打桩分析计算技术规程

中国能源建设集团山西省电力勘测设计院有限公司

目录

1.土壤阻力

1.1 土参数

依据地勘报告的相关内容，输入各层土参数，示意如下：

关键参数为土有效重度、粘土不排水抗剪强度、砂土内摩擦角和相对密实度，注意，在打桩分析中地勘报告中粘土和砂土均取BE值。

		土层参数（选用BE数据）							
层号	土层描述	深度/m		层厚/m	相对密实度/%	有效重度kN/m³	设计抗剪强度kPa	内摩擦角	上覆土压力kPa
		层顶	层底						
1	S P/S1 级配不良的粉质砂土 Poorly graded SAND with silt，Loose	0		5	60	9.5	β=0.37, fmax=81 kPa	35	0
			5				Nq=20, qmax=5 MPa		47.5
2	C L/C1 含粉土的黏土 Silty CLAY，Very soft~Stiff	5		3		8.5	27.5	/	47.5
			8				34		73
3	C L/C1 含粉土的黏土 Silty CLAY，Medium stiff	8		3		8.5	34	/	73
			11				39.5		98.5
4	C L/C1 含粉土的黏土 Silty CLAY，Soft~Stiff	11		12		8.5	39.5	/	98.5
			23				64		200.5
5	M L/M1B 含黏土的粉土 Clayey SILT，Medium stiff	23		3		9	115	/	200.5
			26				126.5		227.5
6	M L/M1B 含砂土的粉土 Sandy SILT，Stiff~Very stiff	26		4		9	126.5	/	227.5
			30				141.5		263.5
7	S M/M1A 粉质或粘土砂 Silty or Clayly SAND，Medium dense	30		11	30	9.5	β=0.29, fmax=67 kPa	30.5	263.5
			41				Nq=12, qmax=3 MPa		368
8	C L/C1 含砂土的黏土 Sandy CLAY，Very stiff	41		3		8.5	109	/	368
			44				114		393.5
9	S P/S1 级配不良的粉质砂土 Poorly graded SAND with silt，Dense	44		2	50	9.5	β=0.37, fmax=81 kPa	33.5	393.5
			46				Nq=20, qmax=5MPa		412.5
10	G M/S2 含粉土的砾石 Silty GRAVEL，Medium dense~Very dense	46		2	50	9.5	β=0.37,fmax=81 kPa	33.5	412.5
			48				Nq=20, qmax=5MPa		431.5
11	W S/S2 含粉土的砂土 Weathered Soil：Sity SAND，Loose~Very dense	48		3	50	9.5	β=0.37, fmax=81 kPa	33.5	431.5
			51				Nq=20, qmax=5MPa		460
12	W R 风化岩、含粉土的砂土、岩石碎块 Weathered Rock,Sity SAND, Rock fragment，Very dense	51		1	55	10	β=0.37, fmax=81 kPa	40.5	460
			52				Nq=20, qmax=5MPa		470
13	S R 凝灰岩软岩 Soft rock of TUFF,Moderately strong~Weak	52		3		9.5			470
			55						498.5

依据《API-2GEO (API RECOMMENDED PRACTICE 2GEO（Geotechnical and Foundation Design）》中 8.1.4 节，根据相对密实度可查取砂土的β、qmax、Nq、fmax。

Table 1—Design parameters for cohesionless siliceous soil

Relative Density[a]	Soil Description	Shaft Friction Factor[b] β (-)	Limiting Shaft Friction Values kPa (kips/ft^2)	End Bearing Factor N_q (-)	Limiting Unit End Bearing Values MPa (kips/ft^2)
Very loose Loose Loose Medium dense Dense	Sand Sand Sand-silt[c] Silt Silt	Not applicable[d]	Not applicable[d]	Not applicable[d]	Not applicable[d]
Medium dense	Sand-silt[c]	0.29	67 (1.4)	12	3 (60)
Medium dense Dense	Sand Sand-silt[c]	0.37	81 (1.7)	20	5 (100)
Dense Very dense	Sand Sand-silt[c]	0.46	96 (2.0)	40	10 (200)
Very dense	Sand	0.56	115 (2.4)	50	12 (250)

NOTE The parameters listed in this table are intended as guidelines only. Where detailed information, such as CPT records, strength tests on high quality samples, model tests, or pile driving performance, is available, other values may be justified.

[a] The definitions for the relative density percentage description are as follows:

— Very loose, 0 – 15;
— Loose, 15 – 35;
— Medium dense, 35 – 65;
— Dense, 65 – 85;
— Very dense, 85 – 100.

[b] The shaft friction factor β (equivalent to the "K tan δ" term used in previous editions of API 2A-WSD) is introduced in this document to avoid confusion with the δ parameter used in the Annex.

[c] Sand-silt includes those soils with significant fractions of both sand and silt. Strength values generally increase with increasing sand fractions and decrease with increasing silt fractions.

[d] Design parameters given in previous editions of API 2A-WSD for these soil/relative density combinations may be unconservative. Hence, it is recommended to use CPT-based methods from the annex for these soils.

1.2 砂土阻力计算

1.2.1 砂土端阻力

依据《API-2GEO (API RECOMMENDED PRACTICE 2GEO（Geotechnical and Foundation Design）》中 8.1.4 节中公式（22）规定，砂土端阻力计算方法如下：

For end bearing of piles in cohesionless soils, the unit end bearing, q, in stress units, may be computed using Equation 22.

$$q = N_q \, p'_{o,\,tip} \tag{22}$$

where

$p'_{o,\,tip}$ is the effective vertical stress at the pile tip;

N_q is the dimensionless bearing capacity factor.

其中 Nq 的计算方法有两种：

方法一：

依据《API-2GEO (API RECOMMENDED PRACTICE 2GEO（Geotechnical and Foundation Design）》中 8.1.4 节，查表进行确定。

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注意：查表得到的 Nq 也需除以安全系数 1.4。

方法二：

依据 ISODIS 19901-4-2022 中公式 A.74，Nq 可根据下式计算：

Nq is $e^{\pi tan\varphi}.\tan^2(45+\varphi/2)$.

其中φ为内摩擦角。最终得到的 Nq 需要除 1.4 的安全系数。

1.2.2 砂土侧阻力

对于无粘结土中的管桩，单位轴摩擦力可通过下列公式计算。

$$f(z) = \beta\, p'_0(z)$$

其中，β是砂土的无因次摩擦系数；$p'_0(z)$ 为深度 z 处的有效垂直应力。参数β可通过土壤参数查询下表得到。（表取自 API-2GEO,中 8.1.4 节表 1）

Relative Density[a]	Soil Description	Shaft Friction Factor[b] β (-)	Limiting Shaft Friction Values kPa (kips/ft^2)	End Bearing Factor N_q (-)	Limiting Unit End Bearing Values MPa (kips/ft^2)
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d Design parameters given in previous editions of API 2A-WSD for these soil/relative density combinations may be unconservative. Hence, it is recommended to use CPT-based methods from the annex for these soils.

注意：查得的β也需要除以 1.5 的材料系数。

1.3 黏土阻力计算

1.3.1 黏土端阻力

如果桩尖在粘性土中，单位端轴承 q 可使用下列计算。

$q = 9\,s_u$

注意：侧阻力需要除以 1.4 的材料系数。

1.3.2 黏土侧阻力

对于粘性土中管桩，单位轴摩擦应力 f(z)可通过下式计算。

$$f(z) = \alpha \cdot s_u$$

其中，α 为粘土的无量纲轴摩擦系数；s_u是土壤的不排水抗剪强度。

α 可由下述公式计算得到：

$\alpha = 0.5\,\psi^{-0.5}$ for $\psi \le 1.0$

$\alpha = 0.5\,\psi^{-0.25}$ for $\psi > 1.0$

α 必须小于等于 1。

公式中的 ψ 可通过下式计算：

$$\psi = \frac{s_u}{p'_o(z)}$$

其中 $p'_o(z)$ 为在深度 z 处的有效垂直应力。

注意：侧阻力需要除以 1.5 的材料系数。

1.4 竖向阻力汇总计算准则

方法一：内外侧阻力+圆环端阻力

竖向承载力=内壁侧阻力+外壁侧阻力+圆环端阻力

注意：内侧阻力应乘以 0.667 的折减系数。

方法二：外侧阻力+土塞端阻力

竖向承载力=外壁侧阻力+土塞端阻力

注意：该方法不考虑内壁侧摩阻力，但考虑土体塞住端口后的端阻力；但需乘以 0.5 的安全系数。

综上所述，承载力最终值为方法一计算值和方法二计算值的较小值。

2.打桩分析理论

2.1 能量传递理论基础

1.1 能量传递

动力沉桩过程中，在锤击能量E_K一定的条件下，永久贯入度s与土阻力R_u成反比，这种阻力阻挡桩的贯入。其中，E_K为锤芯在撞击之前的动能，R_u为桩的极限承载力。动力公式如下：

$$E_s=R_u s \tag{1-1}$$

式中，E_s为用于土做功的能量，R_u包括桩侧阻力R_{us}和桩端阻力R_{ut}两部分。一般情况下，E_s能量并不等于E_K，能量平衡公式如下：

$$E_s=E_K-E_{ds}-E_{pl}-E_{sl} \tag{1-2}$$

式中，E_{ds}、E_{pl}和E_{sl}分别为消耗在打桩系统、桩和土中的能量。E_K的值需要根据打桩锤的“率定能量”E_r得到，计算公式为：

$$E_K=e_h E_r \tag{1-3}$$

式中，e_h为锤的效率，取值范围为 0 到 1。

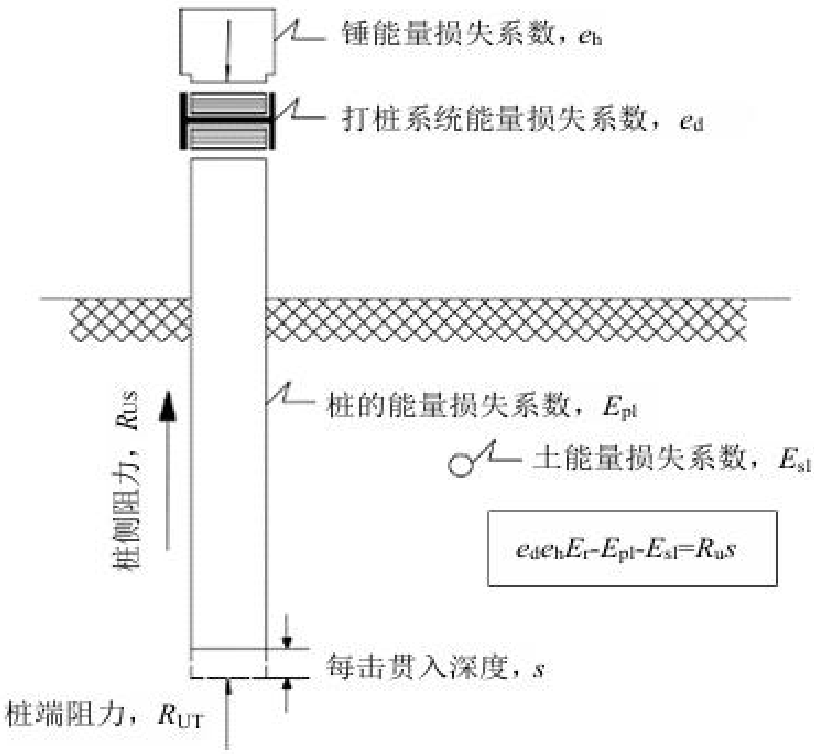
锤击过程中，锤芯动能E_K会传递到打桩系统中，并在打桩系统中损失一部分能量，如图 1-1 所示。E_{ds}为消耗在打桩系统中的能量，因此传递到桩顶的动能为：

$$E_K-E_{ds}=e_d e_h E_r \tag{1-4}$$

式中，e_d为打桩系统的能量损失系数。

最终能量平衡公式为：

$$e_d e_h E_r-E_{pl}E_{sl}=R_u s \tag{1-5}$$



conservation and impact theory. In recent years, by combining the Hiley formula with modern testing technologies, a simplified pile driving formula has been derived: $P_u = E_{MAX}/(e + C/2)$ In the formula: Pu = ultimate bearing capacity of the pile; EMAX = measured energy transmitted to the pile body; e = penetration per blow at final set; C = total elastic deformation of the pile-soil system, taken as 12 mm.

1) When the hammering energy is 600kJ, to meet the design bearing capacity requirement of 27,311kN, the required penetration per blow is:
$P_u = E_{MAX}/(e + C/2) \Rightarrow 27311KN = (0.8 \times 600)KJ/(e + 12mm/2) \Rightarrow e = 0.011m$

注：打桩计算一般采用简化公式计算。即 $P_u=E_{MAX}/(e+C/2)$,E_{MAX} 取 0.8Ek。有效能量作用下产生桩的弹性变形和桩的位移，弹性变形取一半，即 12/2=6mm，这个是经验值，桩长越长，越难以打入，这个值可以越大。

2.2 桩周土静阻力分析

1、基于 API 公式计算，如第一章中内容，其中采用 BE 参数考虑。

2、沉桩过程中侧阻取原来的一半（可以调整），端阻取原来的 100%。

3、沉桩最佳估计为考虑 50%的桩内侧阻（大直径单桩），最高估计为考虑 100%的桩内侧阻（大直径单桩）。

4、土塞计算的参考信息如下：

在贯入过程中可能会形成土塞，影响打桩分析结果，所以采用小泉法对土塞效应进行判断。小泉法的思路是桩端阻力除了壁厚的承载力外，还要考虑管桩内部土塞的剪切应力传递到桩侧表面上的摩阻力，这个摩阻力随着打入持力层的深度增加而增加，该方法考虑了闭塞率的有效面积 $\bar{A}_p$ 替换成代表桩端封闭面积 A_p：

$$\bar{A}_p=\frac{\pi}{4}\left(B^2-B_1^2\right) \tag{2-3}$$

$$B_1=B-2\left(1+\frac{H}{B}\right)t \tag{2-4}$$

式中：$\bar{A}_p$ 为开口桩的桩端有效面积，m^2；B 为管桩外径，m；H 为埋入持力层的深度，m；t 为壁厚，m。

考虑闭塞率的有效面积占桩端封闭面积的比例为闭塞率，即

$$\alpha=\frac{\bar{A}_p}{A_p}=1-\left(\frac{B_1}{B}\right)^2 \tag{2-5}$$

其中α为闭塞率，若$\alpha=1$，则土塞完全闭塞；若 $0<\alpha<1$，则土塞不完全闭塞。

基于以上土塞计算方法，进行多重校核计算，此处 α 保守的取系数为 0.5。（估算值，具体项目需计算）

5.侧摩擦阻力参考依据：

4.5.1.2 Stevens et al. (1982) method

The SRD will be computed combining the parameters as follows:

- The BE SRD corresponds to the SRD assessed using the BE soil profiles and an inside shaft friction equal to 50% of the outside shaft friction;
- The HE SRD corresponds to the SRD assessed using the BE soil profiles and an inside shaft friction equal to 100% of the outside shaft friction.

3.沉桩计算

基于第二节理论分析，沉桩分析公式可以按照下式进行：

conservation and impact theory. In recent years, by combining the Hiley formula with modern testing technologies, a simplified pile driving formula has been derived: $P_u=E_{MAX}/(e+C/2)$ In the formula: Pu = ultimate bearing capacity of the pile; EMAX = measured energy transmitted to the pile body; e = penetration per blow at final set; C = total elastic deformation of the pile-soil system, taken as 12 mm.

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此处 e 作为输入参数，韩国 Nakwol 项目取值为 12mm。

注：贯入度控制在10mm

沉桩灌入度应控制再 10mm 附近。

单桩和导管架计算方法一致。仅考虑直径壁厚不同即可。