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ESTIMATION OF UNCERTAINTY OF IMPEDANCE FUNCTION OF SSI SYSTEM BASED ON EXISTING COMPREHENSIVE BLOCK-SHAKING TEST DATA

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1 INTRODUCTION

Study on advanced seismic design for LWR has been carried out by the Nuclear Power Engineering Corporation (NUPEC), under the sponsorship of the Ministry of International Trade and Industry (MITI) of Japan.

Considerable number of soil-structure interaction (SSI) tests shaking large concrete block (block-shaking tests) have been carried out in various places in Japan to obtain soil-structure interaction data. The researchers compared their test results with analytical results in their papers. They have reached various conclusions reflecting their own test results. So, it is necessary to gather the data altogether and to have common knowledge as to the uncertainty between tests and analyses.

This paper evaluates the uncertainty of impedance functions of SSI system based on the comprehensive existing block-shaking data. It also estimates the uncertainty of responses of reactor buildings due to the uncertainty of impedance functions.

2 UNCERTAINTY OF IMPEDANCE

Eighty-two block-shaking test data carried out in Japan are gathered. All these blocks are set on each ground without embedment. Their test conditions are listed in Table 1. The researchers compared in their papers [1]~[16] the horizontal and rocking impedance functions of their test with those of analytical results based on the theory for uniform half space. From these data, statistical analyses are performed. To take the frequency dependency into account, their impedance functions are compared on the axis of non-dimensional frequencies a_o $(=2\pi f\sqrt{A}/Vs)$.

Where f: frequency (Hz)
A: base area of foundation (m2)
Vs: shear velocity of ground (m/s)

The mean values, coefficients of variation (here after they are written covs), and correlation coefficients are calculated. The probabilistic distributions of the data are also examined using normal and log-normal probability papers.

Fig. 1 shows the distribution of the ratio of test values to analytical values for impedances on the probability papers. We can recognize that the distribution pattern of the test-by-analysis values fit log-normal distribution rather than normal distribution. Fig. 2 shows the medians, the logarithmic standard deviations, the correlation coefficients of each component of impedances and the numbers of data for the test-by-analysis values. The medians for the real parts of the impedance functions are nearly 1.0 in low frequency side and they gradually increase in high frequency side. Though the analytical stiffnesses of the grounds go down in high frequency side, the test values do not go down so sharply as indicated by the analyses. The medians for the imaginary parts of rocking impedance functions are very high in low frequency side and they go down rapidly in high frequency side. Though the analytical dampings for rocking motions are almost zero in low frequency side, there exist some damping in the tests that is caused by other reasons such as material damping of soil. The test dampings do not increase so much as indicated by the analyses in high frequency side. The logarithmic standard deviations are 0.2 to 0.5 for the evaluation of real parts and 0.5 to 1.0 for that of imaginary parts. There contains larger uncertainty in the estimation of damping than in the estimation of stiffness. Though the test by analysis values for the real part of sway impedance strongly correlates to those for the real part of rocking impedance, there is no strong correlation among other impedance functions.

3. ESTIMATION OF UNCERTAINTY RELATED TO NON-LINEAR SEISMIC RESPONSE DUE TO UNCERTAINTY OF IMPEDANCE

To study the effect of the uncertainty in the estimated impedance functions on the non-linear seismic response, Monte Carlo simulation analysis is worked out. Simple SSI models considering sway and rocking motion of foundation and shear deformation of building are employed (see Fig. 3). The variations of impedance and input ground motion are taken into account. The skeleton curve and the hysterisis rule of reinforced concrete building are determined following the design rule for reactor buildings in Japan. The ultimate shear strength of the building Qu is assumed to be equal to the linear response shear caused by the design basis ground motion S1 shown in Fig. 4 (Qu/Qs=1) and to be three times of the response (Qu/Qs=3). Linear response analysis is also carried out. Parameters used in the response analyses are listed in table 2. The parameters for cases 1 to 3 are determined after the BWR on soft rock and those for cases 4 to 6 are determined after the BWR on medium rock. Parameters for cases 7 to 9 are determined after the PWR on medium rock and those for 10 to 12 are determined after the PWR on hard rock.

The mean values and covs of the fundamental frequencies and dampings which are calculated using the probabilistic distribution of the test impedance function are shown in Table 3. The mean damping for BWR on soft rock is as high as 48% and the cov is also as large as 1.75. The mean damping for PWR on hard rock is as low as 5%.

We used 10 ground motions to avoid biased view caused by using one particular wave when we estimate the uncertainty of the seismic response of a reactor building due to the uncertainty of impedance. Response spectra of 10 input ground motions are shown in Fig. 5. Maximum accelerations of 10 ground motions are normalized as 267.4 gal that is equal to maximum acceleration of the design basis ground motion S1.

The results of response analysis employing Monte Carlo simulation are discussed. We estimate the uncertainty of the response in two ways using the response analysis results of 10 ground motions. One way is to estimate the uncertainty using the mean value of covs for 10 ground motions. The calculated mean covs of ductility ratios μ (=$\delta m/\delta y$, where δm is maximum displacement and δy is elastic-limit displacement) in this manner are in Table 4(b). Another way is to estimate it using the equation (1). The calculated results are in Table 4(c).

$$\text{Variance (I)} = \text{Variance (I+W)} - \text{Variance (W)} \qquad \text{eq. (1)}$$

where Variance (I): The variance of response due to the uncertainty of impedance
Variance (I+W): The variance of response due to the uncertainty of impedance and seismic waves
Variance (W): The variance of response due to the uncertainty of seismic waves

The calculated covs in Table 4(c) are larger than the covs in Table 4(b). The covs in Table 4(a) are the mean of the both covs. Fig. 6 shows the covs of shear coefficient due to the uncertainty of the impedance calculated in the manner for table 4(a). The covs of shear coefficients are less than 0.2. They decrease as the shear strength of the building decreases or as the shear velocity of the ground increases. Fig. 7 shows the covs of ductility ratios. They are 0.24 to 0.45 for the BWR constructed on the soft rock whose shear velocity is 500 m/s. The cov decreases as the shear strength decreases, because response shear strain increases as the shear strength decreases. The cov also decreases as the shear velocity of ground increases, because the large radiation damping of a reactor building on soft ground diminishes relating to the inelastic deformation of the building. Fig. 8 shows the covs of response.acceleration .They have similar trend with those for the shear coefficients.

4. CONCLUSION

The uncertainty of impedance function of SSI system is evaluated by the comprehensive exiting test data and the variation of the response is studied considering this uncertainty by Monte Carlo simulation.

The real part of the impedance function agrees well with the theory but the imaginary part of the impedance function differs very much and covs of the imaginary part is also as large as 0.5 ~1.0.

Though the covs for the evaluation of response shears and accelerations for reactor buildings are less than 0.2, those for the ductility ratios are as large as 0.45 for reactor buildings constructed on soft rock when large earthquakes occur.

ACKNOWLEDGEMENTS

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Table 1 Parameters of block-shaking tests

No.	Shape	$\sqrt{A}$ (m)	ν	Vs (ks, m/s)	Vs (ks, m/s)	Reference No.	No.	Shape	$\sqrt{A}$ (m)	ν	Vs (ks, m/s)	Vs (ks, m/s)	Reference No.
1	rectangle	10	0	277	256	1	42	rectangle	15	0.404	1005	1005	4
2	rectangle	10	0	277	256	1	43	rectangle	7	0.33	100	100	5
3	rectangle	16	0	299	283	1	44	rectangle	2	0.453	140	140	6
4	rectangle	16	0	299	283	1	45	rectangle	2.282	0.453	140	140	6
5	rectangle	8	0	339	346	1	46	rectangle	2.282	0.453	140	140	6
6	rectangle	8	0	339	346	1	47	rectangle	4	0.493	80	80	7
7	rectangle	4	0	339	346	1	48	rectangle	4	0.493	80	80	7
8	rectangle	4	0	339	346	1	49	rectangle	2	0.493	80	80	7
9	rectangle	4	0.35	660	660	2	50	rectangle	2	0.493	80	80	7
10	rectangle	4	0.35	640	640	2	51	rectangle	2	0.493	80	80	7
11	rectangle	15	0.4	1550	1460	2	52	rectangle	2	0.493	80	80	7
12	rectangle	15	0.4	1400	1260	2	53	rectangle	4	0.404	400	400	8
13	rectangle	15	0.4	1320	1290	2	54	cylinder	12 ϕ	0.36	1400	1400	9
14	rectangle	15	0.4	1410	1290	2	55	cylinder	12 ϕ	0.36	1400	1400	10
15	rectangle	10	0.4	1420	1540	2	56	rectangle	3.8	0.459	170	170	11
16	rectangle	10	0.4	1330	1290	2	57	rectangle	3.8	0.459	170	170	11
17	rectangle	14	0.38	1350	1490	2	58	rectangle	4.899		130	130	11
18	rectangle	14	0.38	1300	1370	2	59	rectangle	14	0.36	930	930	12
19	rectangle	6	0.38	1150	1200	2	60	rectangle	14	0.36	1050	1050	12
20	rectangle	6	0.38	1220	1240	2	61	rectangle	4		680	680	12
21	rectangle	3	0.38	1100	1180	2	62	rectangle	4		680	680	12
22	rectangle	3	0.38	1100	1240	2	63	rectangle	6		1600	1600	13
23	rectangle	15	0.44	1270	1440	2	64	rectangle	6		1000	1000	13
24	rectangle	15	0.44	1290	1400	2	65	rectangle	5		1250	1250	13
25	rectangle	14	0.434	460	560	2	66	rectangle	2	0.25	150	150	14
26	rectangle	4	0.4	380	370	2	67	rectangle	2	0.25	150	150	14
27	rectangle	4	0.4	360	400	2	68	rectangle	2	0.25	150	150	14
28	rectangle	2	0.4	140	110	2	69	cylinder	12 ϕ	0.36	1200	1200	15
29	rectangle	2	0.4	110	100	2	70	rectangle	14	0.36	930	930	15
30	rectangle	3	0.4	175	165	2	71	rectangle	2	0.3	150	150	16
31	rectangle	4	0.4	240	220	2	72	rectangle	2	0.3	150	150	16
32	rectangle	4	0.4	235	225	2	73	rectangle	2	0.3	150	150	16
33	rectangle	4	0.404	350	350	3	74	rectangle	2	0.3	150	150	16
34	rectangle	4	0.404	350	350	3	75	rectangle	2	0.3	150	150	16
35	rectangle	2	0.404	100	100	3	76	rectangle	2	0.3	150	150	16
36	rectangle	3	0.404	170	170	3	77	rectangle	2	0.3	150	150	16
37	rectangle	4	0.404	240	240	3	78	rectangle	2	0.3	150	150	16
38	rectangle	4	0.404	240	240	3	79	rectangle	2	0.3	150	150	16
39	rectangle	15	0.404	1200	1200	4	80	rectangle	2	0.3	150	150	16
40	rectangle	15	0.404	1160	1160	4	81	rectangle	2	0.3	150	150	16
41	rectangle	15	0.404	1030	1030	4	82	rectangle	2	0.3	150	150	16

Table 2 Parameters of response analysis model

	1	2	3	4	5	6	7	8	9	10	11	12
Fundamental period of building on rigid base (s)	0.30						0.10					
Damping factor of building (%)	3						3					
Shear span ratio	0.35						0.20					
Weight of building/ Weight of foundation	2.00						0.30					
Factor for moment inertia ($D^2m_2/12$)	4.00						9.00					
Non-dimensional frequency a_0*	2.10			1.40			4.20			3.20		
Ratio of fundamental period of building to that of SSI	1.60			1.20			1.20			1.05		
Ultimate shear (Qu) / Linear response shear (Qs)	**	3	1	**	3	1	**	3	1	**	3	1

*) D/Vs=80/500, 80/1000, 80/1000, 80/1500 **) Linear

Table 3 Probabilistic vibrational characteristics of first modes

	Frequency (Hz)		Damping (%)	
	m	cov	m	cov
Case1～3 BWR Vs=500m/s	2.08	0.12	48	1.75
Case4～6 BWR Vs=1000m/s	2.77	0.03	10	0.62
Case7～9 PWR Vs=1000m/s	8.24	0.10	18	2.41
Case10～12 PWR Vs=1500m/s	9.48	0.03	5	1.65

m: mean value
cov: coefficient of variation

Table 4 Coefficient of variation of ductility ratios due to uncertainty of impedance

(a) Mean of (b) and (c)

	BWR		PWR	
	500m/s	1000m/s	1000m/s	1500m/s
Qu/Qs=3	0.24	0.08	0.19	0.04
Qu/Qs=1	0.45	0.14	0.08	0.08

(b) Mean cov for each wave

	BWR		PWR	
	500m/s	1000m/s	1000m/s	1500m/s
Qu/Qs=3	0.18	0.10	0.15	0.07
Qu/Qs=1	0.29	0.07	0.16	0.15

(c) Variance(I+W)-Variance(W)

	BWR		PWR	
	500m/s	1000m/s	1000m/s	1500m/s
Qu/Qs=3	0.30	0.06	0.23	x
Qu/Qs=1	0.60	0.20	x	x

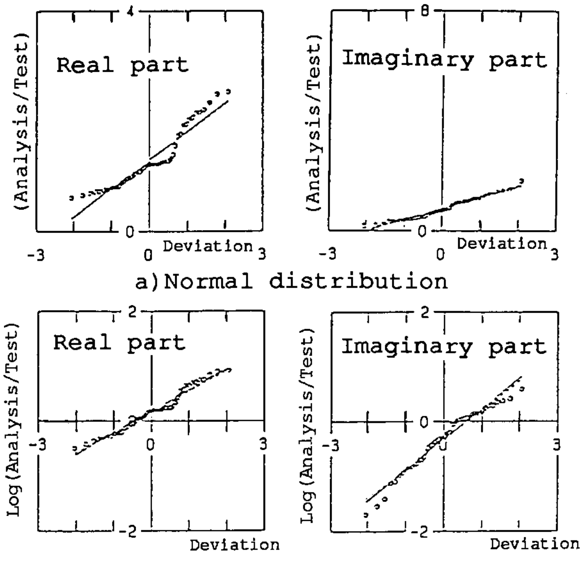

Fig.1 Distributions of ratios of test values to analytical values for sway impedances on probability papers (a_0=1.98)

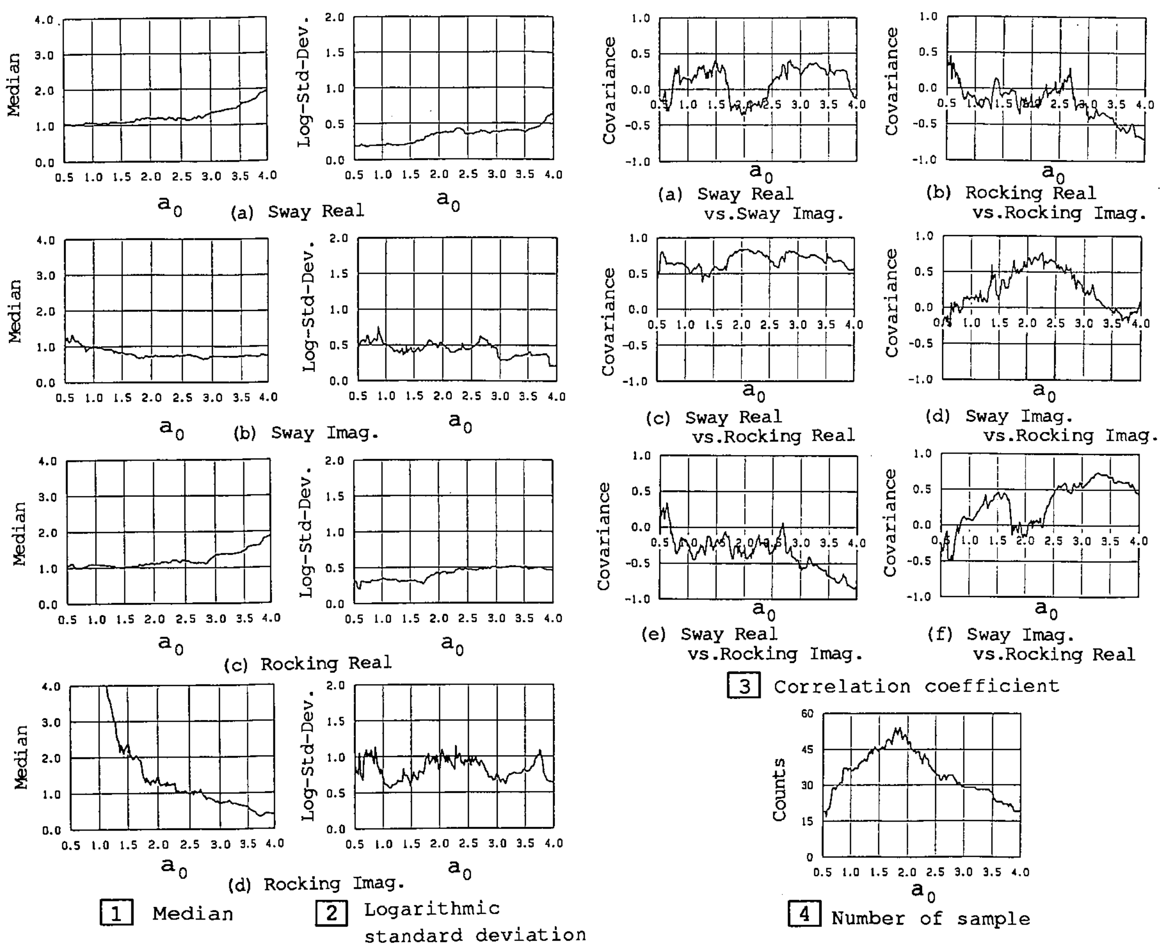

Fig.2 Median and logarithmic standard deviation of ratios of test values to analytical values of dynamic impedance

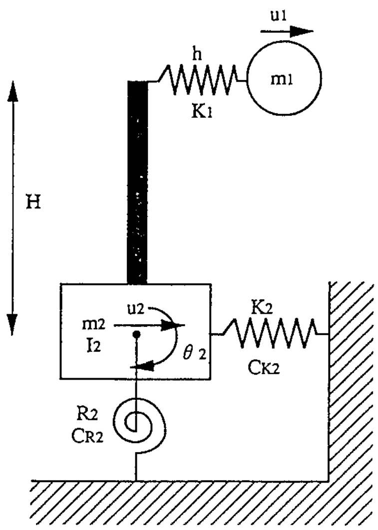

Fig.3 Response analysis model

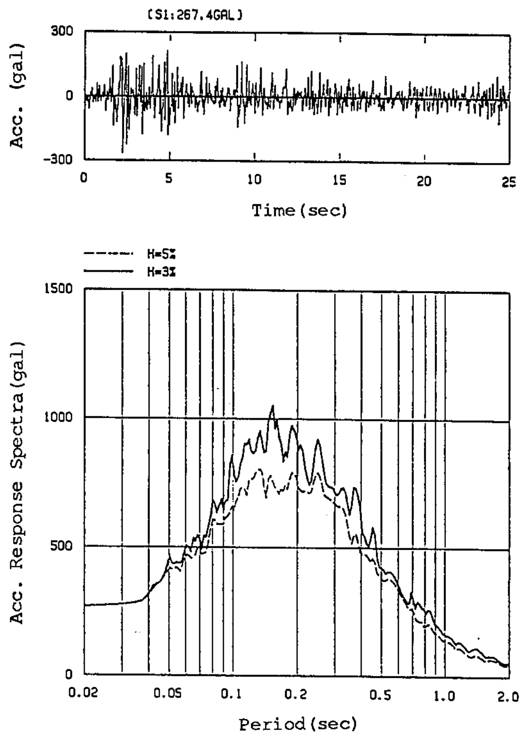

Fig.4 Design basis ground motion

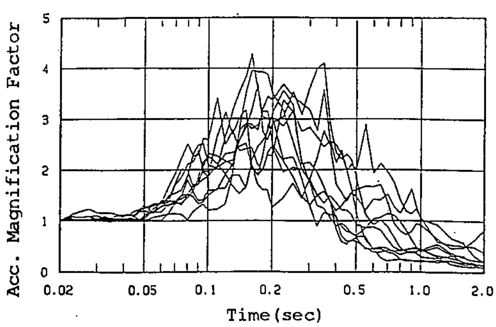

Fig.5 Response spectra of 10 ground motions

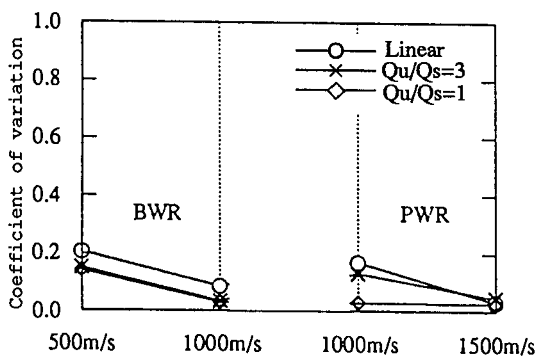

Fig.6 Coefficient of variation of shear coefficient

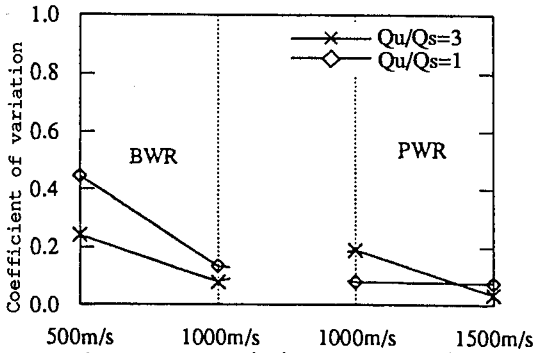

Fig.7 Coefficient of variation of ductility ratio

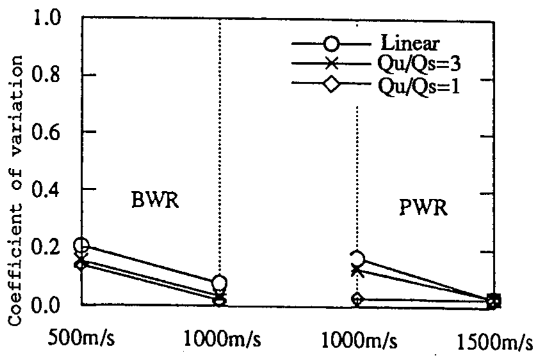

Fig.8 Coefficient of variation of response acceleration