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Research on Relationship between Natural Vibration Periods and Structural Heights for High-rise Buildings and Its Reference Range in China

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Abstract

Natural vibration period is an important parameter for high-rise building, Based on 414 high-rise buildings completed or passed over-limit approval in China, the distribution law of natural vibration periods is analyzied. In order to satisfy the design requirements, such as global stability, story drift limit and minimum shear-gravity ratio, the reference ranges of fundamental periods T_1 are $0.3\sqrt{H}$~$0.4\sqrt{H}$ when the structural heights H ≥ 250 m, when 150 m ≤ H < 250 m, $T_1 = 0.25\sqrt{H}$~$0.4\sqrt{H}$, when 100 m ≤ H < 150 m, $T_1 = 0.2\sqrt{H}$~$0.35\sqrt{H}$, when 50 m ≤ H < 100 m, $T_1 = 0.15\sqrt{H}$~$0.3\sqrt{H}$. These can provide reference data for controlling mass and rigidity of high-rise buildings.

Keywords: High-rise building, Natural vibration period, Reference range

1. Introduction

Natural vibration period is an intrinsic property of high-rise building, and it is determined by the mass and rigidity of the structure (Xu et al., 2006; CABR, 1985; Li et al., 2003; Bao, 2001; Hong et al., 2012). The period will reflect the characteristics of the structure and determine whether the structure can satisfy the requirements of codes on high-rise buildings, such as stability, story drift limit, shear-gravity ratio, etc. (JGJ3, 2010; GB5011, 2010). The reference range of natural vibration period can help engineers to evaluate the suitability for mass and rigidity of high-rise buildings. Based on 414 high-rise buildings completed or passed over-limit approval in China, the distribution law and reference range of natural vibration periods are analyzed and presented in this paper,which could be reference data for engineers.

2. Previous Research on Reference Range of Fundamental Period for High-rise Building

The reference range of fundamental period for high-rise building was presented from the 1960s. It was derived from statistics on results of measurement and calculation for existing high-rise buildings. However, the structural heights of most high-rise buildings were below 50 m, and few of the structural heights were 50~100 m (CABR, 1985). The results of Chile were presented in 2010, but the heights of buildings were less than 135 m (Lagos et al., 2012).

2.1. China

Frame structure:

$$T_1 = 0.1n \tag{1a}$$

Shear wall structure:

$$T_1 = 0.04n\sim0.06n \tag{1b}$$

Frame-shear wall structure:

$$T_1 = 0.014H \tag{1c}$$

where n is the story number of high-rise building and H is the structural height of the building.

2.2. The United States

Frame structure:

$$T_1 = 0.1n \tag{2a}$$

Shear wall structure:

$$T_1=0.04\frac{H}{\sqrt{B}} \tag{2b}$$

Frame-shear wall structure:

$$T_1 = 0.09\frac{H}{\sqrt{B}}\sim0.108\frac{H}{\sqrt{B}} \tag{2c}$$

where B is the width of structure.

Meantime, the approximate fundamental period T_a for high-rise building shall be determined from the following equation in American Society of Civil Engineers (ASCE)

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Standard ASCE/SEI 7-10 (ASCE/SEI 7, 2010):

$$T_d = c_t H^x \tag{2d}$$

For concrete moment-resisting frames, the parameter c_t and x is respectively 0.0466 and 0.9, for other structural systems except steel moment-resisting frames and concrete moment-resisting frames, the parameter c_t and x is respectively 0.0488 and 0.75. The fundamental period T_1 shall not exceed the product of the coefficient for upper limit on calculated period c_u and the approximate fundamental period T_a, the coefficient c_u is between 1.4 and 1.7. When the calculated fundamental period T_1 exceeds $c_u T_a$, then $c_u T_a$ shall be used in lieu of T_1 to calculate the base shear force, but the elastic drifts is computed using seismic design forces based on the calculated fundamental period without the upper limit $c_u T_a$.

2.3. Romania

Frame structure:

$$T_1 = 0.08n \sim 0.12n \tag{3a}$$

Shear wall structure:

$$T_1 = 0.04n \sim 0.045n \tag{3b}$$

Frame-shear wall structure:

$$T_1 = 0.045n \sim 0.075n \tag{3c}$$

2.4. Japan

Frame structure:

$$T_1 = 0.02H \sim 0.03H \tag{4a}$$

Frame-shear wall structure:

$$T_1 = 0.07\frac{H}{\sqrt{B}} \sim 0.13\frac{H}{\sqrt{B}} \tag{4b}$$

2.5. Chile

Guendelman analyzed the relationship between fundamental period and structural height of existing 2,622 high-rise buildings, these buildings were constructed before 2010 (Lagos et al., 2012). The data are shown in Fig. 1. The distribution law of fundamental periods of high-rise buildings in Chile is shown as follows:

Normal:

$$T_1 = 0.014H \sim 0.025H \tag{5a}$$

Flexible:

$$T_1 > 0.025H \tag{5b}$$

Stiff:

$$T_1 = 0.007H \sim 0.014H \tag{5c}$$

Too stiff:

$$T_1 < 0.007H \tag{5d}$$

Considering the analysis of the reference range of fundamental period for high-rise buildings, it can be observed ① The fundamental period T_1 of most high-rise buildings presents linear relation with the storey number or structural height, for the buildings are relatively low. ② Because the different requirements of seismic codes, the reference range of fundamental period for high-rise buildings has some difference in different countries.

In recent decades, number and height of high-rise buildings increased significantly in China, the number of high-rise buildings over 150 m has exceeded 350, and the profiles get increasingly complex. However, the previous reference range of fundamental period for high-rise buildings is derived from the buildings below 50 m, and the design of high-rise building below 50 m is not determined by stiffness, but by bearing capacity. As a result, if the previous statistical law for high-rise buildings is applied to higher high-rise buildings, its rationality and accuracy

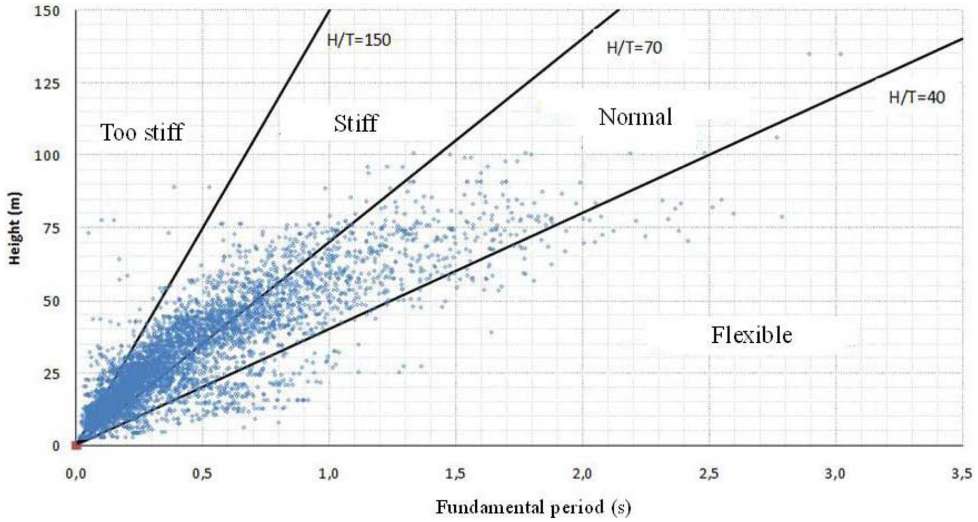


Figure 1. Relationship between fundamental periods T_1 and structural heights H for 2622 Chilean Buildings.

will decrease significantly. Therefore, it is necessary to statistically analyze distribution law and reference range of natural vibration periods for current high-rise buildings.

3. Distribution Law and Reference Range of Natural Vibration Periods for High-rise Buildings in China

The analysis in this paper employs 414 high-rise buildings completed or passed over-limit approval in China. The structural heights of all the buildings exceed 50 m, and most of the high-rise buildings above 300 m are included in the analysis. The data are from reinforced concrete structures or composite structures. Pure steel structures are not included. The structure types are shear wall structure, frame-shear wall structure and frame-core tube structure. The specific data is described in Table 1.

3.1. Fundamental period T_1

Fig. 2 shows the relation between the fundamental period T_1 and the structural height of high-rise building based on the data presented in Table 1. It can be figured out that the relationship of structural height and the fundamental period do not follow the linear relationship. Based on characteristic of the data and classification rules for story drift limitation in Technical specification for concrete structures of tall building JGJ3-2010 (JGJ3, 2010), the distribution law and reference range of high-rise buildings in China are described in as follows:

(1) When the structural heights H ≥ 250 m, the reference range of fundamental periods T_1 is $0.3\sqrt{H}$~$0.4\sqrt{H}$, for $T_1 < 0.3\sqrt{H}$, the structure is stiff, and for $T_1 > 0.4\sqrt{H}$, the structure is flexible.

(2) When 150 m ≤ H < 250 m, the reference range of T_1 is $0.25\sqrt{H}$~$0.40\sqrt{H}$, for $T_1 < 0.25\sqrt{H}$, the structure is stiff, and for $T_1 > 0.4\sqrt{H}$, the structure is flexible.

(3) When 100 m ≤ H < 150 m, the reference range of T_1 is $0.2\sqrt{H}$~$0.35\sqrt{H}$, for $T_1 < 0.2\sqrt{H}$, the structure is stiff and for $T_1 > 0.35\sqrt{H}$, the structure is flexible.

(4) When 50 m ≤ H < 100 m, the reference range of T_1 is $0.15\sqrt{H}$~$0.3\sqrt{H}$, for $T_1 < 0.15\sqrt{H}$, the structure is stiff, and for $T_1 > 0.3\sqrt{H}$, the structure is flexible.

3.2 Second-order period T_2

Utilizing analysis model of ideal bending and shear cantilever structures (mass and stiffness uniformly distributed) and employing dynamics theory of structures:

(1) Bending structure

$$T_1=1.786H^2\sqrt{\frac{G_i}{gEI}}=1.786\sqrt{\frac{8G_iH^4}{8gEI}}=1.612\sqrt{\frac{8G_iH^4}{8gEI}}$$

$$=1.612\sqrt{u_T} \quad (6)$$

$$T_2=0.285H^2\sqrt{\frac{G_i}{gEI}}=0.257\sqrt{u_T} \quad (7)$$

$$T_3=0.102H^2\sqrt{\frac{G_i}{gEI}}=0.092\sqrt{u_T} \quad (8)$$

where T_1, T_2, T_3 are the fundamental, second-order and third-order periods; G_i is gravity load per unit length along the height; g is gravitational acceleration; EI is the bending stiffness of structure; u_T is imaginary horizontal displacement on the top of structure.

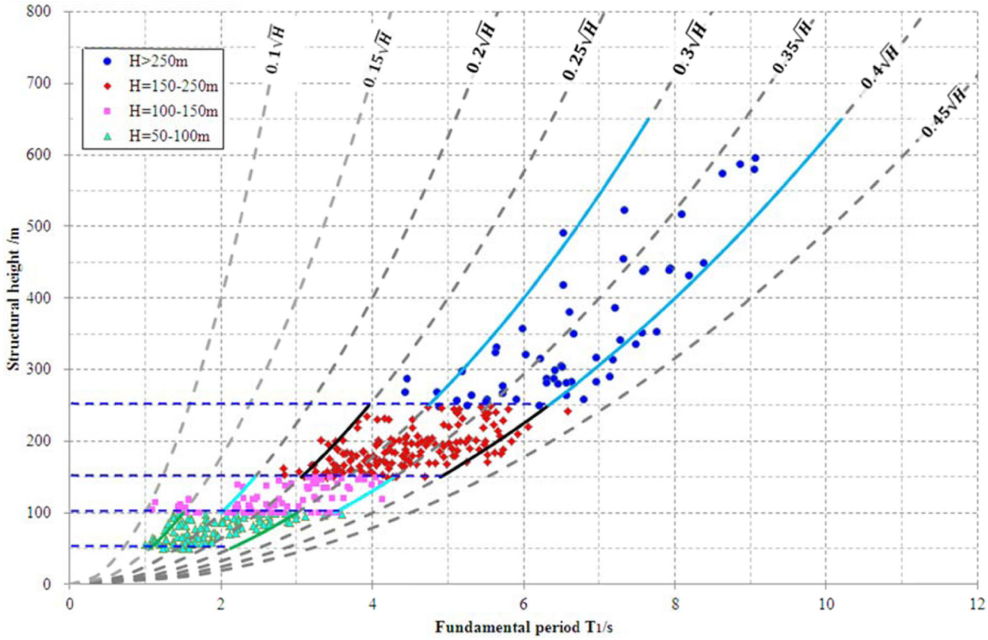


Figure 2. Relationship between fundamental periods T_1 and structural heights H.

Table 1. Statistic data of natural vibration periods for high-rise buildings in China

number	project site	structure type	H/m	T_1/s	T_2/s	T_3/s	number	project site	structure type	H/m	T_1/s	T_2/s	T_3/s
1	Tianjin	frame-core tube	597	9.06	2.93	1.51	208	Shen-yang	frame-core tube	157	3.61	0.99	0.5
2	Shen-zhen	frame-core tube	588	8.85	2.5	1.26	209	Shang-hai	frame-core tube	157	3.98	0.93	
3	Shang-hai	frame-core tube	580	9.05	3.06		210	Nanjing	frame-shear wall	155	4.01	0.99	
4	Wuhan	frame-core tube	575	8.62	2.72		211	Zhujiang	frame-shear wall	155	3.51		
5	Beijing	frame-core tube	524	7.33	2.26	1.18	212	Tianjin	frame-shear wall	154	3.91	1.25	
6	Guang-zhou	frame-core tube	518	8.08	2.4		213	Shen-zhen	frame-core tube	154	3.43	0.74	
7	Shang-hai	frame-core tube	492	6.52	2.09		214	Tianjin	frame-core tube	154	3.35		
8	Shen-yang	frame-core tube	456	7.31	2.2	1.13	215	Foshan	frame-core tube	154	2.84		
9	Suzhou	frame-core tube	450	8.37	2.67	1.41	216	Chang-sha	frame-shear wall	153	4.13		
10	Tianjin	frame-core tube	443	7.93	2.64	1.28	217	Shen-yang	shear wall	152	3.9	1.18	
11	Shen-zhen	frame-core tube	442	7.6			218	Beijing	frame-core tube	151	3.23		
12	Chong-qing	frame-core tube	440	7.92	2.53	1.09	219	Guang-zhou	frame-shear wall	150	4.32	1.18	0.57
13	Guang-zhou	frame-core tube	438	7.57	2.2	1.18	220	Nanjing	frame-core tube	150	3.1	0.9	
14	Dalian	frame-core tube	433	8.19	2.41	1.32	221	Beijing	frame-core tube	150	4.27	1.33	0.78
15	Shang-hai	frame-core tube	420	6.52	1.68	0.77	222	Dalian	frame-shear wall	150	3.5	0.8	
16	Tianjin	frame-core tube	388	7.2	2.42		223	Hang-zhou	frame-shear wall	150	4.7		
17	Nanjing	frame-core tube	381	6.6	1.82		224	Zhujiang	frame-shear wall	150	3.41		
18	Tianjin	frame-core tube	358	5.98	1.6		225	Nanjing	frame-core tube	150	4.21		
19	Nanning	frame-core tube	354	7.75	2.23		226	Nanjing	frame-shear wall	149	3.86		
20	Nanjing	frame-core tube	352	7.56	2.38	1.17	227	Shang-hai	frame-core tube	149	4.06	1.17	0.62
21	Dalian	frame-core tube	351	6.65	1.89	1.23	228	Shen-yang	shear wall	148	3.44	0.85	0.45
22	Shen-yang	frame-core tube	343	7.27	2.29		229	Shen-yang	shear wall	148	3.31	0.87	0.46
23	Tianjin	frame-shear-wall	337	7.48	2.45	1.53	230	Shen-yang	shear wall	148	3.15	0.71	0.34

Table 1. Statistic data of natural vibration periods for high-rise buildings in China (CONT.)

24	Tianjin	frame-core tube	332	5.63	1.63		231	Shen-yang	shear wall	148	3.25	0.86	0.46
25	Shen-zhen	frame-core tube	325	5.62	1.86	0.78	232	Taicuang	frame-core tube	148	3.87		
26	Guang-zhou	frame-core tube	323	6.02	1.61		233	Shang-hai	frame-core tube	148	3.6	1.05	0.54
27	Beijing	frame-core tube	317	6.96			234	Shen-zhen	frame-core tube	147	3.9	1.03	
28	Jiangyin	frame-core tube	317	6.21	1.69		235	Xiamen	frame-core tube	147	3.34		
29	Nanjing	frame-core tube	314	7.18	1.94	1.06	236	Foshan	shear wall	146	3.83		
30	Tianjin	frame-core tube	305	6.49			237	Sanya	frame-shear wall	144	2.77		
31	Shen-yang	frame-core tube	305	6.5	2.16		238	Nanjing	frame-core tube	141	2.94		
32	Chang-zhou	frame-core tube	300	6.4			239	Shang-hia	frame-core tube	140	3.27	0.97	
33	Tianjin	frame-core tube	299	5.18	1.37		240	Shang-hai	frame-shear wall	140	3.55		
34	Wuxi	frame-core tube	292	7.14			241	Shang-hai	frame-core tube	140	4.12		
35	Dong-guan	frame-core tube	289	6.3	1.43		242	Wuhan	frame-shear wall	140	3.23		
36	Dlian	frame-core tube	289	6.39	2.02		243	Shen-yang	frame-core tube	139	4	1.2	
37	Dlian	frame-shear wall	288	4.45	1.39		244	Lanzhou	frame-core tube	138	2.22		
38	Nanjing	frame-core tube	284	6.96	1.78	1.05	245	Beijing	frame-core tube	138	2.86	0.8	0.43
39	Shen-yang	frame-core tube	284	6.63	1.78		246	Beijing	frame-core tube	137	2.6		
40	Shen-yang	frame-core tube	283	6.3	2.11		247	Zhujiang	frame-core tube	137	2.3		
41	Shang-hai	frame-core tube	282	6.56			248	Shen-yang	shear wall	136	3.68	0.99	
42	Nanjing	frame-core tube	281	6.44	1.98	1.12	249	Xiang-gang	frame-core tube	136	3.14		
43	Suzhou	frame-core tube	278	5.72	1.81		250	Chengdu	frame-core tube	135	3.36		
44	Dalian	frame-core tube	269	4.86	1.44	0.75	251	Shen-zhen	frame-core tube	135	3.18	0.83	0.26
45	Beijing	frame-core tube	269	4.43	1.41		252	Nanjing	frame-core tube	134	3.41		
46	Nan-chang	frame-core tube	268	5.72			253	Shang-hai	frame-shear wall	134	3.71	0.86	
47	Beijing	frame-shear wall	265	5.3	1.68		254	Wuhan	frame-shear wall	133	3.16		
48	Guang-zhou	frame-core tube	265	6.55			255	Shen-zhen	frame-core tube	122	3.24		
49	Beijing	frame-core tube	260	5.52	1.65	0.74	256	Shang-hai	frame-core tube	122	2.48		

Table 1. Statistic data of natural vibration periods for high-rise buildings in China (CONT.)

50	Huizhou	frame-core tube	260	6.79			257	Beijing	frame-core tube	120	2.31	0.62	0.34
51	Shen-zhen	frame-core tube	260	5.89	2.07	0.8	258	Nanjing	frame-shear wall	120	3.47		
52	Dalian	frame-core tube	258	5.12	1.39		259	Foshan	frame-shear wall	119	3.63	1.07	
53	Beijing	frame-core tube	256	5.5	1.55	0.91	260	Chengdu	frame-shear wall	119	2.77	0.69	
54	Shang-hai	frame-core tube	250	5.25			261	Chengdu	frame-shear wall	119	2.43	0.65	
55	Wuxi	frame-core tube	250	6.2		1.14	262	Nanjing	frame-core tube	119	4.13	1.02	0.47
56	Kun-ming	frame-core tube	250	4.88		0.69	263	zhaoqing	frame-core tube	118	1.58		
57	Dalian	frame-core tube	249	5.56	1.57	0.87	264	Chengdu	frame-shear wall	118	2.46	0.73	
58	Dalian	frame-core tube	248	4.74	1.33		265	Shen-zhen	frame-shear wall	118	3.29		
59	Dalian	frame-core tube	247	5.44	1.61		266	Zhao-qing	frame-core tube	117	1.58		
60	Shang-hai	frame-core tube	246	4.92			267	Dalian	frame-shear wall	117	3.09	0.75	
61	Lanzhou	frame-core tube	246	5.16	1.49		268	Shang-hai	frame-core tube	115	1.13		
62	Shen-zhen	frame-core tube	245	5.08			269	Zheng-zhou	frame-core tube	112	2.81	0.76	
63	Beijing	frame-core tube	244	5.81	1.85		270	Beijing	frame-shear wall	111	2.23	0.61	0.28
64	Shijiaz-huang	frame-core tube	242	6.58			271	Fujian	frame-shear wall	111	2.61	0.7	0.34
65	Dalian	frame-core tube	241	5.64			272	Nanjing	frame-shear wall	111	1.47		
66	Beijing	frame-shear wall	240	5.5	1.48		273	Shang-hai	frame-core tube	110	2.37	0.6	0.29
67	Shen-zhen	frame-core tube	240	5.12		1.3	274	Guang-zhou	frame-shear wall	110	2.72		
68	Shen-zhen	frame-core tube	239	5.12	1.61		275	Chengdu	frame-shear wall	109	2.88	0.73	
69	Eerduosi	frame-core tube	238	5.54			276	Guang-zhou	shear wall	108	1.44		
70	Nanjing	frame-core tube	236	5.48	1.3	0.99	277	Beijing	frame-core tube	108	3.04	0.77	0.5
71	Beijing	frame-core tube	234	3.93	1.24		278	Qingdao	frame-shear wall	108	2.39		

Table 1. Statistic data of natural vibration periods for high-rise buildings in China (CONT.)

72	Nanjing	frame-core tube	232	5.51	1.82		279	Chang-sha	frame-shear wall	108	2.64	0.61	0.29
73	Nanjing	frame-core tube	232	5.2			280	Tianjin	frame-core tube	107	1.54		
74	Dalian	frame-shear wall	231	4.16	1.18	0.69	281	Shen-zhen	frame-core tube	107	2.23	0.5	0.2
75	Shang-hai	frame-core tube	230	4.53	1.12	0.87	282	Beijing	frame-core tube	106	2.2		
76	Beijing	frame-core tube	230	4.07	1.34		283	Beijing	frame-shear wall	105	2.24	0.61	
77	Shang-hai	frame-core tube	230	4.22	1.14		284	Fuzhou	frame-shear wall	105	1.44	0.42	0.22
78	Shen-yang	frame-core tube	229	5.73	1.48	0.51	285	Beijing	frame-shear wall	105	2.2		
79	Qingdao	frame-shear wall	228	3.8	1.32		286	Beijing	frame-core tube	104	1.1		
80	Shen-yang	frame-shear wall	223	4.94	1.43		287	Beijing	frame-core tube	103	2.4		
81	Hefei	frame-core tube	223	5.6	1.51	0.75	288	Shen-zhen	frame-shear wall	103	1.53		
82	Hefei	frame-core tube	223	5.14	1.42		289	Beijing	frame-core tube	102	1.46	0.38	0.21
83	Beijing	frame-core tube	221	5.02	1.64	0.96	290	Xiamen	frame-core tube	101	2.04		
84	Wuhan	frame-core tube	220	6.06			291	Beijing	frame-core tube	101	2.4	0.59	0.25
85	Nanjing	frame-core tube	218	4.54	1.25	0.62	292	Suzhou	frame-core tube	100	3.3		
86	Wuxi	frame-shear wall	218	5.47			293	Tangs-han	shear wall	100	1.69	0.4	
87	Shen-zhen	frame-core tube	218	3.8	1.34	0.7	294	Suzhou	frame-shear wall	100	3.55		
88	Tianjin	frame-core tube	214	5.66			295	Dalian	frame-core tube	100	2.84	0.63	
89	Wuhan	frame-core tube	210	5.92			296	Chang-shu	shear wall	100	2.56		
90	Shang-hai	frame-core tube	207	5.69			297	Tianjin	frame-core tube	100	1.55	0.42	
91	Ningbo	frame-core tube	207	4.45			298	Tianjin	frame-shear wall	100	1.72		
92	Dalian	frame-core tube	206	4.61			299	Suzhou	frame-shear wall	100	3.47		
93	Chong-qing	frame-core tube	205	5.28	1.77	0.99	300	Zheng-zhou	frame-shear wall	100	2.34	0.7	

Table 1. Statistic data of natural vibration periods for high-rise buildings in China (CONT.)

94	Dalian	frame-core tube	205	4.79	1.27		301	Lanzhou	frame-shear wall	100	2.1		
95	Beijing	frame-core tube	204	4.44	1.16		302	Wen-zhou	frame-core tube	100	2.31		
96	Shen-zhen	frame-shear wall	203	4.24			303	Chang-zhou	frame-shear wall	100	2.7		
97	Tianjin	frame-core tube	202	4.74			304	Shang-hai	shear-wall	100	2.4		
98	Shang-hai	frame-core tube	202	4.35			305	Wuxi	frame-shear wall	100	3.2	0.74	
99	Dalian	frame-core tube	202	4.08	1.19	0.64	306	Guang-zhou	frame-shear wall	100	3.41		
100	Beijing	frame-core tube	202	4.72	1.47	0.74	307	Taicuang	frame-core tube	100	2.68		
101	Wuxi	frame-core tube	201	3.61			308	Shen-zhen	frame-core tube	100	2.8		
102	Dalian	frame-core tube	201	5.37			309	Shen-zhen	frame-shear wall	100	2.5		
103	Haikou	frame-core tube	201	3.33			310	Chang-shu	shear wall	100	2.46		
104	Dalian	frame-core tube	200	4.75	1.4		311	Wulu-muqi	frame-core tube	100	2.5	0.82	
105	Tianjin	frame-core tube	200	4.65	1.21		312	Nanjing	frame-shear wall	100	2.73		
106	Chong-qing	frame-core tube	200	5.17			313	Wuhan	frame-shear wall	100	2.7		
107	Shang-hai	frame-core tube	200	4.29			314	Beijing	shear wall	100	1.68		
108	Guang-zhou	frame-core tube	200	3.51	0.92	0.42	315	Wulu-muqi	frame-core tube	100	2.16		
109	Shen-yang	frame-core tube	200	5.49	1.6	0.87	316	Chang-shu	frame-shear wall	99	2.9		
110	Chong-qing	frame-core tube	199	5.84	1.54		317	Haerbin	frame-shear wall	99	2.73	0.78	0.38
111	Shen-zhen	frame-core tube	199	5.24	1.57		318	Beijing	frame-core tube	99	2.46		
112	Dalian	frame-shear wall	199	5.11	1.28	0.59	319	Beijing	shear wall	99	2.54		
113	Beijing	frame-core tube	198	4.09	1.31	0.71	320	Wuzhon g	frame-core tube	99	2.86		
114	Guang-zhou	frame-core tube	197	4.07			321	Beijking	frame-core tube	99	2.49		
115	Shen-yang	frame-shear wall	197	4.52	1.21		322	Shang-hai	shear wall	99	2.32		
116	Suzhou	frame-core tube	197	4.44			323	Nanjing	shear wall	98	3.6		

Table 1. Statistic data of natural vibration periods for high-rise buildings in China (CONT.)

117	Nanjing	frame-core tube	197	4.52	1.32	0.78	324	Shen-zhen	frame-shear wall	98	3	0.84	0.4
118	Dalian	frame-core tube	197	5.01	1.33	0.64	325	Beijing	frame-core tube	98	1.44		
119	Wuxi	frame-core tube	196	5.02			326	Beijing	frame-shear wall	98	1.8		
120	Dalian	frame-core tube	196	3.42	0.92	0.48	327	Lanzhou	shear wall	97	2.22	0.66	0.34
121	Shang-hai	frame-core tube	196	4.93			328	Shen-zhen	frame-core tube	97	3.37		
122	Shen-yang	frame-core tube	196	4.6	1.29	0.68	329	Beijing	shear wall	96	1.37		
123	Dalian	frame-core tube	196	4.84			330	Shen-zhen	frame-shear wall	96	3.12		
124	Shen-yang	frame-core tube	195	5.48	1.5	0.8	331	Xian	frame-shear wall	96	2.07		
125	Dalian	frame-core tube	194	4.23	1.2	0.71	332	Wulu-muqi	frame-shear wall	95	2.63	0.71	
126	Nan-chang	frame-core tube	194	4.06	1.1	0.55	333	Shang-hai	frame-shear wall	94	2.31		
127	Shen-yang	frame-core tube	194	4.71	1.38		334	Beijing	frame-shear wall	94	1.37	0.32	0.15
128	Dong-guan	frame-core tube	192	4.95	1.46		335	Hefei	frame-shear wall	93	2.52		
129	Wuxi	frame-core tube	190	5.06	1.53		336	Foshan	frame-core tube	92	2.17		
130	Wuxi	frame-core tube	190	5.3	1.52		337	Beijing	frame-core tube	92	1.61		
131	Shen-yang	frame-core tube	190	5.06	1.44		338	Chengdu	frame-core tube	92	3		
132	Xian	frame-core tube	189	3.53	0.94		339	Shang-hai	frame-shear wall	92	1.57	0.51	
133	Guang-zhou	frame-core tube	189	5.42	1.63		340	Shang-hai	frame-shear wall	92	1.8		
134	Nanjing	frame-core tube	189	4.44	1.26		341	Guang-zhou	shear wall	90	1.61		
135	Weifang	frame-shear wall	188	3.55			342	Beijing	frame-shear wall	90	2.23		
136	Suzhou	frame-core tube	188	5.73			343	Shen-yang	frame-shear wall	89	2.65		
137	Dalian	frame-shear wall	187	5.13	1.51		344	Guang-zhou	frame-shear wall	89	2.88	0.96	
138	Shen-zhen	frame-core tube	187	4.21	1.06		345	Beijing	shear wall	88	2		

Table 1. Statistic data of natural vibration periods for high-rise buildings in China (CONT.)

139	Dalian	shear wall	186	3.87	0.97		346	Beijing	frame-shear wall	88	1.82		
140	Dalian	shear wall	186	3.89	0.99		347	Fuzhou	frame-shear wall	88	2.52	0.81	0.35
141	Zhuhai	frame-shear wall	185	4.65			348	Shen-yang	frame-shear wall	88	2.03		
142	Shen-zhen	frame-core tube	185	4.26			349	Shang-hai	shear wall	87	1.93		
143	Guang-zhou	frame-shear wall	185	4.9	1.35		350	Shen-zhen	shear wall	87	2.91	0.9	
144	Shang-hai	frame-core tube	185	3.67			351	Shang-hai	frame-core tube	87	2.02		
145	Guang-zhou	frame-core tube	184	5.62			352	Beijing	frame-core tube	87	1.5		
146	Chang-zhou	shear wall	184	4.16	1.2		353	Qingdao	frame-shear wall	85	1.31		
147	Shen-yang	shear wall	184	4.3	1.3		354	Longkou	frame-shear wall	85	1.46		
148	Shen-yang	shear wall	184	4.45	1.15		355	Suzhou	frame-shear wall	84	2.64		
149	Shen-yang	frame-core tube	183	5.71	1.69		356	Suzhou	frame-shear wall	84	2.58		
150	Dalian	shear wall	183	3.72	1.03		357	Beijing	frame-shear wall	83	2.21		
151	Dalian	shear wall	182	3.64	1.12		358	Wulu-muqi	frame-shear wall	82	1.45		
152	Dalian	shear wall	182	3.61	1.01		359	Beijing	shear-wall	82	1.53	0.44	
153	Suzhou	frame-core tube	182	5.53			360	Shen-yang	frame-shear wall	82	2.43		
154	Shen-yang	frame-shear wall	180	5.07	1.52		361	Zhous-han	frame-shear wall	81	2.11	0.59	
155	Shen-yang	shear wall	180	5.1	1.34		362	Wulu-muqi	frame-shear wall	81	1.78		
156	Beijing	frame-core tube	180	3.79	1.14	0.59	363	Nanjing	frame-shear wall	80	2.28		
157	Shen-zhen	frame-core tube	180	4.39			364	Beijing	frame-core tube	79	1.82	0.44	
158	Nanjing	frame-core tube	180	4.63			365	Zheng-zhou	shear wall	79	1.73		
159	Nanjing	frame-core tube	180	4.53			366	Suzhou	frame-shear wall	78	2.21		

Table 1. Statistic data of natural vibration periods for high-rise buildings in China (CONT.)

160	Hang-zhou	frame-core tube	180	4.01			367	Guang-zhou	frame-shear wall	78	1.66		
161	Nanjing	frame-core tube	179	4.03	0.9	0.45	368	Nanjing	frame-shear wall	78	2.47	0.67	
162	Shen-yang	frame-core tube	178	4.94	1.19		369	Beijing	frame-shear wall	77	1.26		
163	Shen-zhen	frame-core tube	178	3.94	1.11		370	Dalian	frame-shear wall	73	1.38	0.35	0.16
164	Wulu-muqi	frame-core tube	175	3.72	0.97		371	Tianjin	frame-shear wall	73	1.92	0.45	0.2
165	Nanjing	frame-core tube	175	4.44			372	Tianjin	frame-shear wall	72	1.89		
166	Nanjing	frame-core tube	175	3.44			373	Beijing	frame-shear wall	72	1.79	0.46	0.22
167	Shen-zhen	frame-core tube	174	4.48	1.19		374	Beijing	frame-shear wall	72	2.19	0.52	0.26
168	Nanjing	frame-core tube	172	4.1			375	Haerbin	frame-shear wall	71	2.12		
169	Shen-yang	frame-shear wall	172	3.9	1.1		376	Shen-zhen	frame-shear wall	70	1.56		
170	Beijing	frame-core tube	172	3.71	1.06		377	Hang-zhou	frame-shear wall	70	1.55		
171	Shen-yang	frame-core tube	172	4.15	1.26		378	Kun-ming	frame-core tube	69	1.68		
172	Dalian	shear wall	172	4.1			379	Shen-yang	frame-shear wall	68	1.95		
173	Nanning	frame-shear wall	171	5.25	1.48		380	Beijing	frame-shear wall	67	1.97	0.61	0.3
174	Nantong	frame-core tube	171	4.05			381	Beijing	frame-shear wall	67	1.43		
175	Guang-zhou	frame-core tube	170	5.53			382	Tianjin	frame-shear wall	66	1.77		
176	Shen-zhen	frame-core tube	170	4.16	1.14	0.53	383	Shang-hai	frame-shear wall	66	1.51		
177	Nanjing	frame-core tube	170	4.5			384	Shen-yang	frame-shear wall	66	1.48	0.39	0.18
178	Chengdu	shear wall	170	4.26			385	Tianjin	frame-shear wall	65	1.71	0.5	0.26
179	Hang-zhou	frame-core tube	170	4.19	1.11	0.55	386	Taiyuan	frame-shear wall	65	1.09		

Table 1. Statistic data of natural vibration periods for high-rise buildings in China (CONT.)

180	Guang-zhou	frame-core tube	169	4.76			387	Zheng-zhou	frame-shear wall	64	1.28	0.3	0.17
181	Guang-zhou	shear wall	169	4.84			388	Beijing	frame-shear wall	64	1.12		
182	Guang-zhou	frame-shear wall	168	4.99	1.6	0.78	389	Chengdu	frame-shear wall	62	1.87		
183	Nanjing	frame-core tube	168	4.59			390	Beijing	shear wall	62	1.27		
184	Dalian	shear wall	168	3.49	0.95		391	Shen-yang	frame-shear wall	62	1.56		
185	Shen-yang	shear wall	167	3.23	0.82	0.43	392	Beijing	shear wall	60	1.37		
186	Zheng-zhou	frame-core tube	167	4.06			393	Chengdu	frame-shear wall	60	1.65		
187	Shang-hai	frame-core tube	167	3.96			394	Beijing	frame-shear wall	60	1.11		
188	Nanjing	frame-core tube	166	4.38	1.04		395	Beijing	frame-shear wall	59	1.87	0.5	0.26
189	Beijing	frame-core tube	166	3.63	1.12	0.75	396	Nanjing	frame-shear wall	59	1.13		
190	Suzhou	shear wall	166	3.2			397	Zhuhai	frame-shear wall	59	1.88		
191	Nanjing	frame-core tube	166	3.54	0.87		398	Beijing	frame-core tube	58	1.74		
192	Guang-zhou	frame-core tube	165	4.42	1.06	0.54	399	Beijing	frame-shear wall	58	1.66		
193	Shen-yang	frame-shear wall	165	3.83	1.03		400	Chengdu	frame-shear wall	57	1.53		
194	Sheng-zhen	frame-core tube	165	4.43			401	Nanjing	frame-shear wall	57	1.8		
195	Chengdu	frame-core tube	163	4.22			402	Shen-yang	frame-shear wall	57	1.61		
196	Guang-zhou	frame-core tube	162	2.84	0.79	0.4	403	Guang-zhou	shear wall	56	1.19		
197	Dalian	shear wall	161	3.72	0.82		404	Shen-yang	shear wall	56	1		
198	Dalian	shear wall	161	3.5	0.74		405	Xian	frame-shear wall	56	1.37		
199	Nanjing	frame-core tube	160	3.56	0.96		406	Lanzhou	frame-shear wall	55	1.48		
200	Nanjing	frame-core tube	160	3.56			407	Lanzhou	shear wall	54	1.06		

Table 1. Statistic data of natural vibration periods for high-rise buildings in China (CONT.)

201	Fuzhou	shear wall	160	3.51	0.95		408	Chengdu	frame-shear wall	54	1.56
202	Dalian	shear wall	160	3.85	1.08		409	Guang-zhou	frame-shear wall	52	1.4
203	Shen-zhen	frame-core tube	159	3.7			410	Beijing	shear wall	51	1.28
204	Shen-zhen	shear wall	158	3.04			411	Beijing	frame-shear wall	51	1.24
205	Dalian	shear wall	158	3.26	0.84	0.45	412	Hefei	frame-shear wall	50	1.57
206	Dalian	shear wall	157	3.41	1.01	0.5	413	Nanjing	frame-shear wall	50	1.58
207	Dalian	shear wall	157	3.99	1.15	0.57	414	Chengdu	frame-shear wall	50	1.49

Note: The natural vibration periods are periodsof structures in weak axis. The data are according to the data presented when the stucutures passing over-limit approval in China, and may be adjusted in actual construction.

(2) Shear structure

$$T_1=3.997H\sqrt{\frac{G_i}{gGA}}=3.997\sqrt{\frac{2G_iH^2}{2gGA}}=1.805\sqrt{\frac{G_iH^2}{2GA}}$$

$$=1.805\sqrt{u_T} \quad (9)$$

$$T_2=1.333H\sqrt{\frac{G_i}{gGA}}=0.602\sqrt{u_T} \quad (10)$$

$$T_3=0.800H\sqrt{\frac{G_i}{gGA}}=0.361\sqrt{u_T} \quad (11)$$

where GA is the shear stiffness of structure.

It can be seen from Fig.3:

(1) When the structural heights H ≥ 250 m, the reference range of ratio between the second-order period and the fundamental period T_2/T_1 is 0.26~0.34.

(2) When 50 m ≤ H < 250 m, the reference range of the ratio T_2/T_1 is 0.23~0.31.

(3) The total average value of the ratio T_2/T_1 is 0.28 and the dispersion coefficient of the ratio T_2/T_1 is 7.0%.

The analysis result conforms to the fundamental principles of mechanics of high-rise buildings. It can be derived from above theoretical equations: the ratio T_2/T_1 is 0.16 for pure bending structure (shear wall structures), the ratio T_2/T_1 is 0.33 for pure shear structure (frame structures), and the ratios T_2/T_1 for frame-shear wall structure and frame-core tube structure locate between the ratios of the above two types of structures.

The relationship between the second-order period and the structural height of high-rise buildings is shown in Fig. 4. It can be found:

(1) When the structural heights H ≥ 250 m, the reference range of the second-order period T_2 is $0.08\sqrt{H}$~$0.12\sqrt{H}$.

(2) When 150 m ≤ H < 250 m, the reference range of T_2 is $0.065\sqrt{H}$~$0.10\sqrt{H}$.

(3) When 100 m ≤ H < 150 m, the reference range of T_2 is $0.05\sqrt{H}$~$0.1\sqrt{H}$.

(4) When 50 m ≤ H < 100 m, the reference range of T_2 is $0.035\sqrt{H}$~$0.08\sqrt{H}$.

The relationship with the corresponding reference range of the fundamental period T_1 is about 0.28.

3.3 Third-order period T_3

Due to data listed in Table 1, there is small sample for the third-order period. However, it can be found from Table 1 and Fig. 5.

(1) When the structural height H ≥ 250 m, the reference range of ratio between the third-order period and the fundamental period T_3/T_1 is 0.14~0.20.

(2) When 50 m ≤ H < 250 m, the reference range of the ratio T_3/T_1 is 0.10~0.19.

(3) The total average value of the ratio T_3/T_1 is 0.15 and the dispersion coefficient of the ratio T_3/T_1 is 21.1%.

The analysis result confirms to the analyze model of high-rise buildings. The ratio T_3/T_1 is 0.06 for pure bending structure, the ratio T_3/T_1 is 0.2 for pure shear structure, and the ratios T_3/T_1 for frame-shear wall structure and frame-core tube structure locate between the ratios of the above two types of structures.

4. The Relationship between Natural Vibration Period and Structural Heights of High-rise Buildings

Based on the definition of the natural vibration period,

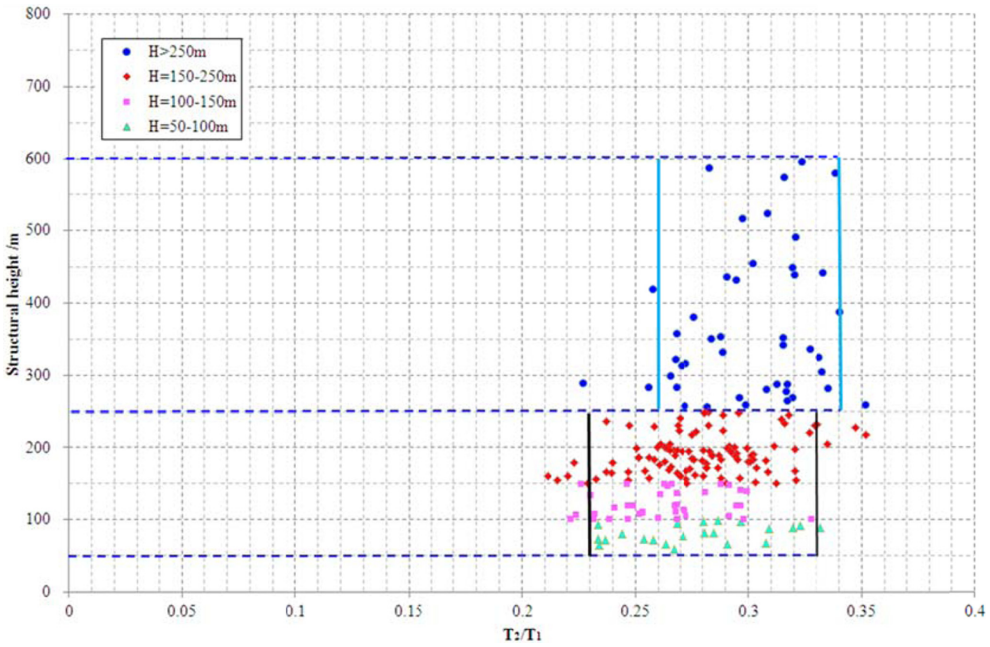


Figure 3. Relationship between T_2/T_1 and structural heights H.

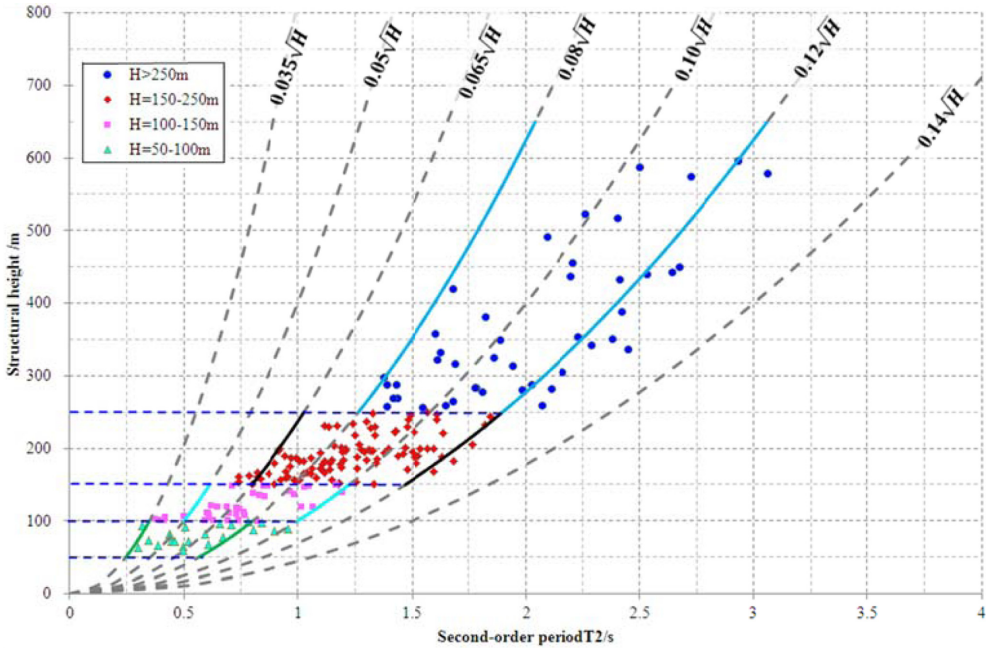


Figure 4. Relationship between second-order periods T_2 and structural heights H.

the natural vibration period and the structural height following relationship:

$$T = C\sqrt{H} \tag{12}$$

where C is a coefficient.

The statistical data and distribution law in Table 1 show that the relationship between the natural vibration period and the structural height of high-rise buildings conforms to the following equations, and the high-rise buildings described above (excluding pure steel structures and frame structures) should satisfy the requirements of Chinese codes and standards on global stability, story drift limit, shear-gravity ratio and so on.

(1) Fundamental period T_1

$H \geq 250$m:

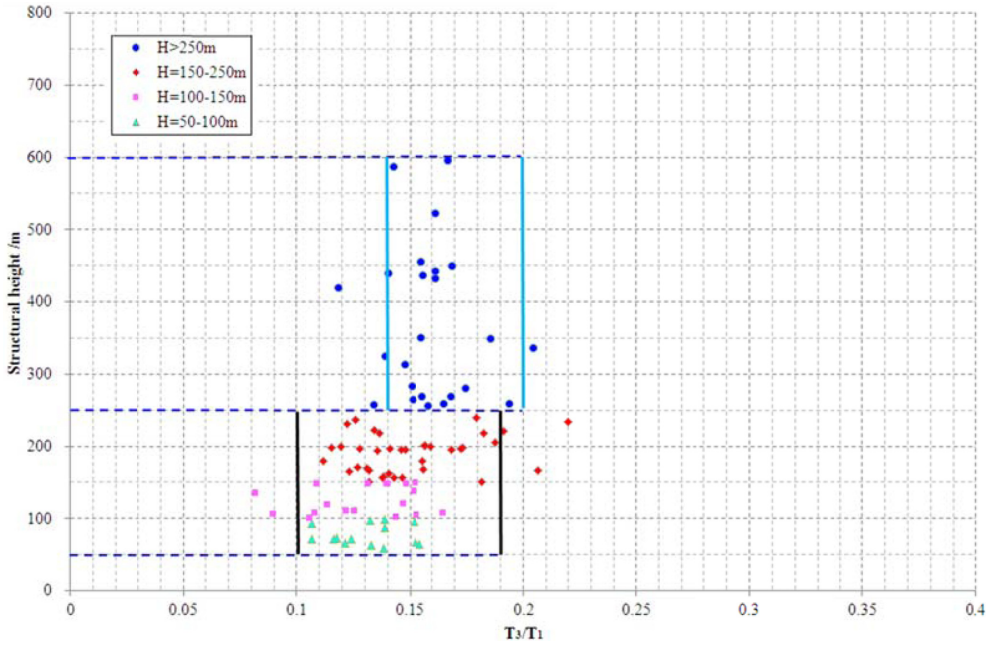


Figure 5. Relationship between T_3/T_1 and structural heights H.

$$T_1 = 0.3\sqrt{H} \sim 0.4\sqrt{H} \quad (13)$$

150 m ≤ H < 250 m:

$$T_1 = 0.25\sqrt{H} \sim 0.4\sqrt{H} \quad (14)$$

100 m ≤ H < 150 m:

$$T_1 = 0.2\sqrt{H} \sim 0.35\sqrt{H} \quad (15)$$

50 m ≤ H < 100 m:

$$T_1 = 0.15\sqrt{H} \sim 0.3\sqrt{H} \quad (16)$$

For the structural heights H < 50 m, the previous linear relationship between the natural vibration period and the structural height satisfies the accuracy required in engineering. It is suggested to use the previous reference range for fundamental period, that is $T_1 = 0.014H \sim 0.025H$ or $T_1 = 0.04n \sim 0.075n$. It can also use $T_1 = 0.08\sqrt{H} \sim 0.15\sqrt{H}$.

(2) Second-order period T_2

H ≥ 250 m:

$$T_2 = 0.26T_1 \sim 0.34T_1 \quad (17)$$

50 m ≤ H < 250 m:

$$T_2 = 0.23T_1 \sim 0.33T_1 \quad (18)$$

Total average value:

$$T_2 = 0.28T_1 \quad (19)$$

(3) Third-order period T_3

H ≥ 250 m:

$$T_3 = 0.14T_1 \sim 0.20T_1 \quad (20)$$

50 m ≤ H < 250 m:

$$T_3 = 0.12T_1 \sim 0.19T_1 \quad (21)$$

Total average value:

$$T_3 = 0.15T_1 \quad (22)$$

Fig. 2 shows that ① If the fundamental period T_1 of high-rise building is larger than $0.4\sqrt{H}$, the structure is flexible. ② If the fundamental period T_1 of high-rise building approaches $0.45\sqrt{H}$, the structure is too flexible.

5. Conclusions

Based on the data and analysis above, the main achievements of this paper are described as follows:

(1) Based on 414 high-rise buildings completed or passed over-limit approval in China, the distribution law of natural vibration periods for high-rise buildings over 50 m follows subduplicate curve along the structural heights.

(2) The reference ranges of fundamental period for high-rise buildings (excluding pure steel structures and frame structures) in China are described as follows ① when the structural height H ≥ 250 m, fundamental period $T_1 = 0.3\sqrt{H} \sim 0.4\sqrt{H}$. ② When 150 m ≤ H < 250 m, $T_1 = 0.25\sqrt{H} \sim 0.40\sqrt{H}$. ③ When 100 m ≤ H < 150 m, $T_1 = 0.2\sqrt{H} \sim 0.35\sqrt{H}$. ④ When 50 m ≤ H < 100 m, $T_1 = 0.15\sqrt{H} \sim 0.3\sqrt{H}$. ⑤ For H < 50 m, the linear relationship between the natural vibration period and the structural height satisfies the accuracy required in engineering. It is suggested that $T_1 = 0.014H \sim 0.025H$ or $T_1 = 0.04n \sim 0.075n$. It can also use $T_1 = 0.08\sqrt{H} \sim 0.15\sqrt{H}$.

(3) The relationships for the first three order periods are described as follows ① when H ≥ 250 m, the ratio between the second-order and the fundamental period T_2/T_1 is 0.26 ~0.34, and the ratio between the third-order and the fundamental period T_3/T_1 is 0.14~0.20. ② When 50 m ≤ H < 250 m, the ratio T_2/T_1 is 0.23~0.33, and the ratio T_3/T_1 is 0.12~0.19.

(4) If the fundamental period T_1 of high-rise building is larger than $0.4\sqrt{H}$, the structure is flexible, and if the fundamental period T_1 of high-rise building approaches $0.45\sqrt{H}$, the structure is too flexible.

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