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

5-2-16

ON RESPONSE AMPLIFICATION FACTOR DUE TO FOUNDATION INTERACTION IN STRUCTURES SUBJECTED TO SEVERE EARTHQUAKES

Kinya KURODA

Department of Architectural Engineering, Nagasaki Institute of
Applied Science, Aba-machi, Nagasaki, Japan

SUMMARY

In order to statistically investigate the inelastic behavior of structure-foundation systems during strong ground motions, the response amplification factor (R.A.F.) which presents the ratio of the response of the structure-foundation system to that of the rigid-based system is defined. Assuming that its frequency distribution is log-normal, the expected values are evaluated through a series of dynamic analyses for the planar unbraced steel frame-foundation systems. And they are discussed for the influence of the dynamic characteristics of earthquakes, the fundamental period of superstructures, and the sort of soil-foundations.

INTRODUCTION

The behavior of soil-foundation-structure systems subjected to strong ground motions has been investigated by many researchers during the last three decades. And some researchers (Refs.1-3) have made it clear that the effects of the structure-foundation interaction can cause either attenuation or amplification in structural response according to many parameters such as the dynamic characteristics of soils, foundations, structures, and input ground motions, as compared with the results of the rigid-based structure. Therefore in order to further discuss the effects of foundation interaction, it may be more preferable to use the statistical procedure for the analytical results of structure-foundation systems. The object of this investigation is to elucidate the statistical tendency in the elastic-plastic behavior of the unbraced steel frame-foundation systems during severe earthquakes. For that purpose, the response amplification factor (R.A.F.) which presents the ratio of the structural response with foundation interaction to that of the rigid-based structure is defined, and a series of elastic-plastic dynamic analyses for those systems is performed. And then, the frequency distribution and expected value of R.A.F. are evaluated from these results, and the statistical tendency of R.A.F. is discussed about the influence of the input ground motion, the fundamental period of superstructures, and the condition of soil-foundations.

DEFINITION OF RESPONSE AMPLIFICATION FACTOR

The analytical method has been previously published (Ref. 4) and employs the assumption that the superstructure consists of the members which have tri-linear flexural springs at their both ends as given in Fig.1. And also, the soil-foundation of a system is modeled as two nonlinear springs which are independent each other and present tri-linear hysteretic behavior for the horizontal direction and poly-linear one for vertical direction as shown in Fig.2, respectively.

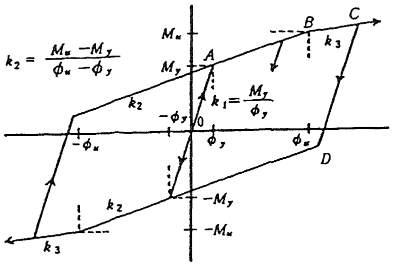
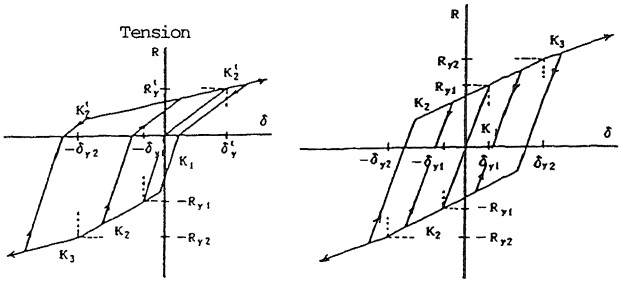


Fig. 1 Moment-Rotation Relation in Flexural Spring of Member



(a) Vertical Spring (b) Horizontal Spring

Fig. 2 Reaction-Displacement Relation of Foundation

Denoting the structural response of the structure-foundation system and the rigid-based system as Rf and Ro, respectively, the response amplification factor Ar can be defined by Eq.(1).

$$Ar = Rf / Ro \qquad (1)$$

where R presents displacement, velocity, acceleration, energy-absorption, and ductility factor in an analyzed system. Taking into account the specified conditions, a series of deterministic analyses is performed for the ground motions with different dynamic characteristics. From the results of these analyses, the R.A.F. for the structural response is evaluated by Eq.(1). Assuming the incremental interval of Ar as ΔAr and counting the number of Ar which lies between Ar,i and Ar,i+1, the frequency distribution and expected values are obtained if the log-normal distribution for the R.A.F. can be postulated.

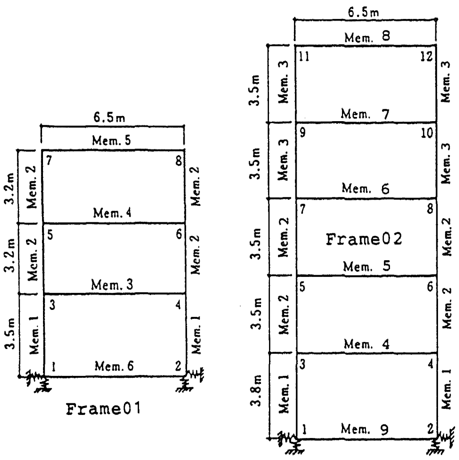


Fig. 3 Dynamic Frame Model

NUMERICAL EXAMPLES AND DISCUSSIONS

(a) Promises of Numerical Examples In order to statistically investigate the frequency distribution and expected value of the response amplification factor due to foundation interaction in the superstructure, the unbraced planar steel frames shown in Fig. 3 are analyzed. The resisting moment values of the flexural springs of members which are constant independently to the fundamental period are listed in Table 1 and 2. The stiffnesses of the elastic part of the members in the frame are modified so that the fundamental period of the rigid-based system becomes to the specified value, i. e. T1 = 0.25, 0.5, 0.75, 1.0, 1.25, and 1.5 seconds for the three-story frame, and T1 = 0.25, 0.5, 0.75, and 1.0 seconds for the five-story frame.

And also, three types for foundation springs are considered, taking into account the soft, medium, and stiff soils. Their mechanical properties are presented in Table 3 and 4. Moreover, the four cases in which the ratio of the first-order plastic stiffness to the elastic stiffness of a foundation spring lies on 0.25, 0.5, 0.75,and 1.0(linear) for each type of foundation springs are considered regarding to their nonlinearity as they are shown in Fig. 4.

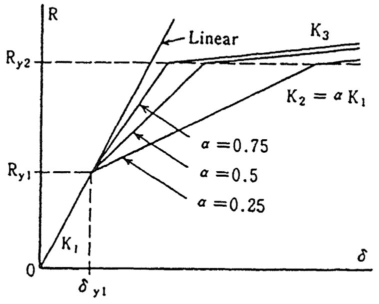


Fig. 4 Initial Foundation Property

Table 1 Yield and Ultimate Moment of Flexural Spring of Member (Frame01)

Mem. No.	1	2	3	4	5	6
My (tf·m)	23.52	20.02	22.32	17.59	14.16	30.00
Mu (tf·m)	25.87	22.02	24.55	19.35	15.58	33.00

Table 2 Yield and Ultimate Moment of Flexural Spring of Member (Frame02)

Mem. No.	1	2	3	4	5	6	7	8	9
My (tf·m)	45.17	34.51	21.02	66.50	60.14	48.55	32.04	19.70	55.0
Mu (tf·m)	49.69	37.96	23.12	73.15	66.15	53.41	35.24	21.67	60.50

The joint masses of these frames are constant irrespective of time and are given as follows.
For the three-story frame (Frame01),
$m_1 = m_2 = 0.0153$ tonf·sec^2/cm, otherwise $m_i = 0.01078$ tonf·sec^2/cm ($i=3,4,\ldots,8$)
For the five-story frame (Frame02),
$m_1 = m_2 = 0.0153$ tonf·sec^2/cm, otherwise $m_i = 0.01327$ tonf·sec^2/cm ($i=3,4,\ldots,12$)

As the input ground motions, the following three earthquakes are employed.

1. El Centro May 18, 1940 Comp. S00E
2. Taft July 21, 1952 Comp. S69E
3. Ferndale December 21, 1954 Comp. N46W

They are enlarged to 400 gals and the first 30 seconds components of them are imposed on the systems at the bottom of the foundation.

Table 3 Properties of Foundation (Frame01)

Spring Type		A	B	C
Horizontal	K_1 (tf/cm)	28.35	47.25	75.6
	K_2 (tf/cm)	1.42	2.36	3.78
	R_{y1} (tf)	14.0		
	R_{y2} (tf)	28.0		
Vertical	K_1 (tf/cm)	81.0	135.0	216.0
	K_2 (tf/cm)	4.05	6.75	10.8
	R_{y1} (tf)	65.0		
	R_{y2} (tf)	140.0		
	K_1' (tf/cm)	4.05	6.75	10.8
	K_2' (tf/cm)	2.03	3.38	5.4
	R_y' (tf)	21.0		

Table 4 Properties of Foundation (Frame02)

Spring Type		A	B	C
Horizontal	K_1 (tf/cm)	42.0	70.0	112.0
	K_2 (tf/cm)	2.1	3.5	5.6
	R_{y1} (tf)	30.0		
	R_{y2} (tf)	60.0		
Vertical	K_1 (tf/cm)	120.0	200.0	320.0
	K_2 (tf/cm)	6.0	10.0	16.0
	R_{y1} (tf)	120.0		
	R_{y2} (tf)	320.0		
	K_1' (tf/cm)	6.0	10.0	16.0
	K_2' (tf/cm)	3.0	5.0	8.0
	R_y' (tf)	15.0		

Table 5 Maximum Displacement of Top-Floor and Absorbed Energy in Rigid-Based Frame (Frame 01) (D_{max} in cm; E_{total}, E_{mem}, E_{ci}, E_{Hi} in tf·m)

Period		0.25	0.50	0.75	1.0	1.25	1.5
El Centro	D_{max}	1.83	6.60	10.73	14.67	16.76	19.12
	E_{total}	2.89	6.85	7.13	5.00	5.10	3.74
	E_{mem}	1.95	4.88	4.29	2.73	0.83	0.02
	E_{ci}	0.68	0.91	0.62	0.51	0.24	0.001
	E_{Hi}	0.22	0.87	0.81	0.55	0.17	0.003
	DF_{ci}	10.05	13.52	9.24	7.53	3.63	0.02
	DF_{Hi}	2.39	9.63	8.96	6.12	1.83	0.03
Taft	D_{max}	2.42	6.72	9.33	13.88	17.09	24.63
	E_{total}	3.68	5.45	6.36	4.21	3.01	5.30
	E_{mem}	2.81	3.47	3.02	1.27	0.59	0.88
	E_{ci}	0.78	0.54	0.22	0.03	0.12	0.26
	E_{Hi}	0.34	0.65	0.60	0.16	0.04	0.06
	DF_{ci}	11.66	8.03	3.29	0.46	1.79	3.85
	DF_{Hi}	3.81	7.16	6.66	1.77	0.40	0.65
Ferndale	D_{max}	2.08	10.40	20.00	30.11	34.84	33.06
	E_{total}	0.76	3.92	5.46	7.31	11.92	17.41
	E_{mem}	0.60	2.93	3.84	5.03	7.54	9.51
	E_{ci}	0.16	0.60	0.78	0.85	0.82	0.89
	E_{Hi}	0.09	0.52	0.69	1.03	1.54	2.02
	DF_{ci}	2.37	8.86	11.56	12.61	12.19	13.20
	DF_{Hi}	0.99	5.71	7.60	11.41	17.11	22.41

Table 6 Maximum Displacement of Top-Floor and Absorbed Energy in Rigid-Based Frame (Frame 02) (D_{max} in cm; Energy in tf · m)

Period		0.25	0.50	0.75	1.0
El Centro	D_{max}	2.59	7.75	11.79	18.64
	E_{total}	5.73	13.30	12.84	10.13
	E_{mem}	3.93	9.36	6.88	5.53
	E_{ci}	0.89	0.89	0.58	0.22
	E_{Hi}	0.29	0.64	0.24	0.15
	DF_{ci}	7.67	7.65	4.95	1.93
	DF_{Hi}	1.58	3.40	1.27	0.82
Taft	D_{max}	3.03	8.79	10.97	15.80
	E_{total}	7.03	10.61	11.92	9.08
	E_{mem}	5.50	6.60	5.49	1.71
	E_{ci}	1.01	0.70	0.50	0.17
	E_{Hi}	0.50	0.26	0.17	0.01
	DF_{ci}	8.66	6.02	4.34	1.47
	DF_{Hi}	2.67	1.41	0.93	0.05
Ferndale	D_{max}	1.81	9.41	20.97	29.84
	E_{total}	1.40	7.34	10.18	12.91
	E_{mem}	1.06	5.48	6.79	8.73
	E_{ci}	0.19	0.77	0.73	0.76
	E_{Hi}	0.16	0.87	0.81	0.85
	DF_{ci}	1.66	6.58	6.29	6.55
	DF_{Hi}	0.83	4.68	4.32	4.54

In the numerical integration of the differential equation of motion by the Newmark's algorithm, the time-step is chosen as $\Delta t = 0.005$ seconds. And the damping ratio is also assumed to be equal to 2 %. Considering the above-mentioned conditions, the deterministic analyses are performed for 30 rigid-based systems and for 360 structure-foundation systems.

(b) Results of Rigid-Based Systems From the analyses according to the above-described premises, the representative results for the rigid-based systems are given in Table 5 and 6. In these tables, each parameter presents the following maximum response of the structure.

Dmax = Displacement of the top-floor level
Etotal = Energy absorption caused by the input earthquake force
Emem = Total energy of the flexural springs of a superstructure
Ecl = Energy absorption in the bottom flexural spring of the first story column
EBl = Energy absorption in the flexural spring of the second floor beam
DFcl, DFBl = Ductility factor of the above-mentioned members, respectively

The results for the El Centro and Taft earthquakes show that the energy absorption of the superstructure significantly decreases in spite of the remarkable increase in the maximum displacement as the fundamental period of the rigid-based system becomes longer. In particular, the frames with the periods of longer than 1.0 second present the trend that they are liable to behave elastically during these earthquakes. On the contrary, the response of frames to the Ferndale earthquake increases in the energy absorption and the maximum displacement with longer fundamental period of the frame.

(c) Frequency Distribution of R.A.F. The R.A.F. for the given conditions is evaluated from the analytical results by using Eq.(1). The frequency distributions of the R.A.F. of the energy absorption of superstructures are presented in Fig. 5, 6, and 7 relating to the sort of an earthquake, the kind of a foundation spring, and the period of the rigid based frame, respectively. And the regression equations approximated under the assumption of the log-normal distribution for the R.A.F. are also described in the figures.

In regard to the input ground motions, the R.A.F. of Emem ranges from 0.2 to 3.8 for the El Centro motion, 0.2 to 2.2 for the Taft motion, and 0.6 to 6.2 for the Ferndale motion as shown in Fig. 5. For all earthquakes, the highest value of the R.A.F. of Emem occurs in the case that the fundamental period of the rigid-based frame is 0.25 seconds. Especially for the Ferndale earthquake with long-period components, the increase of the R.A.F. by the effect of the foundation interaction is much more prominent than those of another two earthquakes. Hence it can be likely said that the response of energy absorption in the structure-foundation system can be amplified when being subjected to the earthquake load with the long-period components and that the R.A.F. of Emem may lie on wider range then.

Concerning the kind of a foundation shown in Fig.6, the R.A.F. of Emem represents 0.2 to 5.0 for the soft foundation A, 0.4 to 6.2 for the medium foundation B, and 0.6 to 4.8 for the stiff foundation C. It is clear from these frequency distributions of the R.A.F. of Emem that its range becomes wider with softer foundation condition.

As to the effect of the the fundamental period of the superstructure, the R.A.F. of Emem shows significantly distinguishing characteristics. As shown in Fig. 7, it ranges from 0.4 to 6.2 for the period of 0.25 seconds, 0.4 to 1.6 for the period of 0.5 seconds, 0.2 to 1.6 for the period of 0.75 seconds, and 0.4 to 1.8 for the period of 1.0 second, respectively and the value of the R.A.F. of Emem decrease rapidly as the fundamental period of a superstructure becomes longer. This result indicates conspicuously that the buildings with shorter fundamental periods can be seriously affected by the foundation interaction.

The frequency distributions of the R.A.F. of the top-floor displacement are presented in Fig. 8 for the sort of foundations. The values of the R.A.F. of Dmax are generally a little larger than those of Emem. For instance, the R.A.F. of Dmax ranges from 0.8 to 8.0 for the foundation A, 0.8 to 7.2 for the foundation B, and 0.4 to 4.4 for the foundation C. And then, the tendency of its frequency distribution is very similar to that of Emem which is mentioned above. This figure shows that the effect of the rocking due to the foundation interaction is apt to increase the top-floor displacement as compared with the case of the rigid-based frame.

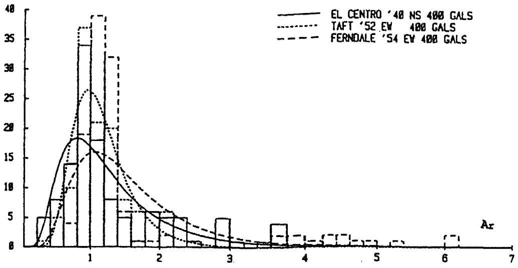


FIG. 5 FREQUENCY DISTRIBUTION OF RESPONSE AMPLIFICATION FACTOR IN ENERGY BY SUPER-STRUCTURE UNBRACED PLANE FRAME

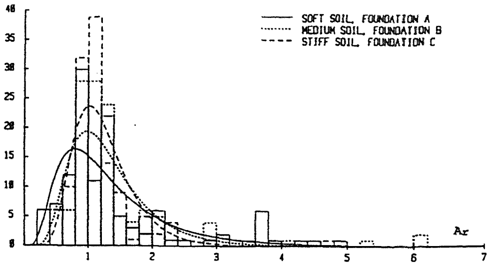


FIG. 6 FREQUENCY DISTRIBUTION OF RESPONSE AMPLIFICATION FACTOR IN ENERGY BY SUPER-STRUCTURE UNBRACED PLANE FRAME

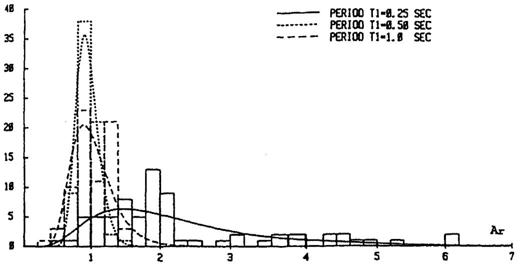


FIG. 7 FREQUENCY DISTRIBUTION OF RESPONSE AMPLIFICATION FACTOR IN ENERGY BY SUPER-STRUCTURE UNBRACED PLANE FRAME

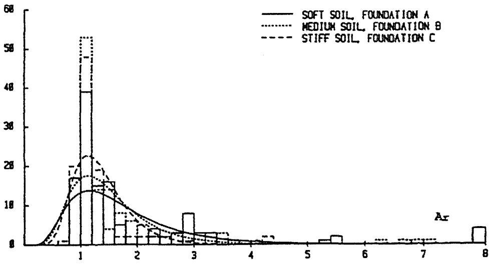


FIG. 8 FREQUENCY DISTRIBUTION OF RESPONSE AMPLIFICATION FACTOR IN TOP-FLOOR DISPLACEMENT UNBRACED PLANE FRAME

(d) Expected Value of R.A.F. In Table 7, the representative expected values of the R.A.F. for the log-normal distribution are given. In general, the expected values of the maximum displacement of the top-floor show a tendency to become larger than 1.0 because the period of the structure-foundation system should be longer than that of the rigid-based system. And, as shown in this table, its expected value comes to 1.73 for the Ferndale earthquake, and 1.74 for the foundation spring A. Therefore, it can be remarkably pronounced that the response of the maximum displacement including foundation interaction has an obvious tendency to significantly increase against the earthquakes which have the longer-period components, and for the softer foundation spring as compared with the corresponding response of the rigid-based system.

The above-mentioned tendency about the maximum displacement is very similar in the energy absorption by the input earthquake force Etotal. In fact, the expected value of Etotal amounts to 1.74 for Ferndale and 1.55 for the foundation A, and the effects of the foundation interaction is strongly prominent for these cases. This tendency in the energy absorption of a superstructure Emem becomes less distinct although it also shows the same trend. However, the expected value of the R.A.F. in the flexural springs of members Ec1 and EB1 appear to be somewhat different from the above-described tendency. For the case of the El Centro earthquake, the expected value of the R.A.F. of Ec1 is conversely 20.3 % smaller than that of Emem, despite the fact that the corresponding value of EB1 is 10.8 % larger than it. And the same tendency can be observed in the case of the 0.25 seconds.

Therefore, it can be statistically concluded that the value Emem influenced by the foundation interaction may be liable to become larger in comparison with that of the rigid-based frame and the energy absorbed in the elastic-plastic flexural springs of the particular members can increase more conspicuously than Emem. This fact means that the energy concentration into some members of a superstructure can sufficiently occur.

And besides, the response in the frames with some specific parameters subjected to the particular earthquakes can be close to the resonance by considering the foundation interaction as described before. Although the occurrence of the resonance may not be so frequent, it can be prone to prominently increase the expected values of the response amplification factor.

Table 7 Expected Value of Response Amplification Factor Relating to Earthquake and Foundation Spring (Log-Normal)

	Eq.	El Cen	Taft	Fern.
Earthquake	D_{max}	1.49	1.39	1.73
	E_{total}	1.30	1.22	1.74
	E_{mem}	1.28	1.16	1.54
	E_{CI}	1.02	1.60	1.48
	E_{BI}	1.39	1.23	1.52
	DF_{CI}	1.02	1.60	1.48
	DF_{BI}	1.39	1.23	1.52
Sort of Foundation	Found.	A	B	C
	D_{max}	1.74	1.51	1.36
	E_{total}	1.55	1.40	1.28
	E_{mem}	1.39	1.34	1.25
	E_{CI}	1.43	1.33	1.31
	E_{BI}	1.54	1.33	1.32
	DF_{CI}	1.43	1.33	1.31
	DF_{BI}	1.54	1.33	1.32

CONCLUSION

This study has presented the concept of the response amplification factor due to the foundation interaction in the superstructure in order to statistically elucidate the dynamic elastic-plastic behavior of the structure-foundation system during an intense earthquake. And through a series of analyses, the frequency distribution and expected value of R.A.F. under the assumption of the log-normal distribution have been evaluated for the given conditions considering the sort of an earthquake, the kind of soil-foundation, and the fundamental period of a rigid-based frame. Consequently, the following conclusions can be summarized from these analyses and examinations.

(1) The short-period frame, the long-period ground motion, and the soft foundation are remarkably susceptible to significantly increase the structural response of frames during severe earthquakes by the effect of foundation interaction.

(2) A few extremely large response values by the resonance of vibration can enlarge the distribution range of the R.A.F. and push up its expected value.

(3) The effects of the rocking and the elongation of the fundamental period due to the foundation interaction are likely to increase the maximum top-floor displacement as compared with the case of the rigid-based frame.

(4) The proposed R.A.F. can be very useful to describe the behavior of the superstructure with foundation interaction. Although the distribution range of R.A.F. becomes here very wide and its expected value is pushed up by a few extremely large values due to the resonance because the parameters used in this paper include many conditions, they should be more confined in practical designs since their conditions can be more accurately specified.

REFERENCES

1. R. A. Parmelee, D. S. Perelman,"Seismic Response of Multi-Story Structures on Flexible Foundations," Bulletin of the Seismological Society of America, Vol. 59, 1061-1070 (1969)

2. R. J. Scavuzzo, J. L. Bailey,D. D. Raftpolous,"Lateral Structure Interaction with Seismic Waves," Journal of Applied Mechanics, 93, 125-134 (1971)

3. P. C. Jennings, J. Bielak,"Dynamics of Building-Soil Interaction," Bulletin of the Seismological Society of America, 63, 9-48 (1973)

4. K. KURODA:"Effects of the Structure-Foundation Interaction on the Energy Absorbed in the Super-Structures Subjected to Strong Ground Motions" Report of Technical Research Lab. No. 3, Nagasaki Inst. of Applied Science, 1-58 (1986)