INVESTIGATION ON THE EARTHQUAKE DAMAGE OF RC BUILDINGS BY CONSIDERING THE SOIL-STRUCTURE INTERACTION

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SUMMARY

RC buildings of a few stories are in many cases heavily damaged by strong earthquakes. In this report, we examine the relationship between the damage of RC buildings and the ground conditions which occured in the 1968 OFF-TOKACHI EARTHQUAKE (March 16, M7.9) and in the 1978 OFF-MIYAGI PREF. EARTHQUAKE (June 12, M7.4) respectively. We tried to study the earthquake damage of RC buildings by using an analytical model which was considered the interaction based on the DYNAMICAL GROUND COMPLIANCE THEORY. We found that we could then predict the earthquake damage of RC buildings, to some extent, by means of the analytical examination.

INTRODUCTION

It is necessary to investigate the earthquake damage of RC buildings in order to prevent earthquake disaster. This report is an investigation of the damage on RC buildings caused by the 1968 OFF-TOKACHI EARTHQUAKE and the 1978 OFF-MIYAGI PREF. EARTHQUAKE using the DYNAMICAL GROUND COMPLIANCE THEORY which takes into account the interaction between the soil and the structure. Various investigations were carried out into the structural properties, the grade of damage (completely-, heavily-, half-, slightly-destroyed and undamaged) and the ground conditions (soils, depth of each soil layer, depth to the bed rock and N-value etc.) of damaged and undamaged buildings. We then prepared an experimental expression which calculates the shear wave velocity from the data of soil exploration and calculates the frequency response function of each ground condition. We also examined the relationships between the damage of RC buildings and the ground conditions from various points of view and we understood that there was a comparatively clear correlation between the damage and the ground conditions. In order to investigate the above relationship analytically, we produced an analytical vibration model of buildings by spring-mass system which took into account the interaction of the soil-structure system. By the CONVOLUTION INTEGRAL METHOD we evaluated the incident seismic waves varying with the ground conditions from the seismic wave records observed near the sites respectively.

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We also made the elasto-plastic response calculation by using the above model and the various incident waves. We are reporting the results of this investigation because we can explain the relationship between the damage of RC buildings and the ground conditions by using the model considered in this report fairly well.

EXPERIMENTAL EXPRESSION OF SHEAR WAVE VELOCITY OF THE GROUND

In order to produce the seismic incident wave for the earthquake response calculation of RC buildings and calculate the frequency response function of the surface ground, it is necessary to estimate the physical constants of the ground especially the shear wave velocity. Therefore we made the experimental presumed expression of the shear wave velocity using the MULTIPLE REGRESSION ANALYSIS METHOD from the data of N-value, the kind of soil and the depth of each soil layer which constitute the surface multi-layered ground conditions obtained by the standard penetration test. The expression is

$$V_s = a . N^b . D^c \quad \text{.................................} \quad (1)$$

Vs ; Estimated shear wave velocity
N ; N-value obtained by the standard penetration test
D ; The depth from surface to the middle point of each soil layer
a, b, c ; Coefficients evaluated by the MULTIPLE REGRESSION ANALYSIS METHOD

By using the above expression, we could estimate the profile of the shear wave velocity corresponding to the arbitrary multi-layered ground conditions given by the standard penetration test at any site. The values of coefficients a, b and c correspond to the soil and the multiple correlation coefficients are given in Table 1. The relationship between the measured values and the estimated values of the shear wave velocity are indicated in Fig. 1

EARTHQUAKE DAMAGE OF RC BUILDINGS

The distribution of the buildings damaged by earthquake in the disaster-striken areas of the 1968 OFF-TOKACHI EARTHQUAKE and the 1978 OFF-MIYAGI PREF. EARTHQUAKE are indicated in Fig. 2-(a) and Fig. 2-(b), respectively. The types of structural damage of RC buildings were shear collapse or cracks of columns and walls arranged in the longitudinal direction of each building and such damage of the structure of RC buildings were frequent. From the boring data of damaged and undamaged sites, we judged the surface ground conditions which were grouped into four classes classified from the first class (I) that is comparatively hard ground to the fourth class (IV), that is very soft ground, according to the aseismic design code for architectural structure in Japan. We also examined the distribution of the damaged RC buildings corresponding to each class of ground condition. The result is indicated in Fig. 3-(a) and Fig. 3-(b).

We produced an analytical model of the ground which assumed that the surface ground is constituted of horizontal multi-layered conditions and we calculated the frequency response function of each ground model using the MULTI-REFLECTION THEORY of SH-WAVE incidents from the vertical direction.
The types of frequency response functions were grouped into four types and indicated in Table 2. Then we examined the relationship between the vibration

characteristics of the surface ground based on the frequency response function and the damage of RC buildings. The result is indicated in Fig. 4-(a) and Fig. 4-(b) and the damage ratio which was considered according to the damage grade is also indicated in Fig. 5-(a) and Fig. 5-(b) against the four classes of ground conditions and the four types of frequency response functions respectively. From these results, in the case of classified types based on the frequency response functions, it shows a tendency that the damage ratio is higher at the sites of A_2 and B types than any other types. The tendency corresponds to the fact that in the case of classified types based on the ground conditions the damage ratio is high in the second and third class in the OFF-TOKACHI EQ. and in the first and the second class in the OFF-MIYAGI PREF. EQ. and so the damaged RC buildings were often at the sites where there were comparatively hard ground conditions. That is to say, in ground conditions of A_2 type the predominant frequency is comparatively high (above 3.2 Hz) and in the B type also many predominant peaks appeared in the frequency domain but it is thought that at a site of this type the average property of ground condition is comparatively hard. When considering the interaction between the soil and the structure, it is thought that this tendency in the relationship between the damage and the ground conditions shows that RC buildings are more likely to be damaged in areas with conparatively hard ground conditions where there is no damping effect dispersing the wave energy into the underground.

Also we examined the distribution of damaged RC buildings according to the thickness of the surface soil (depth from surface to the bed rock) and the average shear wave velocity. The result is indicated in Fig. 6-(a) and Fig. 6-(b). In this result, the tendency was a little different between the both earthquakes. Many damaged buildings were distributed when the ground condition has a depth to the bed rock of about 20 m in the OFF-TOKACHI EQ. and above 30 m in the OFF-MIYAGI PREF. EQ. and the average shear wave velocity was about 250 m/s in both earthquakes.

VIBRATION ANALYTICAL MODEL OF RC BUILDING CONSIDERING THE INTERACTION BETWEEN THE SOIL AND THE STRUCTURE

We produced a vibration analytical model of RC building which considered the interaction between the soil and the structure in order to investigate the damage of RC buildings analytically. The analytical method concerning the interaction had already been given by the DYNAMICAL GROUND COMPLIANCE THEORY which quantitatively estimated the spring effect and the damping effect of the ground around the foundation. Using this method, the transfer function of the soil-structure system considering the interaction was calculated. In this report, we produce a vibration analytical model of spring-mass system which have vibration characteristics equivalent to the characteristics indicated in the above transfer function. In the case of horizontal harmonic excitation affecting a rectangular rigid foundation placed on a half-space elastic ground, the analytical solution for the displacement of the foundation had been given by the DYNAMICAL GROUND COMPLIANCE THEORY.

By using the GROUND COMPLIANCE elements f_{1H} and f_{2H}, the transfer function between the ground surface and the top of building for soil-structure system which is of shear type continumn placed on the half-space elastic ground is given by

$$\frac{U_{RF}}{U_{GL}} = \frac{A}{D_H} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

$$A = [4\ a_0\ (\frac{C_{20}}{C_2} \cdot \frac{\rho_0}{\rho}\frac{c}{b})(f_{1H} + f_{2H})]^{-1}$$

$$\ell_0 k = a_0\ (\frac{C_2}{C_{20}})(\frac{\ell_0}{b})$$

$$D_H = A \cos 2\ell_0 k - \sin 2\ell_0 k$$

U_{RF} ; displacement of top of building

U_{GL} ; displacement of ground surface

ρ_0, ρ ; density of ground and building

C_{20}, C_2 ; shear wave velocity of ground and building

a_0 ; non-dimensional frequency

$2\ell_0$; height of building

2b ; width of building foundation (excited direction)

2C ; width of building foundation (perpendicular to excited direction)

f_{1H}, f_{2H} ; ground compliance elements

We assumed that the physical constant of the half-space elastic ground was varied in 8 cases as shown in Table 3 and the scale of building was 30 m x 5 m x 5 m (b x c x ℓ_0). we calculated the transfer function of each case and the result is shown in Fig. 7. The vibration analytical model which has equivalent vibration characteristics to the above transfer function was the shear type spring-mass model with three degrees of freedom. We considered that the natural frequency of the first mode which is obtained from the frequency equation coincided with the natural frequency of the soil-structure system considering the interaction obtained from the transfer function. And we calculated the eigen values (periods and modes) of the spring-mass system and also calculated the damping constant from the transfer function by the half power band width method. The calculation results of the physical constants on the vibration analytical model corresponding to various ground conditions, by the above mentioned method are indicated in Table 4.

CALCULATION OF INCIDENT SEISMIC WAVE

The property of the incident seismic wave for the earthquake response analysis of buildings will be different according to the surface ground conditions. The seismic wave records were obtained by the SMAC type seismometer at HACHINOHE HOUBER, AOMORI PREF. in the 1968 OFF-TOKACHI EQ. and at TOHOKU UNIV., SENDAI CITY, MIYAGI PREF. in the 1978 OFF-MIYAGI PREF. EQ.. The ground conditions of both observation sites were known due to the boring data.

We calculated the seismic waves at the bed rock (Tertiary) from each observed seismic wave and reproduced the seismic wave on an arbitrary ground surface using the CONVOLUTION INTEGRAL METHOD, varying the thickness and shear wave velocity of the surface ground parametrically as shown in Table 5. The calculated seismic waves were used in the incident wave of the vibration analytical model. Examples of the incident seismic waves are indicated in Fig. 8.

RESULT OF RESPONSE CALCULATION

In order to investigate the damage of RC buildings analytically, we produced a vibration alaytical model considering the interaction varying at the surface ground conditions and we calculated the incident seismic waves corresponding to the same ground conditions. Then we made the elasto-plactic response calculation using the model and incident seismic waves. The elasto-plastic response calculation was made by assuming the restoring force characteristics called POWER FUNCTION TYPE in each story of the vibration model and yielding displacement which was 0.5 cm and the LINEAR ACCELERATION METHOD was used. The calculated response values were the maximum value of displacement, velocity and acceleration at the first story of each model in both the earthquakes and the results are shown in Fig. 9-(a) and Fig. 9-(b) against to the shear wave velocity of the ground. Each maximum response value shows the same tendency. The maximum response values are comparatively large at the ground conditions of 20 m depth to the bed rock and 250 m/s of shear wave velocity in the OFF-TOKACHI EQ. and 30 m depth to the bed rock and 150 m/s or 200 m/s of shear wave velocity in the OFF-MIYAGI PREF. EQ. and the maximum displacement values are much more than the assumed yielding displacement. We also compared the damage ratio of RC buildings (Fig. 6-(a) and Fig. 6-(b)) with the maximum value of displacement response obtained by calculation (Fig. 9-(a) and Fig. 9-(b)). The result is shown in Fig. 10. The result of response calculation shown above is the value for the ground condition when the maximum value was given. The damage ratio of RC buildings and the result of response calculation varied with the shear wave velocity of ground and the both varying tendencies coincided with each other comparatively well. We then thought that the maximum response values were given for the above mentioned mutual correlation between the vibration characteristics of building considering the interaction, the incident seismic wave and the ground condition.

CONCLUSION

The results of this investigation can be summarized as follows.

1) The experimental expression for estimating the shear wave velocity of each type of soil which constitutes surface multi-layered ground conditions from the data of soil exploration is

$$V_S = a \cdot N^b \cdot D^c$$

The expression corresponds well to the measured value of shear wave velocity.

2) In both earthquakes mentioned above, the damage of RC buildings corresponds relatively well to the surface ground conditions which are grouped into four classes according to the aseismic design code for architectural structures in Japan. It is thought that this result indicates the influence of the soil-structure interaction.

3) It is also found that the actual earthquake damage grades of RC buildings are well explained by the results of elasto-plastic response calculation of spring-mass analytical vibration model which considers the soil-structure interaction by using the DYNAMICAL GROUND COMPLIANCE THEORY.

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3. K. Ishida and Y. Osawa, "Transfer Function of Soil-building System Based on Analysis of Earthquake Motions Observed in and around Buildings (Part 1. Two Kinds of Buildings Having Different Foundation)," Trans. of A.I.J., No. 249, 1976.

Table 1 Values of the coefficients a,b and c used in the experimental expression.

(ALLUVIUM)

Soil	Data	a	b	c	R	σ
Clay	59	70.96	0.2300	0.1543	0.88	23.5
Silty Clay	35	28.23	0.3983	0.4698	0.88	47.6
Sandy Clay	26	147.0	0.1263	0.0160	0.81	27.8
Humus Clay	8	48.27	0.5211	0.0249	0.82	30.9
Silt	75	80.21	0.2555	0.1167	0.85	38.0
Clayly Silt	28	83.72	0.0556	0.1544	0.82	14.8
Sandy Silt	53	78.03	0.1030	0.2335	0.87	28.9
Humus Silt	12	44.24	0.3968	0.0812	0.88	10.1
Sand	78	84.91	0.1607	0.1661	0.93	23.8
Fine Sand	82	79.79	0.2055	0.1428	0.84	32.8
Medium Sand	30	56.12	0.3861	0.0557	0.86	68.8
Rough Sand	19	88.78	0.2184	0.1856	0.86	45.4
Clayly Sand	17	67.69	0.3298	0.1294	0.91	30.5
Silty Fine Sand	39	78.18	0.1778	0.1558	0.82	29.2
Silty Sand	43	70.56	0.2096	0.1941	0.86	30.9
Gravelly Sand	21	121.4	0.1546	0.0630	0.81	28.7
Gravel	86	74.39	0.3183	0.0498	0.85	47.5
Claly Gravel	14	138.1	0.2127	0.0032	0.87	39.9
Banking	72	109.5	0.1558	0.0760	0.71	36.8
Humus	8	42.11	0.3583	0.2218	0.95	83.5

(DILUVIUM)

Soil	Data	a	b	c	R	σ
Clay	50	185.5	0.0637	0.0597	0.71	22.8
Silty Clay	37	106.7	0.3236	0.0086	0.80	40.8
Sandy Clay	32	155.7	0.1439	0.0556	0.68	54.2
Silt	18	226.6	0.0391	0.0325	0.47	19.4
Loam	12	87.74	0.0345	0.3467	0.74	50.8
Sand	82	108.0	0.1370	0.1575	0.85	32.9
Fine Sand	31	125.4	0.0681	0.1468	0.84	24.9
Clayly Sand	19	180.0	0.0763	0.1253	0.62	46.9
Silty Sand	54	116.7	0.1007	0.1950	0.80	47.0
Gravelly Sand	43	156.4	0.0318	0.2266	0.80	50.7
Gravel	118	155.0	0.0578	0.2192	0.81	55.3

R : Multiple Correlation Coefficient
σ : Standard Deviation

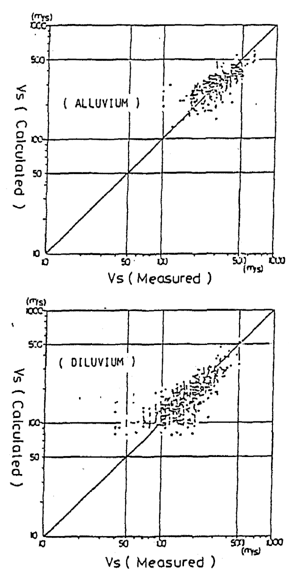


Fig.1 Correlation between the measured value and the calculated value of the shear wave velocity.

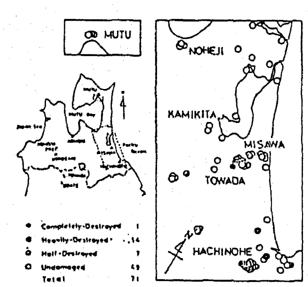
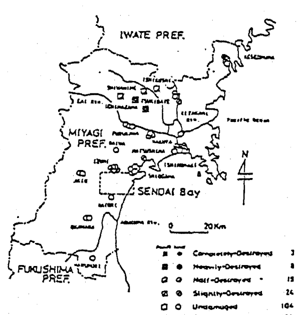


Fig.2-(a) Distribution of the RC buildings in the 1968 OFF-TOKACHI EARTHQUAKE.



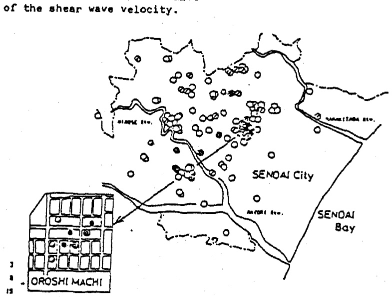


Fig.2-(b) Distribution of the RC buildings in the 1978 OFF-MIYAGI PREF. EARTHQUAKE.

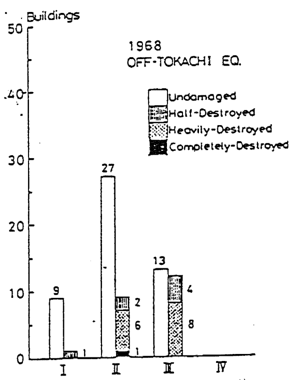


Fig.3-(a) Relationship between the damage of RC buildings and the ground conditions. (1968 OFF-TOKACHI EQ.)

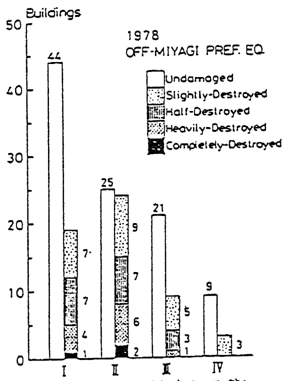
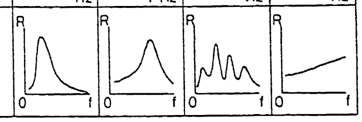


Fig.3-(b) Relationship between the damage of RC buildings and the ground conditions. (1978 OFF-MIYAGI PREF. EQ.)

Table 2 Classification of the ground condition by the pattern of frequency response function.

TYPE for Pattern of Freq. Response Function				
PATTERN \ TYPE	A-TYPE		B-TYPE	C-TYPE
	A_1	A_2		
Eminent Frequency f_0	one peak for $0<f_0<3.2$ Hz $0<f\leq 10$ Hz	one peak for $3.2\leq f_0$ Hz $0<f\leq 10$ Hz	more than one peak for f_0 $0<f\leq 10$ Hz	no peak for f_0 $0<f\leq 10$ Hz
Shape				



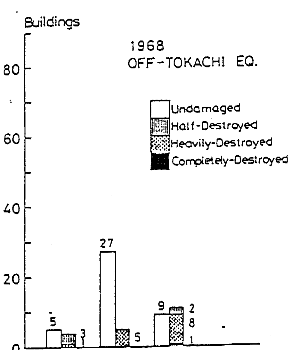


Fig.4-(a) Relationship between the damage of RC buildings and the types of ground conditions. (1968 OFF-TOKACHI EARTHQUAKE)

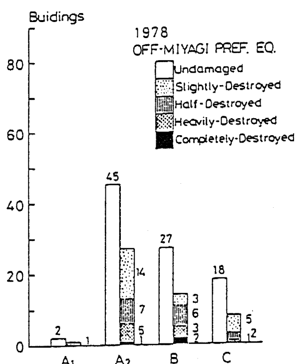


Fig.4-(b) Relationship between the damage of RC buildings and the types of ground conditions. (1978 OFF-MIYAGI PREF. EARTHQUAKE)

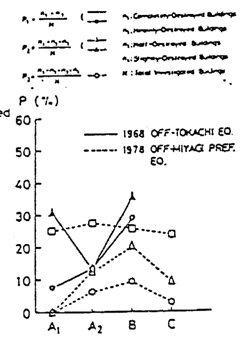


Fig.5-(a) Damage ratio of RC buildings in regard to the class of ground conditions. (1968 OFF-TOKACHI EQ.)

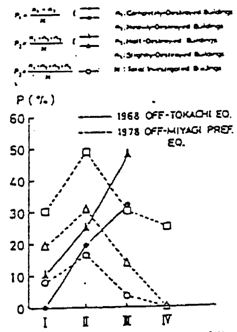


Fig.5-(b) Damage ratio of RC buildings in regard to the class of ground conditions. (1978 OFF-MIYAGI PREF. EQ.)

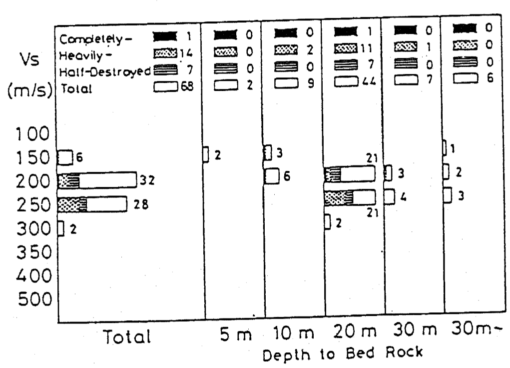


Fig.6-(a) Relationship between the damage of RC buildings and the surface ground conditions. (1968 OFF- TOKACHI EQ.)

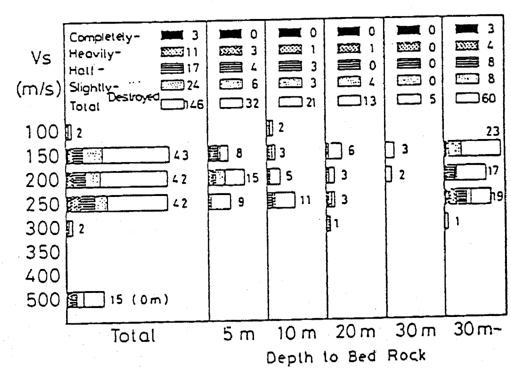


Fig.6-(b) Relationship between the damage of RC buildings and the surface ground conditions. (1978 OFF-MIYAGI PREF. EQ.)

Table 3 Assumed physical constants of the ground in order to calculate the transfer function of soil-structure system.

VS (m/s)	ρ_s (g/cm³)	σ (Poisson's Ratio)
100	1.60	0.40
150	1.70	0.38
200	1.70	0.36
250	1.80	0.34
300	1.80	0.33
350	1.90	0.31
400	1.90	0.29
500	2.00	0.25

Table 4 Calculted physical constants of the vibration analytical model.

No	VS (m/s)	ρ_s (g/cm³)	R	R/√2	ω_0 (rad/s)	ω_1 (rad/s)	ω_2 (rad/s)	h	X=M/K
1	100	1.60	2.042	1.44	19.63	10.83	33.07	0.565	0.00051
2	150	1.70	3.720	2.63	26.18	20.60	31.73	0.213	0.00029
3	200	1.70	5.958	4.21	27.32	24.64	31.42	0.124	0.00027
4	250	1.80	9.461	6.69	28.56	26.74	,	0.082	0.00024
5	300	1.80	13.275	9.39	29.92	27.80	,	0.060	0.00022
6	350	1.90	20.251	14.32	•	28.82	31.11	0.038	•
7	400	1.90	25.259	17.86	•	28.96	,	0.036	•
8	500	2.00	24.306	17.19	•	29.09	31.83	0.047	•

Vs ; S-Wave Velocity of Surface Ground
ρ_s ; Density of Surface Ground
R ; Magnification Factor Estimated by Transfer Function
ω_0 ; Natural Circular Frequency Estimated by Transfer Function
ω_1, ω_2 ; Two Circular Frequencies Correspond to The Value of $R/\sqrt{2}$
h ; Damping Constant Calculated by Half Power Band Width Method

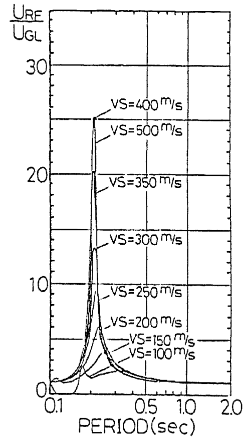


Fig.7 Transfer functions of soil-structure system.

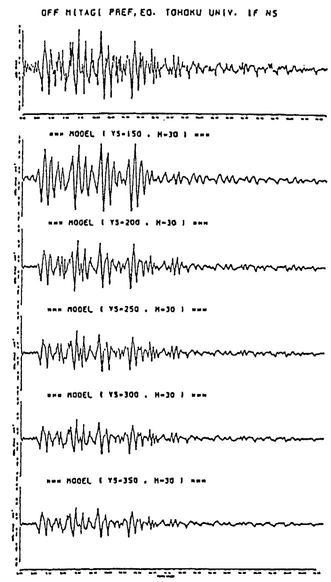


Fig.8 Examples of the reproduced incident seismic waves. (1978 OFF- MIYAGI PREF. EQ.)

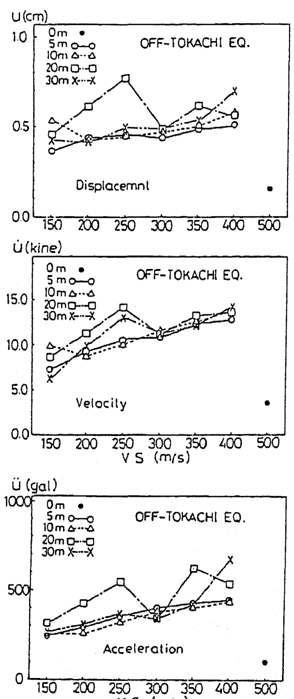


Fig.9-(a) Results of response calculation. (1968 OFF- TOKACHI EQ.)

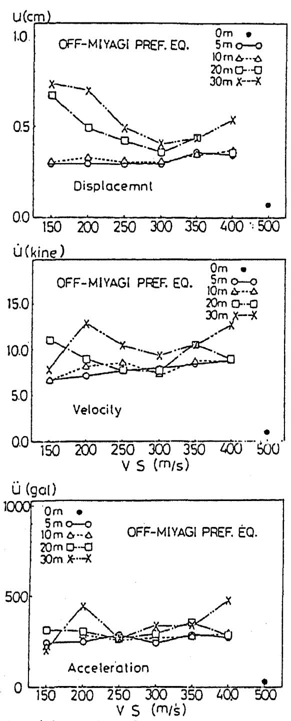


Fig.9-(b) Results of response calculation. (1978 OFF-MIYAGI PREF. EQ.)

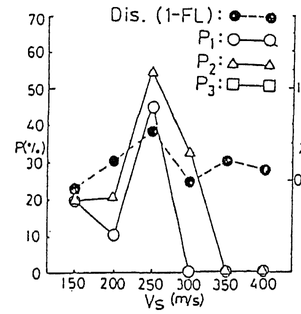


Fig.10-(a) Comparison the damage of RC buildings with the results of response calculation. (1968 OFF-TOKACHI EQ.)

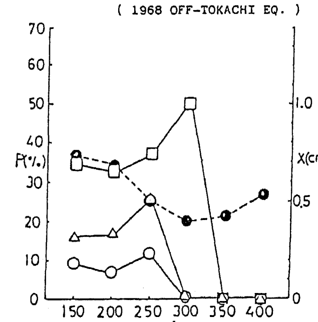


Fig.10-(b) Comparison the damage of RC buildings with the results of response calculation. (1978 OFF-MIYAGI PREF. EQ.)