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SHAKING TABLE TEST FOR ELASTIC DAMPING RATIO OF RC WALLS WITH ASPECT RATIO OF 0.6 AND 1.0

Hyeon-Keun Yang[1], Hong-Gun Park[2], Ju-Hyung Kim[2]

[1] Doctoral Student, Department of Architecture and Architectural Engineering, Seoul National University, Seoul, Korea

[2] Professor, Department of Architecture and Architectural Engineering, Seoul National University, Seoul, Korea

[3] Doctoral Student, Department of Architecture and Architectural Engineering, Seoul National University, Seoul, Korea

ABSTRACT

In Korea where high frequency earthquakes has occurred, it is necessary to re-evaluate seismic performance of nuclear power plant buildings under high frequency earthquake. In this study, shaking table test was conducted for reinforced concrete squat walls with aspect ratio 0.6 and 1.0 to evaluate the elastic damping ratio of nuclear power plant wall. The test variables were the natural frequency of walls and types of earthquakes. The test results are compared with the predicted base shear force. The comparison result showed that the elastic damping ratio of the walls was 3.6% in mean, and 0.18 in standard deviation. Damping ratio of walls with low aspect ratio (4.5%~4.8%) or high frequency structures was higher (4.0%~4.4%). On the other hand, damping ratio for high frequency earthquakes has 10% lower than the mean value.

INTRODUCTION

Due to the 912 earthquake of magnitude 5.8(2016), Wol-song nuclear power plant were shut down manually, which was the first incident in the history of Korean nuclear power plants. In 2017, the Po-Hang earthquake of magnitude 5.4 occurred near the nuclear power plant site. Concerns about the safety of nuclear power plants has increased as the 912 earthquake and the Po-Hang earthquake that occurred in the eastern coast of Korea where the nuclear power plants are concentrated.

In the seismic performance evaluation of an operational nuclear power plant, due to the high safety factor of the structure, most main causes of the core damage frequency (CDF) is not a destruction of the structure but malfunction of equipment or a failure of pipes that connecting devices. Especially, the earthquakes of Korea have many high frequency contents, so it is required to caution to the safety of devices with high natural frequencies. In the case of a high frequency earthquake, a peak ground acceleration (PGA) at the level of failure due to the equipment malfunction or interference between devices is evaluated to be lower than the seismic performance of the structure. In addition, in the level of high confidence of low probability of failure (HCLPF) of nuclear power plants, the structure behaves elastic range.

Therefore, floor response time histories and floor response spectra, which used for evaluating equipment, are important factors in seismic performance evaluation of nuclear power plants in high frequency earthquakes. Since the floor response is obtained from time history analysis of structure, an accurate structure model is required to evaluate the equipment exactly. In the same context, to predict the exact elastic damping ratio of the structural wall model that affects the response of the structure is important. EPRI (Electric Power Research Institute) report TR-103959 assumes the damping ratio of 5% when a structural wall reach an extreme condition[1]. The damping ratio of 4% is assumed when evaluate a reinforce concrete structure based on operating basis earthquake (OBE) level and the damping ratio of 7% is assumed when safe-shutdown earthquakes (SSE) level at USNRC (United States Nuclear Regulatory Commission) Regulatory guide 1.61[5]. In NP-6041, which was published by EPRI, the damping ratio is recommended to use 3% for a reinforced concrete structure with few cracks or a half of the yielding strength and use 10% for a reinforced concrete structure under over yielding strength or a pre-yielding reinforced concrete members when seismic margin assessment (SMA).

As such, the existing standards or the guidelines recommend using from 3% to 4% for damping ratios of a reinforced concrete structure before yielding. However, these values are empirical values, so require evidence from experiments. In addition, verification for the structures under high frequency earthquakes is require. To define a mean value of the damping ratio and a standard deviation of uncertainty is necessary for applying in the seismic probabilistic risk assessment (SPRA). In this study, shaking table test was conducted for reinforced concrete squat walls, which usually use main structural elements of nuclear power plants, and the damping ratio of the squat walls was evaluated.

TEST PLAN

Major Test Parameters and Specimen Details

In nuclear power plant walls, because of the high design requirements of shear capacity, shear reinforcement ratio is required high value and a low aspect ratio of walls (=h_w/l_w). Two reinforced concrete walls with aspect ratio 1.0 (A1.0) and 0.6 (A0.6) were prepared for the shaking table test. **Figure 1** shows the dimensions and details of the specimens. The dimensions of the specimen with aspect ratio 1.0 were 1500 mm (length) x 1500 mm (height) x 200 mm (thickness) (59.10 x 59.10 x 7.88 in.). The dimensions of the other specimen with aspect ratio 0.6 were 2500 mm (length) x 1500 mm (height) x 200 mm (thickness) (98.43 x 59.10 x 7.88 in.).

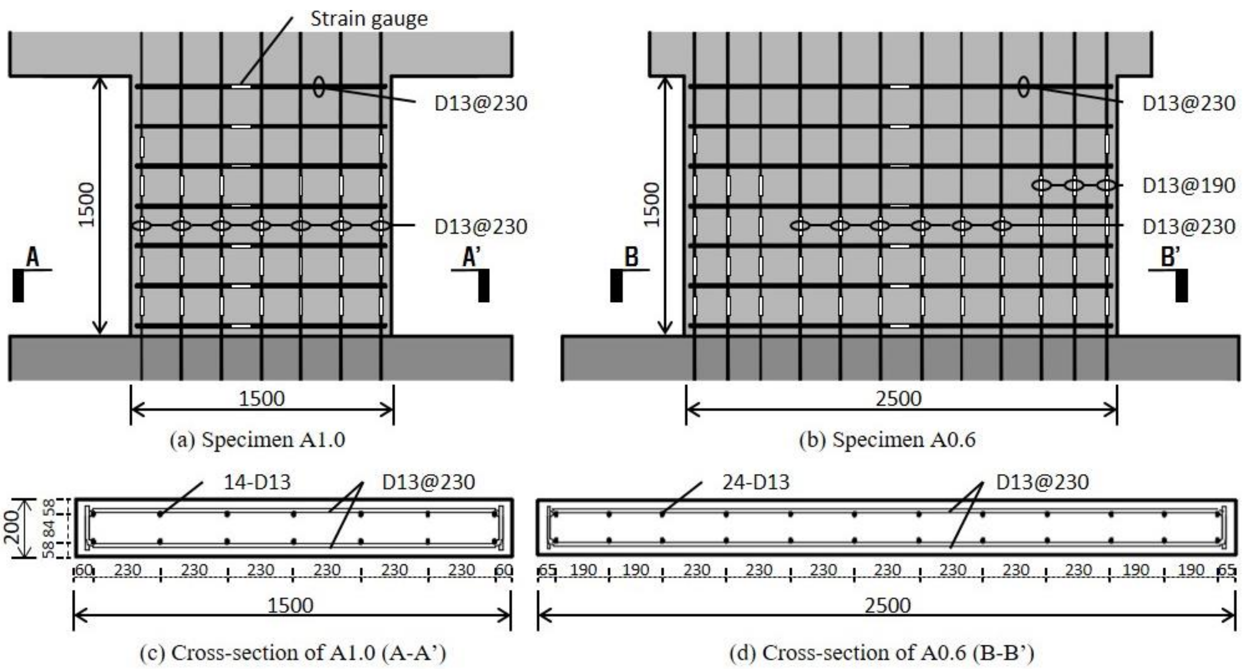


Figure 1. Dimensions and reinforcement details of specimens (Units: mm)

The compressive strength of used concrete was 40MPa (5.71 ksi) and grade 420 MPa (60 ksi) reinforcing bars were used. At the all specimens, D13 reinforcing bars were used and the actual yielding strength was 497MPa (71 ksi). The shear reinforcement ratio and vertical reinforcement ratio were both

0.6%. In the specimen A1.0 with aspect ratio 1.0, the nominal flexural strength was V_f=312 kN (70.2 kip) and the nominal shear strength was V_s=983 kN (221.175 kips). In the specimens A0.6 with aspect ratio 0.6, the nominal flexural strength was V_f=643 kN (144.68 kip) and the nominal shear strength was V_s=1383 kN (311.18 kips).

In order to induce the specimens with various natural frequencies with same wall, various steel mass (4.89 ton, 8.52 ton, 13.06 ton, 17.59 ton, 26.66 ton [10781 lb, 18783 lb, 28792 lb, 38779 lb, 38779 lb, 58775 lb]) was installed on the top slab of specimens.

Table 1 Earthquake inputs

EQ	Name	Station	Magnitude	High Frequency contents
(1)	UHS	-	-	Included
(2)	RG1.60	-	-	-
(3)	Imperial Valley	Westmorland	5.62	Included
(4)	ChiChi-1	CHY016	6.2	-
(5)	ChiChi-2	CHY116	6.2	Included
(6)	ChiChi-3	TTN010	6.2	-
(7)	ChiChi-4	CHY059	6.3	-
(8)	912 (Gyeong-Ju)	DKJ	5.8	Included

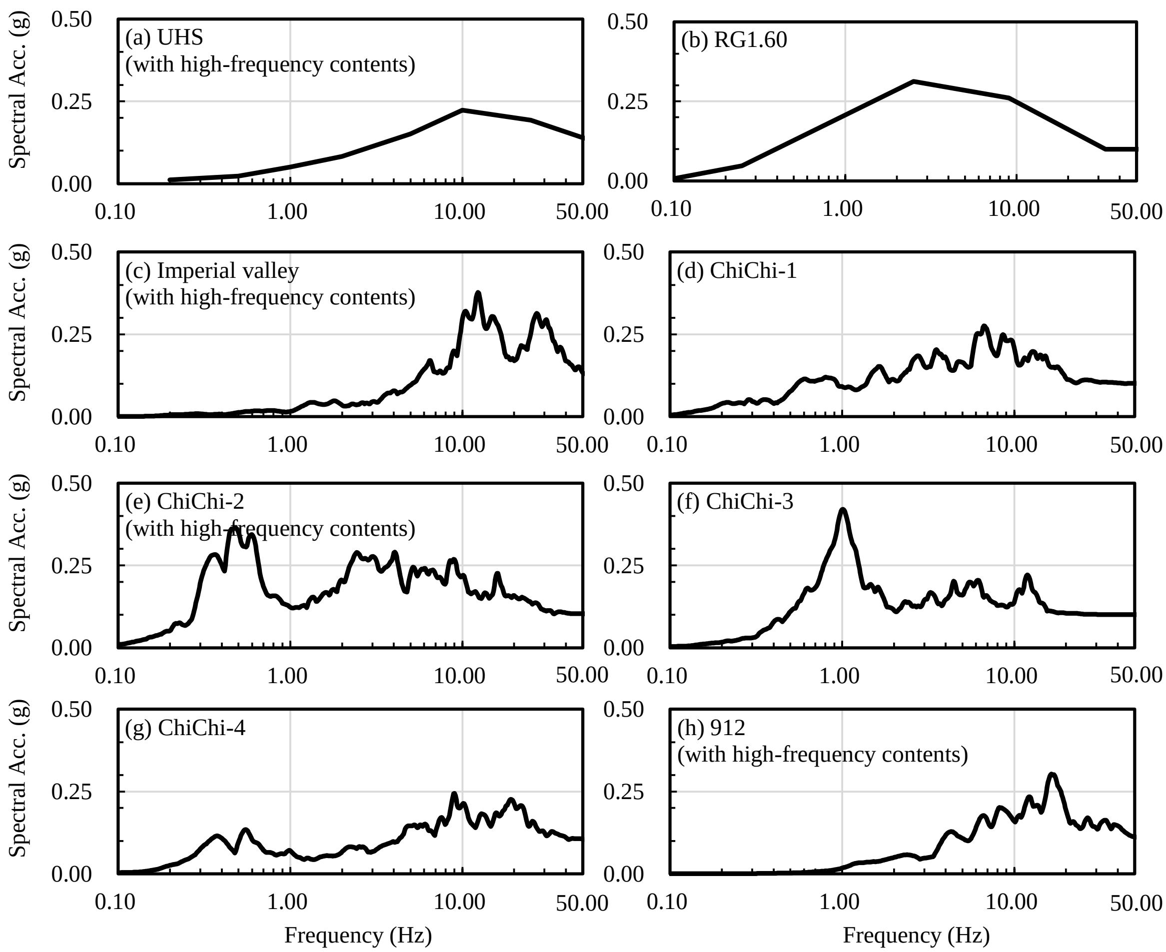


Figure 2. Elastic response spectrum (Scaled to PGA 0.1g)

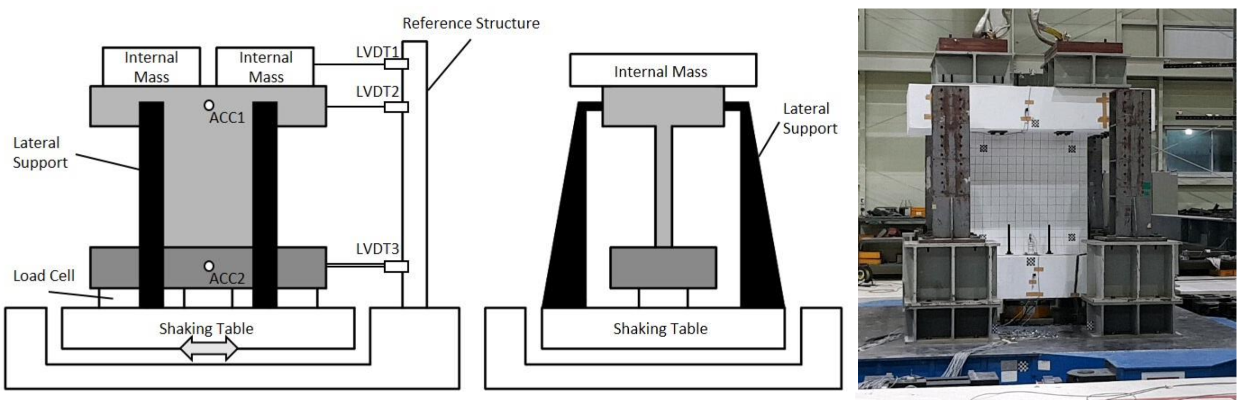
Input Earthquakes

Total types of input earthquakes were 8 and **Table 1** shows the information of the input earthquakes. EQ (1), UHS is an artificial seismic earthquake based on a uniform hazard spectrum (UHS) of the site-specific earthquake ground motion[4] of Ul-jin where the nuclear power plants are concentrated. EQ (2), RG1.60 is an artificial seismic earthquake based on the design spectrum of nuclear power plants[3]. The other six input earthquakes are measured earthquakes. In the case of EQ (1), high frequency contents are included relatively high compared to the design spectrum (EQ (2)). **Figure 2** shows the elastic response spectra of the input earthquakes with adjusting the peak ground acceleration (PGA) level to 0.1g (g: gravimetric unit).

The selection criteria of input earthquakes is the earthquake magnitude of 5.6~6.2 range and the record with a maximum time interval of 0.01 seconds. To confirm the effect of the high frequency contents of earthquakes for reinforced wall, four earthquakes with high frequency contents were used and the others were normal.

Test Procedure and Instrumentation

Figure 3 shows the places of the accelerometers, the linear variable displacement transducers (LVDTs) and the load cells for measurement of time history. The accelerometers (ACC1, ACC2) were installed at the center of top and bottom slab of the specimen. The LVDTS were installed at the top and bottom slab for measurement of relative displacements. **Figure 1** shows the strain gauges used to measure the strains of the flexural reinforcing bars and shear reinforcing bars. Because of rapid data changing during the shaking table test, dynamic data loggers were used to record data of the accelerometers, the LVDTs, the load-cells and the strain gauges with 512 Hz.



(a) N-S face (b) E-W face (c) Test setting

Figure 3 Test set-up

If the shaking table test is performed several times on one specimen, cracks can occur and the natural frequency of the specimen can be changeable. Therefore, three times of resonance search for the specimen were performed at before test, after EQ (1) ~EQ (4) and after EQ (5) ~EQ (8) in every test sets. From the resonance search results, natural frequencies of the specimen were obtained through the transmissibility. For the various natural frequencies of the specimens due to changing external mass, repeated experiments were conducted. The PGA of the input earthquakes that used in the shaking table test was adjusted to 0.1g. In order to minimize damage of the specimens, PGA 0.1g was selected as enough acceleration that the maximum tensile stress is lower than 4 MPa (0.57 ksi) which is 10% of compressive strength of concrete. The total number of tests except for the resonance searches was 88 times that is sum of 40 times for the aspect ratio of 1.0 specimen and 48 times for the aspect ratio of 0.6 specimen.

TEST RESULT

Resonance Test and Acceleration Record

Table 2 shows the natural frequencies from the results of the resonance searches that were conducted three time in every test sets.

Table 2 External mass & natural frequency

Set No.	External Mass	Natural frequency (Hz)	
		A1.0	A0.6
1	0	29.58	49.42
2	4.89	20.01	31.44
3	8.52	16.65	26.29
4	13.06	13.57	21.83
5	17.59	-	18.34
6	26.66	9.13	14.77

The average of maximum acceleration at the bottom slab of speciemen was 0.12g. The maximum acceleration was 0.16g at specimen A0.6 with external mass 8.52 ton (18783 lb) during EQ (7) and the minimum acceleration was 0.08g at specimen A0.6 without external mass during EQ (6). The maximum acceleration at the top slab record was 0.439g at specimen A1.0 without external mass during EQ (3), and the minimum value was 0.096g at specimen A0.6 with external mass during EQ (6). The average of acceleration amplification due to dynamic effects of the specimens was 1.44 times. The maximum acceleration amplification appeared at the specimen A1.0 with external mass 8.52 ton (18783 lb) during EQ (8) and the value was 3.0 times.

The natural frequencies of the specimens got lower as the external mass of the top slab increased. From the resonance searches, the highest natural frequency was 49.42 Hz at specimen A0.6 with no external mass and the lowest natural frequency was 9.13 Hz at specimen A1.0 with the maximum external mass (26.66 ton [58775 lb]).

Response Spectrum

In order to verify structural analysis and damping ratio, the result of the time history analysis based on the bottom slab acceleration and the measured of time history acceleration at the top slab were compared. In structural analysis for response spectra according to NP-6041[2], the specimen was assumed to have no damage and damping ratio of 3%. **Figure 4** shows the maximum acceleration at the top slab of each test case (round marks), elastic response spectra based on the input motions (broken lines), elastic response spectra based on the bottom slab accelerations (light lines), and the average of response spectra based on the bottom slab acceleration (bold lines). The elastic response spectra based on input motions (broken lines) are the same as **Figure 2.**

The actual maximum acceleration at the top slab (round mark) was compared with the response spectra (light lines) generated by single-degree-of-freedom (SDOF) dynamic analysis. The average ratio of the measured maximum acceleration at the top slab to the response spectra results with damping ratio of 3% was 0.97 for EQ (1) with high frequency contents (**Figure 4 (a)**). On the other hand, for EQ (2) without high frequency contents, the average ratio of measured to analysis was 0.93 (**Figure 4 (b)**). The average rate of the results of the other six actual earthquakes was 0.95. This result indicates that the elastic response spectra, using 3% damping ratio can predict the actual acceleration of the top slab acceleration with reasonable precisions. However, in the range of natural frequency of the specimen over 20 Hz, the ratio of the measured maximum acceleration to the predicted analysis is 0.88, which include that the damping ratio were higher for the natural frequency over 20 Hz.

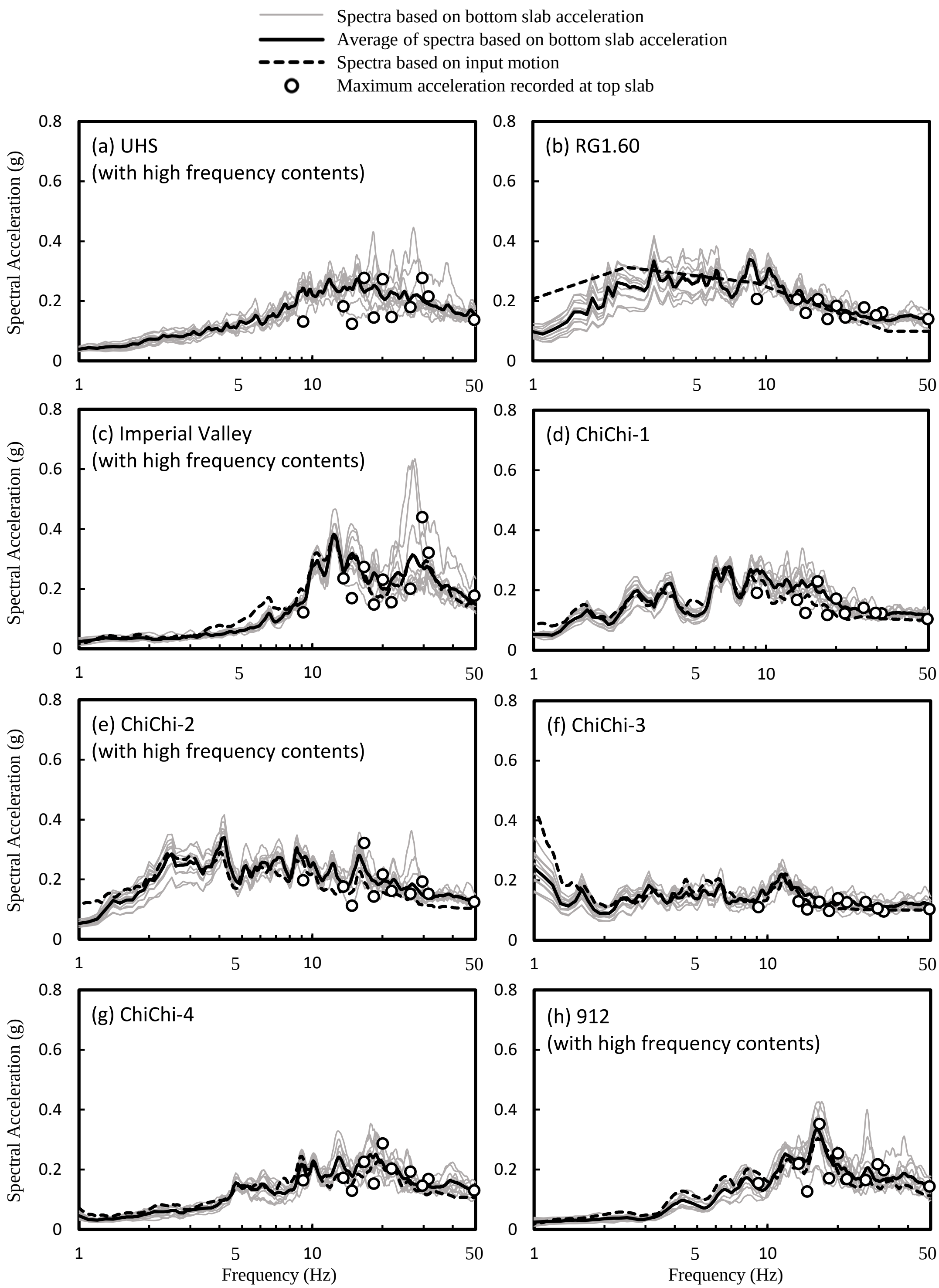


Figure 4 Response spectrum based on bottom slab accelerations versus top slab accelerations

Interestingly, in the case of earthquakes with high frequency contents, **Figure 6 (a), (c), and (e)** the measured acceleration of the specimen with the natural frequency lower than 20Hz, tend to be lower than the average of response spectra in the interest frequency band. Partially, in the case of EQ (1) and EQ (3), this tendency is pronounced. Further studies are required to confirm this result.

ESTIMATION OF ELASTIC DAMPING RATIO

Estimation based on top slab acceleration

The predicted acceleration using damping ratio of 3% and the measured acceleration are shown in **Figure 4**. When the all experiments were calculated with the damping ratio of 3%, the average ratio of the measured acceleration to predicted maximum acceleration is 0.96, which means that predictions are slightly greater than the measured acceleration. In the case of A1.0, the ratio of the measurement to prediction is 1.037. This results redirects that the actual damping ratio of A1.0 would be lower than 3% used for the prediction. In the case of A0.6, the ratio is 0.905, which means that the damping ratio could be higher than 3%.

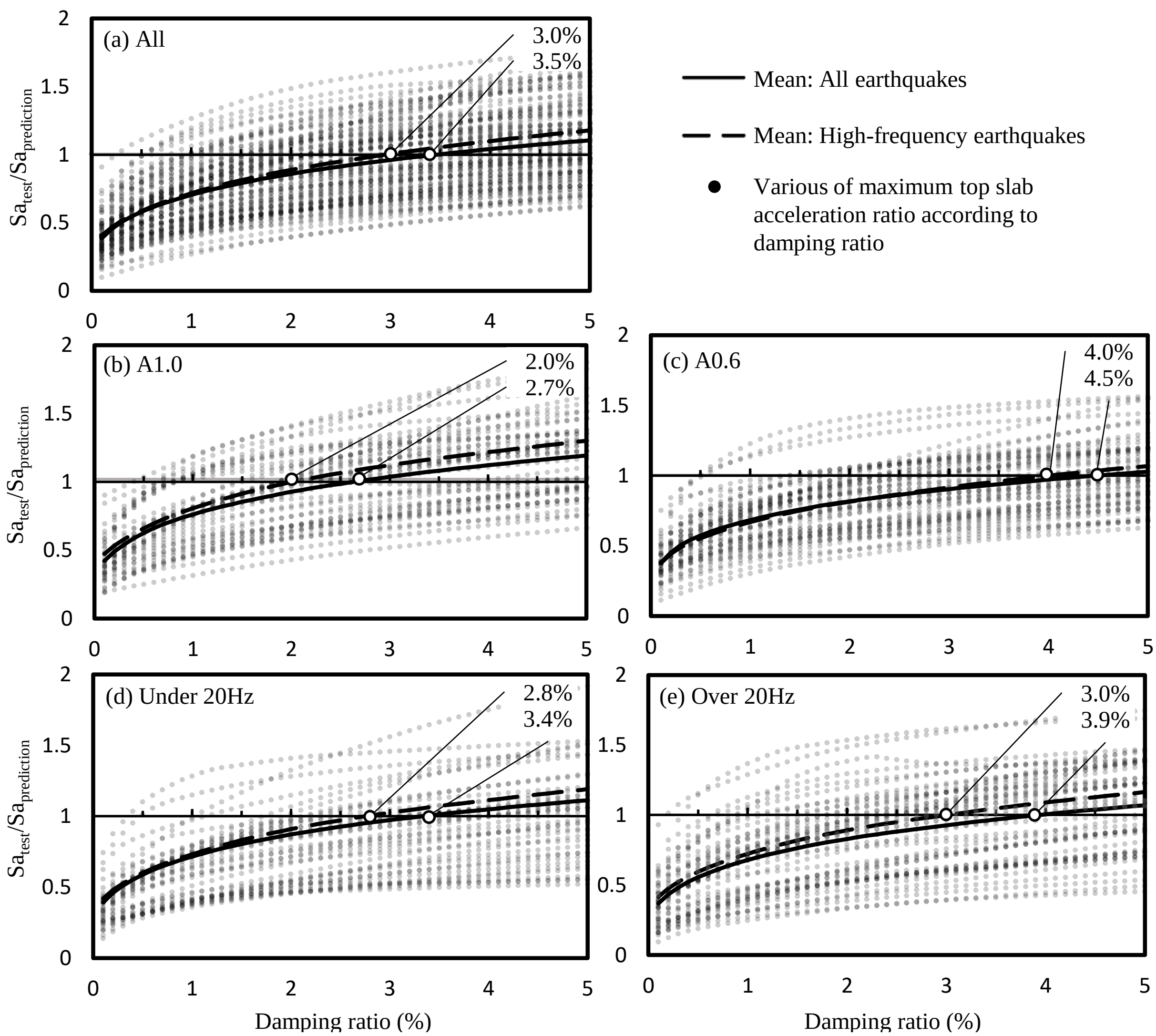


Figure 5 Variety of predicted the maximum top slab acceleration ratio according to damping ratio.

To more accurately estimate the damping ratio, numerical analysis was performed changing damping ratios from 0.1% to 5.0% in 0.1 increment. Eight-node plane stress elements were used. Finite element analysis was performed for verification for the damping ratio. The load cells under the specimens were modeled by using an elastic spring support applying the actual stiffness of the load cells. The superimposed mass was set to behave with top slab motion using rigid body The time history analysis based on the measured acceleration at the floor of the shaking table was performed for the finite element model The prediction result was compared with the measured top slab acceleration (test results). **Figure 5** shows the comparison results. The ratio of the test results to predictions was 1.00 at the damping ratio of 3.5% and the standard deviation was 0.252. That outcome best reflect the experimental result.

In the case of specimen A1.0, the ratio of the test result to prediction was 1.00 at the damping ratio of 2.7%, and the standard deviation in the case was 0.270. In the case of specimen A0.6, the best estimated damping value was 4.5% and in the standard deviation was 0.242.

For earthquakes with high frequency contents, the damping ratio was evaluated to be relatively low. For the high frequency earthquakes the damping ratios of A1.0 and A0.6 were 2.0% and 4.0% respectively, and the combined results of the two specimens were 3.0%. This is a result of 14.3% (from 3.5% to 3.0%), 25.9% (from 2.7% to 2.0%) and 11.1% (from 4.5% to 4.0%) decrease in the case of the all specimens, the specimen A1.0 and A0.6.

CONCLUSION

To evaluate the damping ratio of squat reinforced concrete walls without several concrete cracking, shaking table test was conducted. The specimens with aspect ratio of 1.0 and 0.6 were tested. Shaking table tests were conducted changing the natural frequency of the specimens with superimposed mass on the top slab. Eight earthquake input motions were used for each test set. The input earthquakes were adjusted to 0.1g PGA level. The PGA measured at the bottom slab of the specimens regard from 0.08g to 0.16g, and the average was 0.12g. The damping ratio of the specimens was estimated by comparing test result and numerical predictions of the maximum top slab acceleration. The major findings of the present study are summarized as follows:

Table 3. Elastic damping ratio according to the maximum top slab acceleration

Frequency contents	**All Earthquakes**					**Earthquakes with High-frequency contents**					**Earthquakes without high-frequency contents**				
Specimens	**All**	**A1.0**	**A0.6**	**Under 20Hz**	**Over 20Hz**	**All**	**A1.0**	**A0.6**	**Under 20Hz**	**Over 20Hz**	**All**	**A1.0**	**A0.6**	**Under 20Hz**	**Over 20Hz**
Mean	3.5%	2.7%	4.5%	3.4%	3.9%	3.0%	2.0%	4.0%	2.8%	3.0%	4.3%	3.6%	5.3%	4.3%	5.5%
Standard deviation	0.267	0.270	0.242	0.438	0.311	0.309	0.309	0.281	0.489	0.298	0.195	0.205	0.166	0.343	0.295

1. In general, the response spectrum predicted by SDOF model analysis using 3% damping ratio agreed with the measured top slab accelerations.
2. However, in the case of earthquakes with high frequency contents, the measured accelerations in the range of 10~20Hz frequencies, tended to be lower than the predicted response spectra. Further studies is required to confirm the results.
3. For better predictions, finite element analysis was performed changing damping ratio. The result showed that for the best prediction, the damping ratio was 3.6% with the corresponding standard deviation was 0.180
4. **Table 3** shows the estimate of elastic damping ratio of RC wall with various cases. When the natural frequency is lower than 20Hz, the estimated damping ratio is 3.2%. On the other hand, when the natural frequency is higher than 20Hz, the damping ratio is 4.8%. In addition, when the test cases classified according to the existence of high frequency contests, the estimated damping ratio

was decreased to 3.2%, 3.0% and 3.6% for all, the natural frequency lower and higher than 20 Hz respectively

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