From the perspective of universality, the periods of structures are uncertain for the time being. The site characteristic period T_g is used as the demarcation point to divide spectrum into one platform band [0.1s, T_g] and the basic period T_1 multiple period bands including $[T_g, T_i)$,$[T_i, T_{i+1})$,$[T_{i+1}, T_{i+2})$,$[T_{i+2}, T_{i+3})$,$[T_{i+3}, T_{i+4})$…, where T_i, T_{i+1}, T_{i+2}, T_{i+3} and T_{i+4} are different points of the period. When selecting records, the platform range and one of the period ranges are controlled simultaneously. It is assuming that the η_i decreases by 50%, since the η_i is unknown. And the structure periods of higher modes are also assumed to decrease by 50%.

(3) Use Equation (8) to calculate the $\delta\left(T_{n,}T_m\right)$ in all controlled ranges. And then, the ground motion records with $\delta\left(T_{n,}T_m\right) \leq 10\%$ are selected.

CONSTRUCTION OF GROUND MOTION RECORDS SET

The Method of Set Construction

The records in existing structure design software or structure finite element analysis software lack matching in earthquake environment and structural form according to the Chinese seismic design code requirements, and they are only selected from several typical earthquakes that have occurred in the past. Thus, a complicated process is followed to select the appropriate records in application. Therefore, the SDB method was put forth to select records, and record sets were constructed. The record sets with various seismic fortification intensities and site characteristic periods compose a record database. Records can be directly selected from the database once the structure basic period is determined. The establishment and use of record database steps are shown in Figure 1. That is only a way to select ground motion records and to build a record set provided, so the record set constructed by the SDB method can be based on the records selected not only from the PEER system, but also from other databases of ground motion records (such as the databases of Japan, China, etc.).

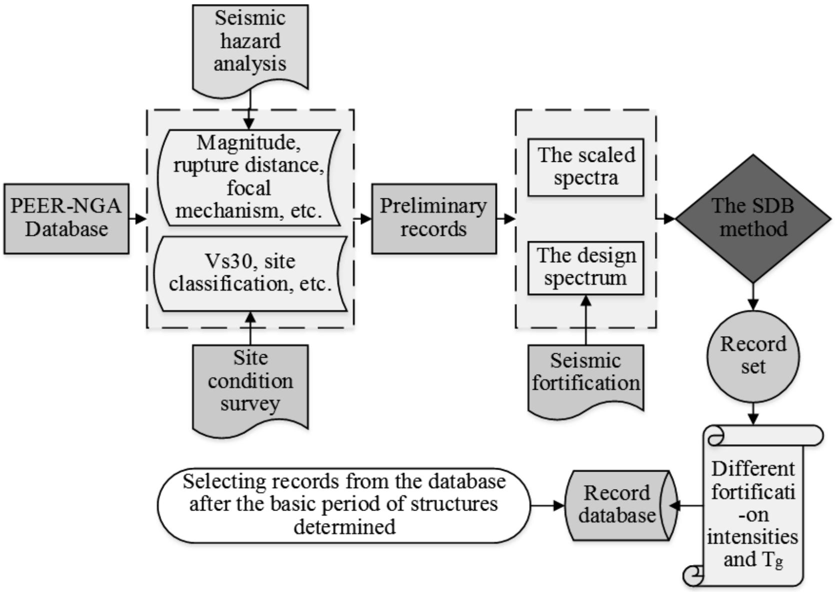


Figure 1. Construction and application steps of the record database.

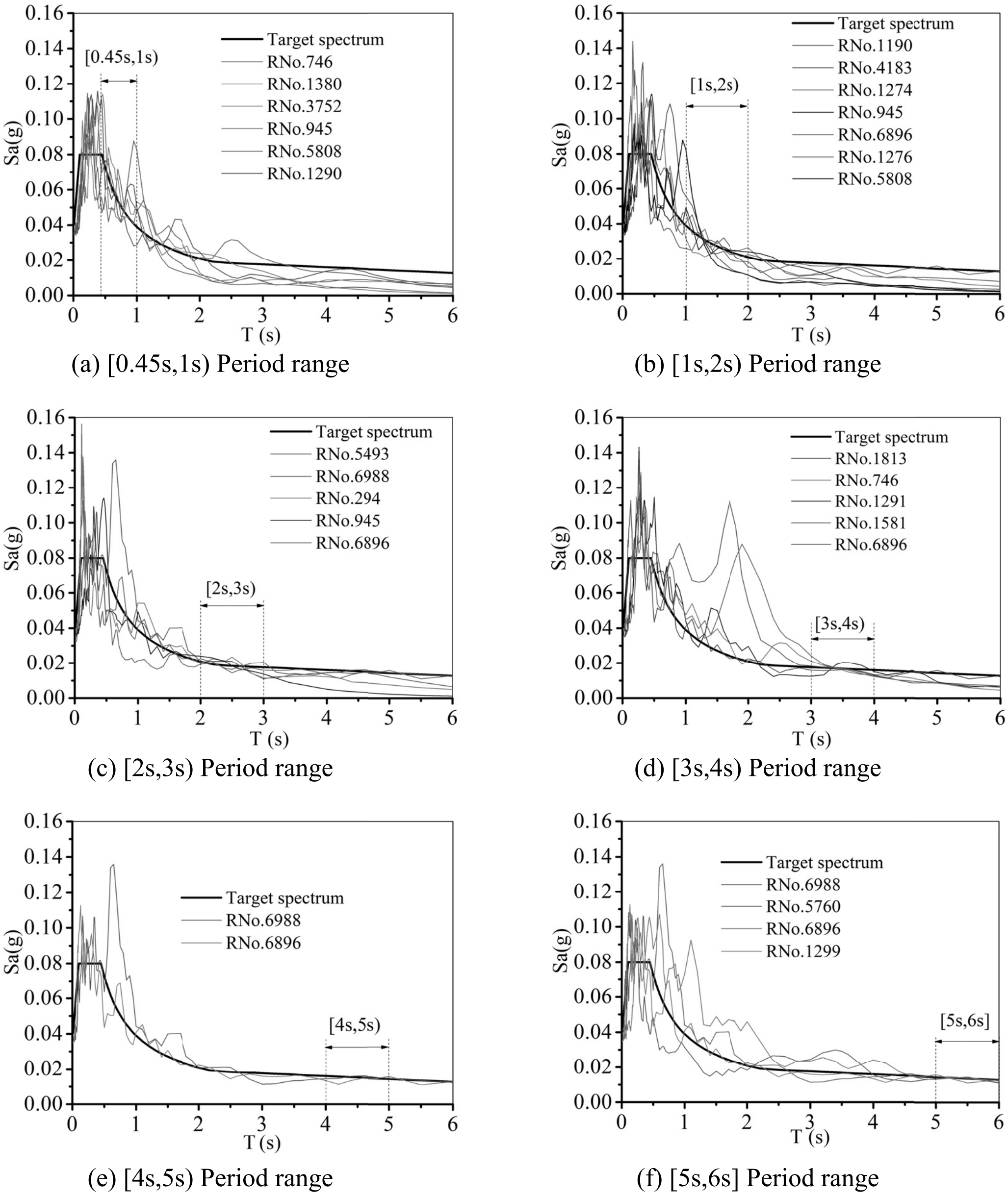
An Example of Construction in the Areas of Chinese Seismic Fortification Intensity 7

According to the jurisdiction approved by China, the seismic fortification intensity can be obtained by using the basic seismic intensity of Chinese seismic parameter zoning map. An example of seismic fortification intensity 7, site classification II, and design earthquake group III was taken to select ground motion records and construct record set, which considered 5 modes of structures.

Initially, one hundred ground motion records were selected from the PEER. Then, these records were controlled according to the SDB method. The results of selected records are shown in Table 1. The comparisons between record spectra selected by SDB method and design spectrum are shown in Figure 2, which present good consistency in the platform range and the corresponding period ranges.

Table 1. The record set constructed by the SDB method.

δ			**Earthquake name**	**Record number**	**Year**	**M_L**	**Effective duration(s)**	**R-rup (km)**	**V_{s30} (m/s)**	**Lowest Frequency (Hz)**
Periods band		**Platform band**								
[0.45s,1s)	0.061	0.063	Loma Prieta	746	1989	6.93	17.8	53.6	391.01	0.096
	0.051	0.069	Chi-Chi_ Taiwan	1380	1999	7.62	32.5	30.85	497.22	0.05
	0.032	0.073	Landers	3752	1992	7.28	27.3	45.34	436.14	0.125
	0.089	0.074	Northridge-01	945	1994	6.69	15.5	38	349.6	0.2
	0.052	0.087	Iwate_ Japan	5808	2008	6.9	19.2	39.06	317.41	0.2
	0.098	0.094	Chi-Chi_ Taiwan	1290	1999	7.62	26.6	58.05	543.06	0.0625
[1s,2s)	0.073	0.015	Chi-Chi_ Taiwan	1190	1999	7.62	39.1	50.53	497.53	0.0375
	0.076	0.056	Niigata_ Japan	4183	2004	6.63	46	55.94	303.73	0.0375
	0.010	0.067	Chi-Chi_ Taiwan	1274	1999	7.62	20.5	53.79	494.32	0.1875
	0.041	0.074	Northridge-01	945	1994	6.69	15.5	38	349.6	0.2
	0.072	0.077	Darfield_ New Zealand	6896	2010	7	27.9	32.91	280.26	0.125
	0.075	0.080	Chi-Chi_ Taiwan	1276	1999	7.62	17	51.62	437.8	0.0375
	0.043	0.087	Iwate_ Japan	5808	2008	6.9	19.2	39.06	317.41	0.2
[2s,3s)	0.038	0.007	Iwate_ Japan	5493	2008	6.9	45.9	48.14	288.82	0.0375
	0.061	0.024	Darfield_ New Zealand	6988	2010	7	26.2	26.93	344.02	0.175
	0.031	0.059	Irpinia_ Italy-01	294	1980	6.9	22.9	53.16	496.46	0.15
	0.017	0.074	Northridge-01	945	1994	6.69	15.5	38	349.6	0.2
	0.076	0.077	Darfield_ New Zealand	6896	2010	7	27.9	32.91	280.26	0.125
[3s,4s)	0.072	0.013	Hector Mine	1813	1999	7.13	24.4	53.21	396.41	0
	0.054	0.063	Loma Prieta	746	1989	6.93	17.8	53.6	391.01	0.096
	0.034	0.071	Chi-Chi_ Taiwan	1291	1999	7.62	31.4	58.22	534.41	0.025
	0.061	0.075	Chi-Chi_ Taiwan	1581	1999	7.62	28.5	56.3	510.62	0.0375
	0.099	0.077	Darfield_ New Zealand	6896	2010	7	27.9	32.91	280.26	0.125
[4s,5s)	0.019	0.024	Darfield_ New Zealand	6988	2010	7	26.2	26.93	344.02	0.175
	0.10	0.077	Darfield_ New Zealand	6896	2010	7	27.9	32.91	280.26	0.125
[5s,6s]	0.023	0.024	Darfield_ New Zealand	6988	2010	7	26.2	26.93	344.02	0.175
	0.069	0.064	Iwate_ Japan	5760	2008	6.9	50.6	36.73	410.57	0.0375
	0.052	0.077	Darfield_ New Zealand	6896	2010	7	27.9	32.91	280.26	0.125
	0.068	0.085	Chi-Chi_ Taiwan	1299	1999	7.62	36.1	43.01	452.83	0.075



(a) [0.45s,1s) Period range (b) [1s,2s) Period range

(c) [2s,3s) Period range (d) [3s,4s) Period range

(e) [4s,5s) Period range (f) [5s,6s] Period range

Figure 2. Comparisons between the record spectra selected by SDB method and the design spectrum.

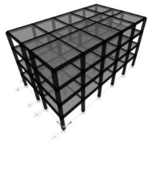
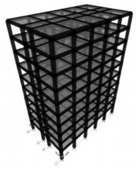
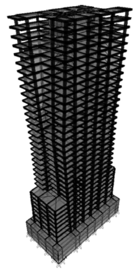
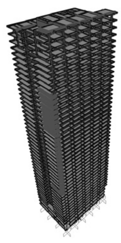
The records in Table 1 constituted the set grouped by seismic fortification intensity 7, site classification II, and design earthquake group III. The basic acceleration of ground motion is 0.1g, which is obtained from the relation between seismic fortification intensity and the basic acceleration values of ground motion (GB50011-2016 version, 2016). If the basic period of the structure is decided, the records within the period range, where the structure basic period stays in, can be directly chosen from the set. Considering that structures practically enter into the plastic state under the strong earthquake, the structural stiffness degrades, and the basic period of structure is elongated. When a structure's basic period is just the division value of period ranges, the records in the period range lagging behind the division value are selected. And when the structure's basic period is in the platform range [0.1s, T_g], the records in the range of [0.1s, T_g]+[T_g, 1s) are selected.

For the record set shown in Table 1, there are only 3~7 records in each period range, but the records characterize the uncertainty of the 100 records, as they are selected from the 100 records; thus, structures belong to every period range choosing records within the set that is reasonable and feasible. Of course, if the preselection number of the records from the PEER increases, the number of records constituting the set will increase.

EVALUATION OF THE GROUND MOTION RECORDS SET

Four engineering structures were regarded as study objects to demonstrate the effectiveness of the records in the set. SAP2000 (a software of finite element analysis) was used to establish the structural models to do time-history dynamic analysis and obtain the base shear. The seismic fortification intensity was 7, the site classification was II, the design earthquake group was III, and the maximum earthquake acceleration was 0.35m/s² (standard value of frequent seismic) (GB50011-2016 version, 2016). The concrete strength of the two frame structures was that of C40, and the concrete strength of the two frame-shear structures was between C30 and C55. The strength of the stirrup was that of HRB335, and the strength of the other longitudinal bars was that of HRB400. In the models, the 3d frame element was used to simulate beams and columns, the membrane element was used to simulate the floor slab, and the load between beams was 6.0 kN/m^2. The structural damping adopted the classical Rayleigh damping, and the ratio was 0.05. The default hinge properties in SAP2000 were specified for the frame element: the bending hinge in the spindle direction (M3) was specified at both ends of the frame beam, and the coupling hinge (p-m2-m3) was specified at the bottom of the frame column to allow the interaction between the axial force and bending moment. The key parameters of the four structures are shown in Table 2.

Table 2. Parameters of engineering structures.

Structures		Structure 1	Structure 2	Structure 3	Structure 4
Floors		4	10	35	46
Structure style		Frame structure	Frame structure	Frame-shear structure	Frame-shear structure
Period	**Mode 1**	0.59s	1.02s	3.46s	4.65s
	Mode 2	0.18s	0.34s	1.03s	1.19s
	Mode 3	0.11s	0.19s	0.51s	0.72s
	Mode 4	0.07s	0.13s	0.31s	0.54s
	Mode 5	/	/	0.29s	0.37s
η_i	**Mode 1**	84.0%	77.4%	63.4%	61.1%
	Mode 2	10.9%	12.4%	15.7%	18.2%
	Mode 3	3.9%	4.0%	6.0%	5.3%
	Mode 4	1.2%	2.2%	5.3%	4.1%
	Mode 5	/	/	1.3%	2.7%
Models					

According to the *Chinese code for seismic design of buildings* (GB50011-2016 version, 2016), the evaluating principle of ground motion records is that the base shear obtained from the elastic time-history analysis with one record should be over 65% of the base shear obtained from the response spectrum modal analysis, and the average base shear obtained from the elastic time-history analysis with multiple records should be over 80% of the base shear obtained from the response spectrum modal analysis.

The appropriate records can be selected from the set (Table 1) according to the basic period of every structures. The comparisons of base shear results between elastic time-history dynamic analysis and response spectrum modal analysis are shown in Table 3. To draw a comparison of records selected from the set, one hundred records were selected randomly from the PEER without any selection condition and then selected through the DB method. Then, time-history dynamic analyses were done with the selected records. The results are shown also in Table 3. The base shear by response spectrum modal analysis is V_s, and the base shear by time-history dynamic analysis is V_t.

Table 3. Comparison of the records in set and the records selected by DB method.

Structures	V_s kN	Alternative set			Selected by DB method (proposed by Yang *et al.*)					
		Time-history analysis		V_t / V_s	Time-history analysis				V_t kN	V_t / V_s
					Period range			Platform range		
		Record number	V_t kN		Period segment	Ground motion number	δ	δ		
Structure 1	994.30	746	910.25	91.55%	[0.39s, 1.09s]	N-216	1.52%	0.72%	1253.24	126.04%
		1380	1123.05	112.95%		B-8	1.85%	7.23%	747.81	75.21%
		3752	1190.05	119.69%		*N-140	3.18%	6.94%	558.25	56.15%
		945	700.80	70.48%		N-204	8.53%	1.10%	1449.81	145.81%
		5808	678.32	68.22%		N-184	8.93%	7.96%	1015.71	102.15%
		1290	809.94	81.46%		N-244	9.23%	0.95%	1028.05	103.39%
		Mean	902.07	90.73%		Mean			1008.81	101.46%
Structure 2	1709.23	1190	1983.20	116.03%	[0.82s, 1.52s]	N-140	4.85%	6.94%	1390.36	81.34%
		4183	2261.57	132.32%		N-256	5.32%	7.69%	1845.75	107.99%
		1274	1657.67	96.98%		N-68	9.33%	8.94%	1346.08	78.75%
		945	2144.75	125.48%		N-92	9.98%	1.93%	1215.88	71.14%
		6896	1917.24	112.17%						
		1276	2158.05	126.26%						
		5805	1153.42	67.48%						
		Mean	1896.56	110.96%		Mean			1449.52	84.81%
Structure 3	17511.63	1813	26193.39	149.58%	[3.45s, 4.15s]					
		746	24109.82	137.68%						
		1291	17209.56	98.28%						
		1581	28088.31	160.40%						
		6896	18065.32	103.16%						
		Mean	22733.28	129.82%						
Structure 4	21371.47	6988	16514.79	77.27%	[4.45s, 5.15s]					
		6896	23107.88	108.12%						
		Mean	19811.34	92.70%						

From the calculating results, twenty-nine ground motion records from the set were selected for the four structures; furthermore, all the results meet the requirements of base shear statistical rule. Six and four records were selected, respectively, for structure 1 and structure 2 with shorter structure periods by the DB method, and even structure 3 and structure 4 with longer structure periods failed to select records by the DB method. If requirements of base shear statistical rule are added, only four and five records for structure 1 and structure 2 can be qualified separately (with * part of Table 3 is failure in meeting the requirements of base shear statistical law); thus, no record is qualified for structure 3 and structure 4. It shows that the records are selected from the set with a wide range of application, which are beneficial not only for shorter period structures, but also for longer period structures, especially since the DB method failed to do so in long period ranges. Furthermore, all records can meet the base shear requirement, which demonstrates high availability of records in the set.

CONCLUSIONS

The SDB method was set forth in this paper, which considered the higher modes to select ground motion records. And the record set was constructed by the SDB method based on response spectrum. Furthermore, the records in the set were put into structures to do time-history dynamic analysis. The conclusions are as follows:

(1) The modal participating mass ratio η_i was used as the weight coefficient to consider the higher modes, which represents the contribution of the ith mode to the seismic response of the structure. The sectionalized-dual-band method considering the influence of higher modes to select ground motion records was proposed. And the period range was determined by the weight coefficient of multiple frequency bands composed of several vibration periods of the structures.

(2) Ground motion records were initially selected by the PEER and then selected by the SDB method to construct the record set, observing the principle of consistency between record spectrum and design spectrum. Furthermore, the record sets with various fortification intensities and site characteristic periods can compose the ground motion record database. Hence, the records in the database can be used directly as the basic period of structure is determined, which can avoid tedious work for reselecting records due to various different structures. To omit the complicated process and save time, facilities will be offered for records selection in practical engineering.

(3) The time-history dynamic analysis of engineering structures verified the effectiveness of records in the set, under the evaluation principle of base shear according to the Chinese seismic design code. And the amount of records (selected by the SDB method) in the set was proved to be more adequate than that selected randomly by the DB method. Especially, for long period structures, the record set can offer qualified records, but the dual-band method cannot.

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