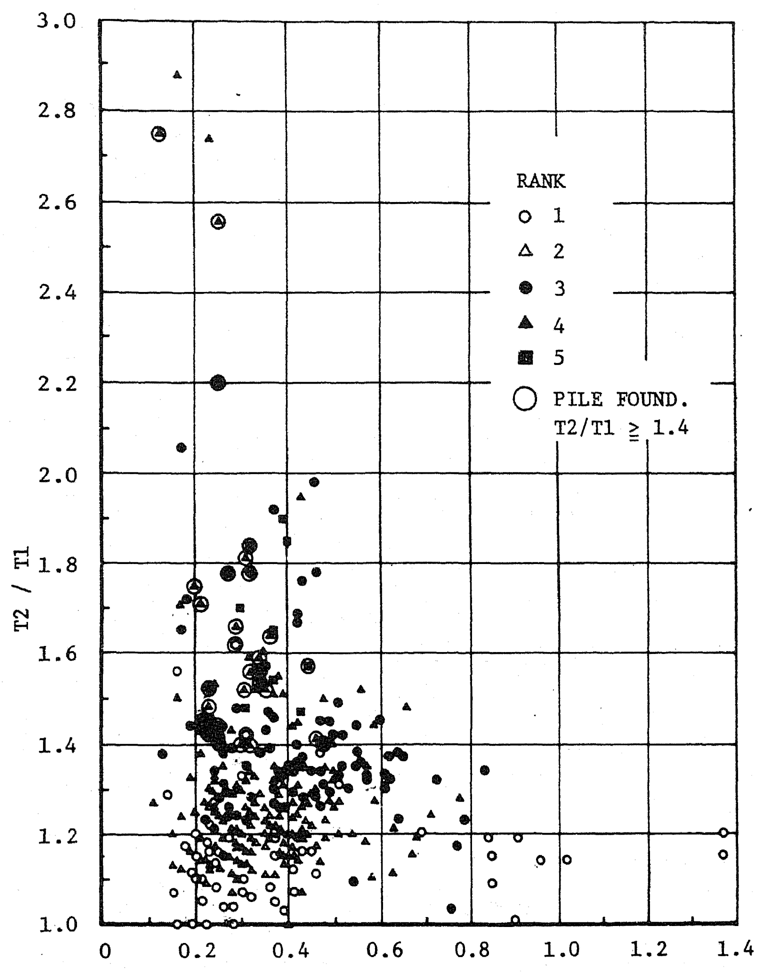

Fig. 3 The relation between the natural period measured before the quakes and the natural periods ratio (T2/T1), for the damage rank.

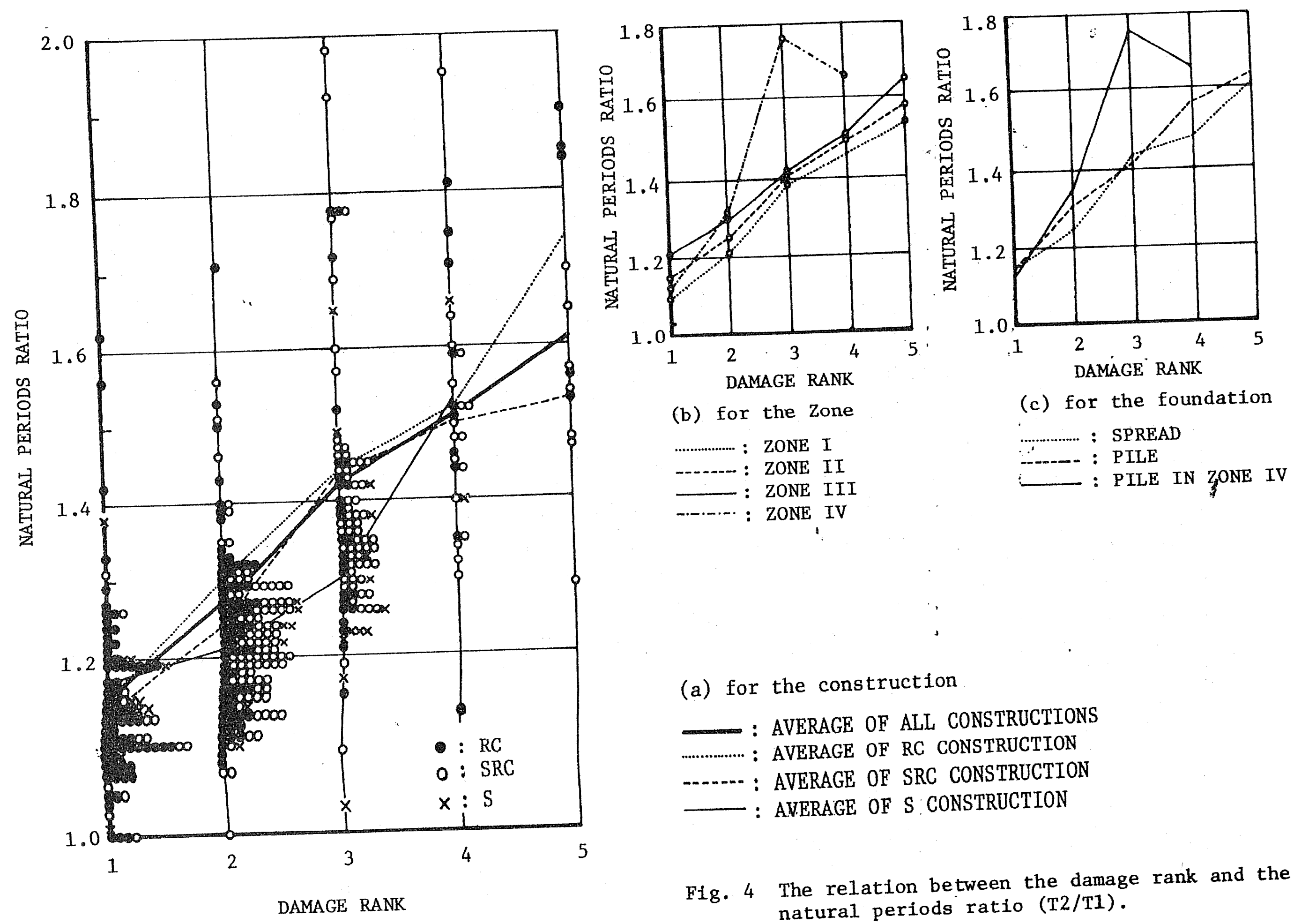

Fig. 4 The relation between the damage rank and the natural periods ratio (T2/T1).

CONCLUSIONS

It is a complex problem to discuss the effect of the strong earthquake to actual buildings. However, according to the results of the microtremor measurement both before and after the strong quakes in 1978, the following conclusions can be deduced:

1) The average value of the ratio of the natural period measured before the quakes to that measured after the quakes is 1.31 for the whole components of buildings. (0.42 in the expression of the stiffness degradation)
2) The average value of the natural periods ratio of the steel framed reinforced concrete construction is the largest, and that of the steel frame construction is the smallest.
3) There is a strong correlation between the damage extent and the value of the natural periods ratio of the building.
4) The shear crack damage can be found by visual observation of buildings, of which the value of the natural periods ratio is more than 1.3.
5) The average value of the natural periods ratio of the buildings on alluvial soil is larger than that on diluvial soil.
6) The largest value of the natural periods ratio is the case of the spread foundation buildings with the longer natural periods than 0.3 sec. on alluvial soil. On the contrary, the smallest value of the natural periods ratio is the case of the pile foundation buildings with the shorter natural period than 0.3 sec. on diluvial soil.
7) In the case of the pile foundation on soft alluvial soil, the value of the natural periods ratio is much larger than other cases. This suggests that the damage might occur in the precast pile foundation.
8) From the view point of the response spectrum, the largest value of the natural periods ratio was the case of the buildings which had the 0.2 and 0.4 seconds natural periods before the quakes.

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