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嵌岩桩的极限端阻力发挥特性及其端阻力系数

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摘　要:嵌岩桩极限端阻力发挥特征及端阻力系数取值是岩土工程中嵌岩桩应用的重要研究课题之一。收集整理了不同地区学者在不同时期、不同岩石性质和不同嵌岩条件下开展的 165 个嵌岩桩端阻力试验成果,主要包括嵌岩段岩石类型及其天然单轴抗压强度、嵌岩直径与嵌岩深度、嵌岩桩极限端阻力等。定义嵌岩桩极限端阻力与岩石天然单轴抗压强度的比值为嵌岩桩端阻力系数,分析了桩径、嵌岩深度、嵌岩深径比和岩石强度对嵌岩桩极限端阻力和端阻力系数的影响规律,建立了嵌岩桩极限端阻力及端阻力系数与岩石单轴抗压强度之间的拟合关系式。

关键词:嵌岩桩;端阻系数;端阻力;嵌岩深径比;抗压强度

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Statistical analysis on end-bearing capacity and resistance factor for rock-socketed piles

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Abstract: It is of great importance to investigate the characteristics of end-bearing capacity and to determine the resistance factor for rock-socketed piles. In this study, based on the results of 165 compression load tests several key issues with regard to the end-bearing capacity behavior of rock-socket piles were examined. These load tests were conducted on different rocks with different rock-socketed pile conditions throughout the world. The influential factors include the type and the uniaxial natural compressive strength of rocks, the diameter and the embedment depth of socketed piles, and the ultimate end-bearing resistances. In this study, the ratio of ultimate end-bearing capacity to the unconfined compressive strength of the rock was defined as the end-bearing resistance factor of rock-socketed pile. Effects of the key factors on the ultimate end-bearing capacity and the end-bearing resistance factor were comprehensively investigated. An empirical equation between the unconfined compressive strength.

Keywords: rock-socket pile; end-bearing resistance factor; end-bearing capacity; ratio of pile rocketed depth to diameter; compressive strength

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嵌岩桩作为承受大型建（构）筑物荷载的主要基础型式，已在工程中得到了广泛应用。然而，由于嵌岩桩具有承载力大、试验费用高、难以进行破坏性试验等特点，系统且完整的静载试验实测数据不多，从而制约了人们对嵌岩桩承载性状的全面认识[1-2]。目前，各行业规范对嵌岩桩承载力计算主要是经验和半经验公式，经验参数较多[3]，设计方法及其参数取值也不尽相同，其原因主要源于对嵌岩桩荷载传递机理与承载性状认识存在偏差[4]。

中国建筑地基基础设计规范[5]认为嵌岩桩是端承桩，按端承桩设计。但学术界和工程界都普遍认为，嵌岩桩抗压承载力主要由基岩上覆土层桩侧阻力、嵌岩段桩侧阻力和桩端阻力 3 部分组成，这已体现在中国相关规范[6-9]所给出的嵌岩桩承载力设计方法中。鲁先龙等[10]通过收集整理嵌岩桩竖向下压承载力试验成果，分析了桩径、嵌岩深度、嵌岩深径比和岩石强度对嵌岩桩嵌岩段桩侧极限阻力和岩石极限侧阻力系数的影响规律，建立了嵌岩段岩石极限侧阻力系数与岩石单轴抗压强度之间的拟合关系式，给出了不同可靠度水平下岩石侧极限阻力系数取值建议。但大量现场试验表明[11-14]，嵌岩桩在竖向荷载作用下，桩体首先发生竖向位移，桩体和桩侧岩土体之间发生相对位移，桩顶荷载通过桩侧岩土体阻力逐渐传递至桩端，嵌岩段桩侧阻力一般先于桩端阻力发挥。嵌岩桩岩石端阻力发挥过程更加复杂，研究嵌岩桩极限端阻力发挥特征将具有重要的理论和实践意义。

本文收集整理了学者们在不同时期、不同地区、不同岩石强度和不同嵌岩条件下所完成的 165 个嵌岩桩竖向下压承载力试验成果，分析了桩径、嵌岩深度、嵌岩深径比和岩石强度对嵌岩桩极限端阻力和端阻力系数的影响规律，建立了嵌岩桩极限端阻力及端阻力系数与岩石天然单轴抗压强度之间的拟合关系式，可为嵌岩桩极限端阻力计算提供借鉴。

1　试验数据收集与整理

1.1　数据收集

所收集的试验数据来源于 34 篇文献[15-48]，共 165 个嵌岩桩竖向下压承载力试验结果，主要包括嵌岩段岩石类型、嵌岩段桩径 d、嵌岩深度 h_r、岩石天然单轴抗压强度 σ_c 以及嵌岩桩极限端阻力 q_p 等。相关文献作者与发表时间列于表 1。全部嵌岩桩嵌岩条件及其极限端阻力试验结果列于表 2。

表 1　文献作者与年代[15-48]

Table 1　Authors and years for the references in this study[15-48]

序号	作者及年代	序号	作者及年代	序号	作者及年代
1	Reese and Hudson (1968)	13	Baker (1985)	25	Abu-Hejleh et al. (2003)
2	Vijayvergiya et al. (1969)	14	Seik et al. (1985)	26	Bullock (2003)
3	Engeling and Reese (1974)	15	Hummert and Cooling (1988)	27	Mc Vay et al. (2003)
4	Aurora and Reese (1976)	16	Orpwood et al. (1989)	28	Mello et al. (2003)
5	Webb (1976)	17	Radhakrishnan and Leung (1989)	29	Miller (2003)
6	Wilson (1976)	18	Leung and Ko (1993)	30	Nam (2004)
7	Goeke and Hustad (1979)	19	Thompson (1994)	31	Abu-Hejleh and Attwooll (2005)
8	Thorne (1980)	20	Carrubba (1997)	32	Basarkar and Dewaikar (2006)
9	Williams (1980)	21	O'Neill (1998)	33	GEO (2006)
10	Jubenville and Hepworth (1981)	22	Tchepak (1998)	34	Kulkarni and Dewaikar (2017)
11	Glos et al. (1983)	23	Osterberg (2001)		
12	Horvath et al. (1983)	24	Gunnink and Kiehne (2002)		

当前，学者们都通常定义嵌岩桩极限端阻力 q_p 和岩石单轴抗压强度 σ_c 之间的比值为嵌岩桩极限端阻力系数，记为 ξ_p，即

$$\xi_p = q_p/\sigma_c \tag{1}$$

根据表 2 试验结果，按式(1)得到各试验基础的极限端阻力系数 ξ_p 值，结果也列于表 2。

这里需特别说明，引用文献的试验工作是不同时期、不同地区学者，分别在不同岩石类型与强度、不同桩端嵌岩条件下完成的，作者对嵌岩桩极限端阻力的测试方法、极限承载力确定原则等方面也不尽相同。本文分析中均直接采用了原文献结果，这种方法分析得到的研究结论将更具一般性。

表 2 嵌岩桩极限端阻力试验结果

Table 2 Database for the load test results of end-bearing capacities of piles socketed into rock

基础编号	岩石类型	d/mm	h_r/m	σ_c/MPa	q_p/MPa	ξ_p	基础编号	岩石类型	d/m	h_r/m	σ_c/MPa	q_p/MPa	ξ_p
1/1	黏土岩	610	1.80	0.50	1.642	3.285	22/2	页岩	600	1.40	2.40	2.500	1.042
2/1	页岩	760	2.40	0.60	3.637	6.062	23/1	石灰石	—	—	120.00	12.162	0.101
3/1	黏土岩	760	4.00	0.40	3.329	8.322	23/2	石灰石	—	—	120.00	35.421	0.295
4/1	泥页岩	890	1.83	0.62	2.643	4.263	23/3	页岩	—	—	2.90	15.417	5.316
4/2	泥页岩	740	1.14	1.42	5.680	4.000	23/4	页岩	—	—	22.10	23.940	1.083
4/3	泥页岩	790	1.19	1.42	5.125	3.609	23/5	石灰石	—	—	84.10	69.426	0.826
4/4	泥页岩	750	1.61	1.42	6.111	4.304	23/6	石膏岩	—	—	38.00	7.795	0.205
5/1	辉绿岩	615	10.0	0.52	2.650	5.096	23/7	页岩	—	—	0.80	9.720	12.150
6/1	泥岩	670	3.00	4.20	6.880	1.638	23/8	页岩	—	—	2.30	6.895	2.998
7/1	页岩	762	3.30	0.81	4.690	5.790	24/1	石灰石	460	1.10	60.70	21.400	0.353
8/1	页岩	2 000	5.00	8.00	3.650	0.456	24/2	石灰岩	460	1.10	60.70	9.100	0.150
8/2	砂岩	2 000	5.00	12.50	14.000	1.120	24/3	石灰石	460	1.20	60.70	22.900	0.377
8/3	页岩	2 000	5.00	18.20	7.500	0.412	25/1	砂岩	1 067	—	1.96	11.300	5.765
9/1	泥岩	600	—	0.50	4.510	9.020	25/2	砂岩	1 372	—	10.50	15.200	1.448
9/2	泥岩	1 000	—	0.60	5.530	9.217	25/3	砂岩	1 070	4.90	0.40	2.633	6.584
9/3	泥岩	100	—	0.60	8.910	14.850	25/4	黏土岩	1 220	4.30	0.50	2.542	5.085
9/4	泥岩	300	—	0.70	6.390	9.129	25/5	黏土岩	1 070	6.30	2.60	11.300	4.346
9/5	泥岩	100	—	0.60	14.010	23.350	25/6	黏土岩	1 370	9.20	11.40	15.226	1.336
9/6	泥岩	1 000	—	2.50	5.880	2.352	26/1	石灰石	1 585	—	1.50	6.280	4.187
9/7	泥岩	1 000	—	2.30	6.620	2.878	26/2	石灰石	1 940	—	3.80	6.220	1.637
9/8	泥岩	1 000	—	2.30	7.000	3.043	26/3	石灰石	1 880	—	0.92	3.570	3.880
9/9	泥岩	1 000	—	2.30	6.660	2.896	27/1	石灰石	1 500	7.30	2.80	8.810	3.146
10/1	页岩	305	1.50	1.08	3.660	3.383	27/2	石灰石	1 800	8.50	2.80	6.703	2.394
11/1	砂岩	610	15.6	8.36	10.600	1.268	27/3	石灰石	2 100	10.7	2.80	5.746	2.052
11/2	砂岩	610	16.9	9.26	13.100	1.415	27/4	石灰石	2 100	15.9	2.80	6.224	2.223
12/1	页岩	710	1.40	11.10	2.652	0.239	27/5	石灰石	1 800	6.10	2.80	3.830	1.368
12/2	页岩	710	1.40	5.50	7.577	1.378	27/6	石灰石	1 500	7.60	2.80	4.213	1.505
13/1	砂砾岩	1 281	—	1.38	5.840	4.232	28/1	泥岩	800	2.00	7.50	5.000	0.667
13/2	砂砾岩	1 920	—	0.57	2.290	4.018	28/2	泥岩	800	3.00	7.50	5.000	0.667
13/3	砂砾岩	762	—	1.11	4.790	4.315	29/3	泥岩	1 189	—	1.21	5.830	4.818
14/1	泥页岩	2.31	0	0.80	1.085	1.356	30/1	泥页岩	762	—	1.50	3.600	2.400
15/1	页岩	457	2.70	3.82	10.800	2.827	30/2	石灰石	762	—	10.90	10.500	0.963
16/1	砂砾岩	762	3.60	0.70	4.000	5.714	31/1	黏土岩	787	—	1.21	9.480	7.835
16/2	砂砾岩	762	3.60	0.81	4.150	5.123	31/2	黏土岩	762	—	0.48	2.250	4.688
16/2	砂砾岩	762	3.60	1.00	5.500	5.500	31/3	黏土岩	762	—	1.10	5.030	4.573
17/1	粉砂岩	705	1.50	9.00	13.100	1.456	32/1	玄武岩	1 000	—	14.14	11.300	0.799
17/2	页岩	—	—	34	28	0.824	32/2	玄武岩	1 000	—	19.43	13.200	0.679
17/3	砂岩	—	—	12.50	14.000	1.120	32/3	玄武岩	1 000	—	11.77	10.300	0.875
17/4	砂岩	—	—	27.50	50.000	1.818	32/4	玄武岩	1 000	—	12.46	10.600	0.851
18/1	石膏岩	1 060	4.20	2.10	6.510	3.100	32/5	玄武岩	1 000	—	7.07	8.000	1.132
18/2	石膏岩	1 060	4.20	4.20	10.900	2.595	32/6	凝灰岩	1 200	—	11.49	10.200	0.888
18/3	石膏岩	1 060	4.20	5.40	15.700	2.907	32/7	凝灰岩	1 200	—	28.50	16.000	0.561
18/4	石膏岩	1 060	4.20	6.70	16.100	2.403	32/8	角砾岩	1 200	—	6.40	7.600	1.188
18/5	石膏岩	1060	4.20	8.50	23.000	2.706	32/9	玄武岩	1 200	—	39.40	18.800	0.477
18/6	石膏岩	1 060	4.20	11.30	27.700	2.451	32/10	玄武岩	1 200	—	28.04	15.900	0.567
19/1	页岩	1 803	—	2.21	10.800	4.887	32/11	玄武岩	900	—	35.70	17.900	0.501

续表 2

基础编号	岩石类型	d/mm	h_r/m	σ_c/MPa	q_p/MPa	ξ_p	基础编号	岩石类型	d/m	h_r/m	σ_c/MPa	q_p/MPa	ξ_p
20/1	泥灰岩	1200	7.50	0.90	5.300	5.889	32/12	玄武岩	900	—	21.83	14.000	0.641
20/2	石灰石	1200	2.50	15.00	8.900	0.593	32/13	角砾岩	1 200	—	5.36	7.000	1.306
20/3	角砾岩	1 200	2.50	2.50	8.900	3.560	32/14	角砾岩	1 100	—	40.80	19.100	0.468
21/1	砂岩	1 220	3.66	4.30	3.700	0.860	32/15	玄武岩	1 050	—	15.30	11.700	0.765
22/1	页岩	750	1.00	4.60	2.500	0.543	32/16	玄武岩	600	—	11.80	10.300	0.873
32/17	玄武岩	600	—	14.24	11.300	0.794	34/31	玄武岩	600	3.00	43.70	3.840	0.088
33/1	花岗闪长岩	1 320	—	35.00	16.000	0.457	34/32	玄武岩	600	3.00	9.20	2.620	0.285
34/1	玄武岩	150	1.00	44.20	14.320	0.324	34/33	玄武岩	600	3.00	8.70	2.370	0.272
34/2	玄武岩	400	1.20	9.20	1.950	0.212	34/34	玄武岩	600	3.00	9.20	2.620	0.285
34/3	玄武岩	1 200	7.50	54.70	9.810	0.179	34/35	玄武岩	600	3.00	9.20	2.620	0.285
34/4	玄武岩	1 000	2.50	12.70	8.790	0.692	34/36	玄武岩	600	3.00	9.20	2.230	0.242
34/5	玄武岩	400	2.00	9.20	2.290	0.249	34/37	玄武岩	600	3.00	9.20	2.620	0.285
34/6	玄武岩	400	1.50	9.20	2.190	0.238	34/38	玄武岩	600	2.50	64.70	7.500	0.116
34/7	玄武岩	400	3.80	9.20	2.290	0.249	34/39	玄武岩	600	1.00	64.60	5.030	0.078
34/8	玄武岩	400	2.00	57.10	4.390	0.077	34/40	玄武岩	600	1.00	12.30	3.320	0.270
34/9	玄武岩	400	1.60	57.10	5.410	0.095	34/41	玄武岩	650	4.00	22.10	3.770	0.171
34/10	玄武岩	400	2.00	9.20	2.620	0.285	34/42	玄武岩	750	2.00	57.10	10.240	0.179
34/11	玄武岩	400	2.00	9.20	2.660	0.289	34/43	玄武岩	750	2.00	28.35	8.260	0.291
34/12	玄武岩	500	2.00	14.60	3.360	0.230	34/44	玄武岩	800	6.00	12.70	8.660	0.682
34/13	玄武岩	500	0.50	28.40	6.780	0.239	34/45	玄武岩	900	3.00	14.60	6.580	0.451
34/14	玄武岩	500	1.50	35.62	8.610	0.242	34/46	玄武岩	900	3.50	14.60	6.580	0.451
34/15	玄武岩	500	3.20	9.20	2.290	0.249	34/47	玄武岩	900	1.80	60.72	10.880	0.179
34/16	玄武岩	500	5.30	9.20	2.290	0.249	34/48	玄武岩	900	3.50	14.90	4.370	0.293
34/17	玄武岩	500	5.30	9.20	2.190	0.238	34/49	玄武岩	900	2.30	42.70	7.220	0.169
34/18	玄武岩	500	2.00	11.00	4.500	0.409	34/50	玄武岩	1 000	2.30	35.70	4.450	0.125
34/19	玄武岩	500	2.00	16.47	4.080	0.248	34/51	玄武岩	1 000	8.90	9.20	2.440	0.265
34/20	玄武岩	500	1.40	64.70	12.540	0.194	34/52	玄武岩	1 100	5.80	40.80	7.680	0.188
34/21	玄武岩	500	2.00	3.70	3.170	0.857	34/53	玄武岩	1 200	4.00	64.70	8.480	0.131
34/22	玄武岩	500	3.90	3.70	3.170	0.857	34/54	玄武岩	1 200	3.60	24.70	4.990	0.202
34/23	玄武岩	500	3.00	3.70	3.170	0.857	34/55	玄武岩	1 200	3.00	39.40	5.330	0.135
34/24	玄武岩	500	2.50	3.68	3.160	0.859	34/56	玄武岩	1 200	0.60	35.70	8.480	0.238
34/25	玄武岩	570	5.40	1.81	1.820	1.006	34/57	玄武岩	1 200	1.50	40.80	7.440	0.182
34/26	玄武岩	600	3.00	9.20	2.190	0.238	34/58	玄武岩	1 200	6.00	13.80	6.300	0.457
34/27	玄武岩	600	3.00	9.20	2.190	0.238	34/59	玄武岩	400	1.50	11.90	4.340	0.365
34/28	玄武岩	600	1.00	35.62	3.670	0.103	34/60	玄武岩	750	1.20	35.71	4.660	0.130
34/29	玄武岩	600	3.00	43.70	3.090	0.071	34/61	玄武岩	2 000	7.70	65.60	20.660	0.315
34/30	玄武岩	600	3.20	9.20	2.620	0.285							

注：1）基础编号中“/”的前一个数字代表文献序号、后一个数字代表该文献中试验基础个数的序号。2）表中“—”表示原文献中无相应数据。

1.2　数据整理与分析

如表 2 所示，嵌岩桩抗压承载性能差异主要由嵌岩段岩体性质和桩端嵌岩特征不同引起。桩端嵌岩特征主要包括桩径、嵌岩深度、嵌岩深径比。表 2 中，嵌岩段岩石主要包括黏土岩、页岩、泥页岩、砂砾岩、石膏岩、石灰石、凝灰岩和角砾岩等多种类型。

中国规范[49]指出，影响岩体性质的因素主要是岩石物理力学性质、构造发育情况、荷载（工程荷载和初始应力）、应力应变状态、几何边界条件、水的赋存状态等。在这些因素中，岩石坚硬程度则是反映岩体基本特性的一个重要因素。这里还需要特别说明的是，规范[49]中岩石坚硬程度是按岩石饱和单轴抗压强度大小进行划分，而本文所引用文献中的

岩石强度 σ_c 均为岩石天然单轴抗压强度，这是二者的不同。

2 岩石极限端阻力与端阻力系数影响因素

根据表2所收集与整理的嵌岩桩端阻力试验数据，分析桩径、嵌岩深度、嵌岩深径比和岩石强度对嵌岩桩极限端阻力和端阻力系数的影响规律。

2.1 桩径

图1和图2分别为嵌岩桩极限端阻力及端阻力系数随桩径变化的规律。图1和图2结果表明，桩径对嵌岩极限桩端阻力影响并不显著，嵌岩桩极限端阻力与桩径之间无明显相关性。桩端阻力系数总体随桩径增加而呈下降趋势，当桩径小于0.5 m时尤为明显，当桩径大于0.5 m后，这种下降趋势表现得并不显著。

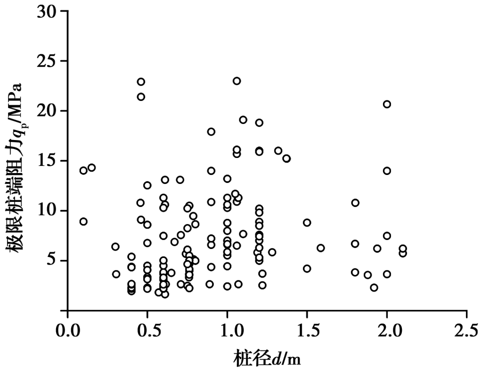

图1 嵌岩桩极限端阻力随桩径变化

Fig. 1 Variation of ultimate end-bearing capacity with diameter of the pile socketed into rock

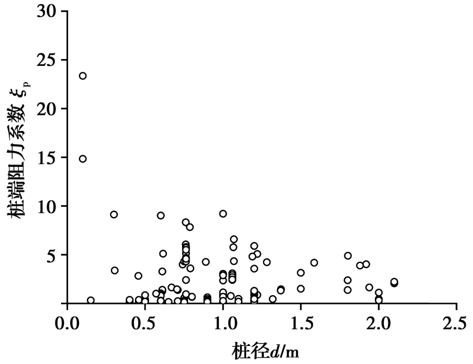

图2 嵌岩桩端阻力系数随桩径变化

Fig. 2 Variation of ultimate end-bearing resistance factor with diameter of the pile socketed into rock

2.2 嵌岩深度

嵌岩深度不仅影响嵌岩段侧阻力发挥性状，对桩端分担的荷载大小也有较大影响。此外，嵌岩深度也直接关系到嵌岩桩应用的安全性和经济性。嵌岩深度大，虽安全可靠，但施工难度大、费用高。反之，嵌岩深度过小，若桩端岩性差，嵌岩桩承载力和沉降可能不满足上部结构要求。图3给出了嵌岩桩极限端阻力随嵌岩深度变化规律。

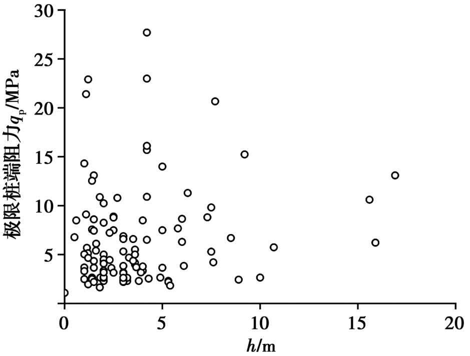

图3 嵌岩桩极限端阻力随嵌岩深度变化

Fig. 3 Variation of ultimate end-bearing capacity with depth of the pile socketed into rock

图3表明，嵌岩桩极限端阻力随嵌岩深度变化虽有一定离散性，但总体上随嵌岩深度增加而略有减小，这与Rowe等[50]研究结论一致。即在一定嵌岩深度范围内，增加嵌岩深度可提高嵌岩桩承载力，但超过一定深度后，嵌岩深度的增加对单桩承载力几乎没有影响，即嵌岩桩存在最佳嵌岩深度，这也与我国学者对嵌岩深度普遍看法一致，嵌岩桩存在最佳嵌岩深度，可使嵌岩段桩侧阻力和桩端阻力发挥最为协调和充分。但不同学者对最佳嵌岩深度取值研究结论也不一致。黄求顺[12]认为最佳嵌岩深度为 $3d$，而刘兴远等[51]认为一律将嵌岩深度取为 $3d$ 不合理，应根据桩端所嵌入岩体状态确定。明可前[52]通过试验认为最佳嵌岩深度为 $4d$。许锡宾等[53]认为硬质岩和软质岩最佳嵌岩深度分别取 $3d$ 和 $5d$ 较合理。

2.3 嵌岩深径比

图4为嵌岩桩极限端阻力随嵌岩深径比 h_r/d 的变化规律。结果表明，嵌岩桩极限端阻力总体随嵌岩深径比的增大而减小，这与史佩栋等[13]统计分析结果一致。史佩栋等[13]根据150根嵌岩桩下压实测结果，绘制了嵌岩桩极限端阻分担荷载比与桩身嵌岩深径比 h_r/d 之间的关系曲线。结果表明，嵌岩桩极限端阻力总体随嵌岩深径比的增大而减小，当 $1.0<h_r/d<20$ 时，嵌岩桩端阻分担荷载比随 h_r/d 增大迅速从100%递减至约20%；当 $20<h_r/d<63.7$ 时，嵌岩桩端阻分担的荷载比一般不超过

30%，且大部分桩为 20%以下，不少桩为 5%以下。

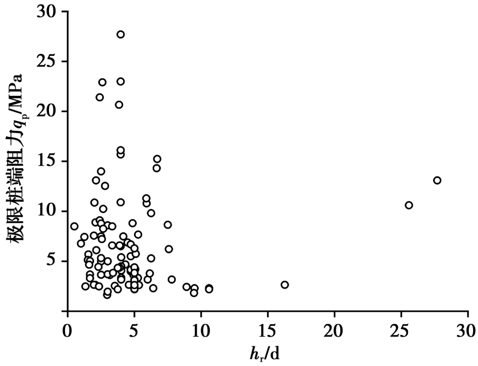

图 4　嵌岩桩极限端阻力随嵌岩深径比变化

Fig. 4　Variation of ultimate end-bearing capacity with the ratio of rock socketed depth to diameter

中国桩基规范[6]中嵌岩段侧阻和端阻综合系数是随嵌岩深度变化而变化的，在较小嵌岩深径比下，嵌岩段总阻力的发挥程度随嵌岩深度的增加而增大，而随着嵌岩深度继续增加，嵌岩段总阻力发挥程度有所变缓，嵌岩桩极限端阻力系数存在深度效应。图 5 给出了嵌岩桩极限端阻力系数随嵌岩深径比变化规律，也给出了规范[6]中二类岩石强度条件下，嵌岩桩极限端阻力系数随嵌岩深径比变化曲线。

从图 5 可看出，对极软岩和软岩(岩石饱和单轴抗压强度≤15 MPa)、较硬岩和硬岩(岩石饱和单轴抗压强度＞30 MPa)，中国规范取值总体偏小。同时，图 5 中端阻力系数与嵌岩深径比之间并无明显的相关性。而中国规范[6]中嵌岩桩端阻力系数取值与嵌岩深径比相关，随嵌岩深径比增加而略有下将，这与收集整理的试验结果并不吻合。

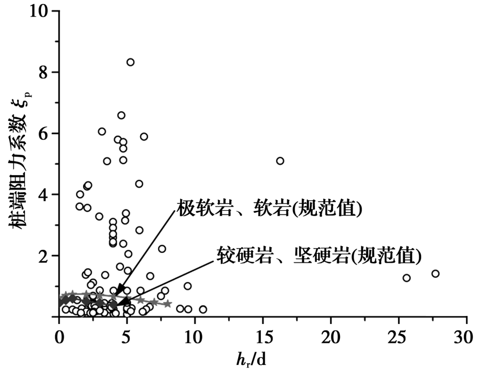

图 5　嵌岩桩端阻力系数随嵌岩深径比变化

Fig. 5　Plots of ultimate end-bearing resistance factor with the ratio of rock rocketed depth to diameter

2.4　岩石强度

根据表 2 数据，可得到嵌岩桩极限端阻力随岩石天然单轴抗压强度变化规律，如图 6 所示。为便于更加直观地比较，将图 6 结果采用双对数坐标轴表示，如图 7 所示。图 6 和图 7 表明，嵌岩桩极限端阻力随岩石天然单轴抗压强度增加而呈非线性增加，可采用式(2)进行拟合。

$$q_p = 4.99\sigma_c^{0.30} \tag{2}$$

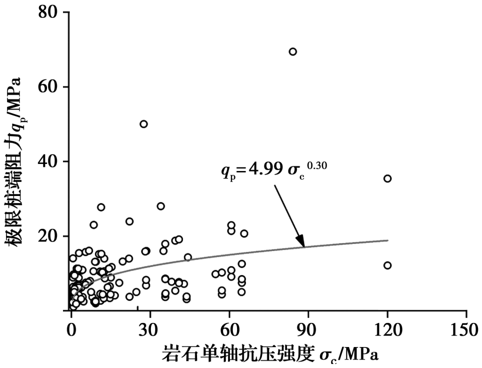

图 6　嵌岩桩极限端阻力随岩石强度变化关系

Fig. 6　Ultimate end-bearing capacity versus unconfined compressive strength of rock

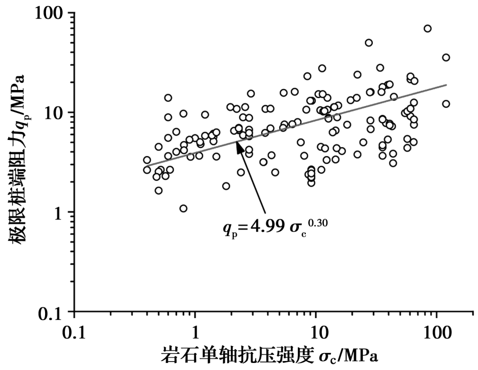

图 7　双对数坐标轴下嵌岩桩极限端阻力随岩石强度变化

Fig. 7　Log-log plots of ultimate end-bearing capacity versus unconfined compressive strength of rock

图 8 给出了嵌岩桩端阻力系数随岩石单轴抗压强度的变化规律。嵌岩桩端阻力系数随岩石单轴抗压强度增加而下降，可采用式(3)拟合。

$$\xi_p = 4.99\sigma_c^{-0.70} \tag{3}$$

显然，式(3)与按照式(1)、式(2)计算的结果一致。

与嵌岩段桩的极限侧阻力研究[10]相似，国外学者也都是通过桩端阻力系数将嵌岩桩极限端阻力和岩石单轴抗压强度联系在一起，嵌岩桩极限侧阻力和岩石天然单轴抗压强度之间的典型关系式如表 3 所示。图 9 给出了嵌岩桩端阻力系数随岩石天然单轴抗压强度变化的结果比较。

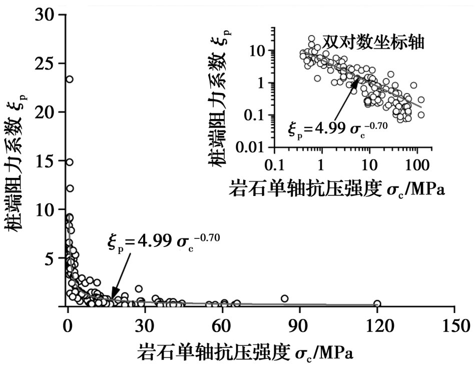

图 8　嵌岩桩端阻力系数随岩石强度变化关系

Fig. 8　Ultimate end-bearing resistance factor versus unconfined compressive strength of rock

表 3　嵌岩段桩的极限侧阻力表达式

Table 3　Summary of equations of ultimate end-bearing capacity for piles rocketed into the rocks

作者与时间	极限侧阻力 q_p/MPa
Teng (1962)[54]	$q_p=(5\sim8)\sigma_c$
Coates (1967)[55]	$q_p=3\sigma_c$
Rowe and Armitage (1987)[50]	$q_p=2.7\sigma_c$
Zhang and Einstein (1998)[56]	$q_p=4.83\sigma_c^{0.51}$
Vipulanandan et al. (2007)[57]	$q_p=4.66\sigma_c^{0.56}$

从图 9 可看出，基于收集整理的 165 个嵌岩桩端阻力试验成果，所给出的嵌岩桩端阻力系数和岩石单轴抗压强度之间的拟合结果总体偏于安全，可作为今后工程设计计算依据。

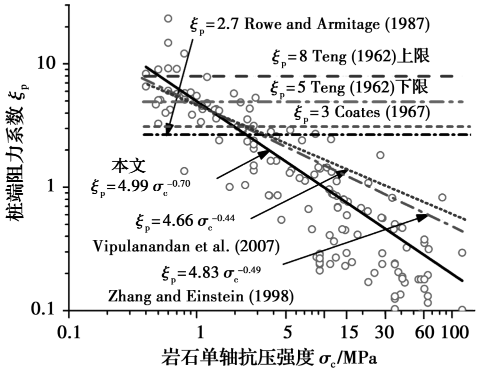

图 9　嵌岩桩端阻力系数随岩石单轴抗压强度变化结果比较

Fig. 9　Comparison of end-bearing resistance factor against the unconfined compressive strength of rock

3　结论

根据 165 个嵌岩桩端阻力试验成果，分析了桩径、嵌岩深度、嵌岩深径比和岩石强度对嵌岩桩极限端阻力和端阻力系数的影响规律。主要结论如下：

1)嵌岩桩极限端阻力与桩径间无显著相关性，但其总体上随嵌岩深度、嵌岩深径比增加而略有减小。嵌岩桩极限端阻力 q_p 随岩石单轴抗压强度 σ_c 增加而呈非线性增加，可采用 $q_p=4.99\sigma_c^{0.30}$ 进行拟合。

2)岩石强度是影响嵌岩桩极限端阻力系数的最主要因素，可采用 $\xi_p=4.99\sigma_c^{-0.70}$ 拟合嵌岩桩端阻力系数与岩石天然单轴抗压强度之间的关系。

3)嵌岩桩端阻力系数随桩径、嵌岩深度增加而略呈下降趋势，但二者之间相关性并不显著。嵌岩桩极限端阻力系数与嵌岩深径比之间无显著相关性。中国现行桩基规范[6]中嵌岩桩端阻力系数取值总体偏小，且其取值与嵌岩深径比相关，随嵌岩深径比增加而减小，这与本文试验分析结果并不吻合。

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