# 桩竖向承载力计算技术规程

中国能源建设集团山西省电力勘测设计院有限公司

# 目录

# 1.参数选取

## 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，地勘报告中粘土参数取谨慎估计值，砂土参数取低估计值。

| | | 土层参数 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 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 | SP/S1<br>级配不良的粉质砂土<br>Poorly graded SAND with silt，Loose | 1.5 | | 3.5 | 60 | 9.5 | β=0.37, fmax=81 kPa | 33 | 0 |
| | | | 5 | | | | Nq=20, qmax=5 MPa | | 33.25 |
| 2 | CL/C1<br>含粉土的黏土<br>Silty CLAY，Very soft~Stiff | 5 | | 3 | | 8.5 | 15.5 | / | 33.25 |
| | | | 8 | | | | 22 | | 58.75 |
| 3 | CL/C1<br>含粉土的黏土<br>Silty CLAY，Medium stiff | 8 | | 3 | | 8.5 | 22 | / | 58.75 |
| | | | 11 | | | | 27.5 | | 84.25 |
| 4 | CL/C1<br>含粉土的黏土<br>Silty CLAY，Soft~Stiff | 11 | | 12 | | 8.5 | 27.5 | / | 84.25 |
| | | | 23 | | | | 52 | | 186.25 |
| 5 | ML/M1B<br>含黏土的粉土<br>Clayey SILT，Medium stiff | 23 | | 3 | | 9 | 66.5 | / | 186.25 |
| | | | 26 | | | | 74 | | 213.25 |
| 6 | ML/M1B<br>含砂土的粉土<br>Sandy SILT，Stiff~Very stiff | 26 | | 4 | | 9 | 74 | / | 213.25 |
| | | | 30 | | | | 84 | | 249.25 |
| 7 | SM/M1A<br>粉质或粘土砂<br>Silty or Clayly SAND，Medium dense | 30 | | 11 | 30 | 9.5 | β=0.29, fmax=67 kPa | 28.5 | 249.25 |
| | | | 41 | | | | Nq=12, qmax=3 MPa | | 353.75 |
| 8 | CL/C1<br>含砂土的黏土<br>Sandy CLAY，Very stiff | 41 | | 3 | | 8.5 | 97 | / | 353.75 |
| | | | 44 | | | | 102 | | 379.25 |
| 9 | SP/S1<br>级配不良的粉质砂土<br>Poorly graded SAND with silt，Dense | 44 | | 2 | 50 | 9.5 | β=0.37, fmax=81 kPa | 31 | 379.25 |
| | | | 46 | | | | Nq=20, qmax=5MPa | | 398.25 |
| 10 | GM/S2<br>含粉土的砾石<br>Silty GRAVEL，Medium dense~Very dense | 46 | | 2 | 50 | 9.5 | β=0.37,fmax=81 kPa | 31 | 398.25 |
| | | | 48 | | | | Nq=20, qmax=5MPa | | 417.25 |
| 11 | WS/S2<br>含粉土的砂土<br>Sity SAND，Loose~Very dense | 48 | | 3 | 50 | 9.5 | β=0.37, fmax=81 kPa | 31 | 417.25 |
| | | | 51 | | | | Nq=20, qmax=5MPa | | 445.75 |
| 12 | WR<br>风化岩、含粉土的砂土、岩石碎块<br>Weathered Rock,Sity SAND, Rock fragment，Very dense | 51 | | 1 | 55 | 10 | β=0.37, fmax=81 kPa | 38 | 445.75 |
| | | | 52 | | | | Nq=20, qmax=5MPa | | 455.75 |
| 13 | SR<br>凝灰岩软岩<br>Soft rock of TUFF,Moderately strong~Weak | 52 | | 3 | | 9.5 | | | 455.75 |
| | | | 55 | | | | | | 484.25 |

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/ft²) | End Bearing Factor $N_q$ (-) | Limiting Unit End Bearing Values MPa (kips/ft²) |
|---|---|---|---|---|---|
| Very loose<br>Loose<br>Loose<br>Medium dense<br>Dense | Sand<br>Sand<br>Sand-silt[c]<br>Silt<br>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<br>Dense | Sand<br>Sand-silt[c] | 0.37 | 81 (1.7) | 20 | 5 (100) |
| Dense<br>Very dense | Sand<br>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 安全系数

依据 DNVGL-ST-0126 中 7.6.1.7 节和 7.6.1.8 节，计算桩轴向承载力时，材料系数可取 1.25。（7.6.1.7 节）

若通过建模分析具有设计强度的土壤并允许完全塑性再分配直至达到单一整体地基失效，对基础桩系统最终阻力进行分析，则压缩状态下摩擦力和桩尖阻力的材料系数应增加至$\gamma_m = 1.4$。若上拔荷载桩对整个下部结构的强度至关重要，则材料系数应为$\gamma_m = 1.5$。（7.6.1.8 节）

基于以上两条规定，出于安全角度考虑，在计算桩侧摩阻力时，材料系数取 1.5；在计算桩端阻力时，材料系数取 1.4。（这样取值的原因是，在桩受到上拔荷载时，端阻力不起作用，侧摩阻力全部承担上拔阻力，因此侧阻力取 1.5。）

**7.6.1.7** If the axial pile loads are determined by a calculation of the complete foundation structure with the target, that no single pile reaches its ultimate capacity, a material factor $\gamma_m$ = 1.25 shall be applied to all characteristic values of soil resistance to determine its design capacity. This material factor is valid for the characteristic limit skin friction in tension and compression and for the characteristic tip resistance.

**Guidance note:**

The above material factor $\gamma_m$ = 1.25 for axially loaded piles should be applied to jacket pile foundations which still have, apart from the pure axial pile bearing capacity, a possibility to activate additional bearing capacity working against the overall failure of the wind turbine support structure. This means, a load redistribution is still possible after the maximum soil bearing strength for the most critical pile is reached. If the most critical pile is loaded in tension, usually a load redistribution is not possible.

The design pile loads should be determined from structural analyses in which the pile foundation is modelled either with an adequate equivalent elastic stiffness or with non-linear models that reflect the true non-linear stress-strain properties of the soil in conjunction with the characteristic ground strength.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

**7.6.1.8** If the ultimate resistance of the foundation pile system is analyzed by modelling the soil with its design strength and allowing full plastic redistribution until a single global foundation failure chain is reached, the material factor for skin friction in compression and tip resistance shall be increased to $\gamma_m$ = 1.4. If piles loaded in tension are critical for the overall strength of the substructure the material factor shall be $\gamma_m$ = 1.5.

# 2.砂土阻力计算

## 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。

**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<br>Loose<br>Loose<br>Medium dense<br>Dense | Sand<br>Sand<br>Sand-silt[c]<br>Silt<br>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<br>Dense | Sand<br>Sand-silt[c] | 0.37 | 81 (1.7) | 20 | 5 (100) |
| Dense<br>Very dense | Sand<br>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.

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：

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

其中φ为内摩擦角。最终得到的 Nq 需要除 1.4 的安全系数。

## 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。

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

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/ft²) | End Bearing Factor $N_q$ (-) | Limiting Unit End Bearing Values MPa (kips/ft²) |
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[b] The shaft friction factor β (equivalent to the "$K$ tan $\delta$" 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.

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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。

# 3.黏土阻力计算

## 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。

## 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：

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

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

α 必须小于等于 1。

公式中的 $\psi$：可通过下式计算：

$$\psi = \frac{s_u}{p'_0(z)}$$

其中 $p'_0(z)$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。

## 4.竖向承载力汇总计算准则

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。