导管架灌浆强度及疲劳计算技术规程

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目录

1.剪力键构造要求

剪力键构造要求依据 DNVGL-ST-C502 第 C.1.4.6~11 节和 C.1.8.1~2 中的规定进行计算，参考如下：

C.1.4.6 The following requirement for the vertical distance between shear keys shall be fulfilled:

Post-installed pile: $s \geq \min\begin{cases}0.8\sqrt{R_P t_P}\\ 0.8\sqrt{R_s t_s}\end{cases}$

Pre-installed pile: $\boxed{s \geq \min\begin{cases}0.8\sqrt{R_P t_P}\\ 0.8\sqrt{R_{JL} t_{JL}}\end{cases}}$

C.1.4.7 The following requirements for the geometry of the shear keys shall be fulfilled:

$$h \geq 5\ mm \qquad 1.5 \leq \frac{w}{h} \leq 3.0 \qquad \frac{h}{s} \leq 0.10$$

where s is the vertical centre-to-centre distance between the shear keys, h is the height of the shear keys and w is the width of the shear keys. It is recommended that $h/D_p \leq 0.012$ for the post-installed pile, resp. $h/D_{JL} \leq 0.012$ for the pre-installed pile is fulfilled, where D_p denotes the outer pile diameter and D_{JL} denotes the jacket leg diameter

C.1.4.8 It is recommended that the grout-length-to-pile-diameter ratio is kept within the following range:

Post-installed pile: $1 \leq \frac{L_g}{D_p} \leq 10$

Pre-installed pile: $1 \leq \frac{L_g}{D_{JL}} \leq 10$

where L_g denotes the effective length of the grouted section and D_P denotes the outer pile diameter. When $L_g/D_P < 2.5$, resp. $L_g/D_{JL} < 2.5$, then the design procedure in [C.1.3] for grouted connections in monopiles can be used as an alternative for documentation of grouted connections in jacket structures.

C.1.4.9 It is recommended that the grout dimensions meet the following limitations:

$$10 \leq \frac{D_g}{t_g} \leq 45$$

where D_g denotes the outer diameter of the grout and t_g denotes the nominal grout thickness.

C.1.4.10 The following requirement for the geometry of the pile shall be fulfilled:

Post-installed pile: $10 \leq \frac{R_P}{t_p} \leq 30$

Pre-installed pile: $\boxed{10 \leq \frac{R_{JL}}{t_{JL}} \leq 30}$

C.1.4.11 The following requirement for the geometry of the sleeve shall be fulfilled:

Post-installed pile: $15 \le \frac{R_s}{t_s} \le 70$

Pre-installed pile: $15 \le \frac{R_p}{t_p} \le 70$

C.1.8 FLS for tubular grouted connections with shear keys in jacket structures

C.1.8.1 The following requirement for vertical distance between shear keys in jacket structures with postinstalled piles shall be fulfilled:

$$s \ge min\begin{cases} 0.4\sqrt{R_p t_p} \\ 0.4\sqrt{R_s t_s} \end{cases}$$

C.1.8.2 The following requirement for vertical distance between shear keys in jacket structures with preinstalled piles shall be fulfilled:

$$s \ge min\begin{cases} 0.4\sqrt{R_p t_p} \\ 0.4\sqrt{R_{JL} t_{JL}} \end{cases}$$

此外，规范规定后桩法导管架灌浆连接段在 13（a）所示的受力情况下，距离底端 $l_e/2$ 的长度内受弯矩作用比较明显，为防止在反复弯矩作用下出现浆体的碎裂，与单桩基础灌浆连接段类似，规范建议在此区域内不布置剪力键。

如前所述，先桩法导管架可由后桩法导管架灌浆连接段上下颠倒得到，规范中公式推导过程与上述过程类似，而规范中关于导管架基础灌浆连接段的其余计算公式都比较容易理解，在此不做赘述。

注：导管架灌浆段在上下两端留出 $0.5l_e$ 不布置剪力键。

2.混凝土界面抗剪强度计算（导管架连接套管位于桩内部）

2.1 输入参数

输入参数示意如下表所示：

			数值	单位	
输入参数	剪力键高度	h_{j1j}	25	mm	
	相邻剪力键中心距	s_{j1j}	300	mm	
	相邻剪力键宽度	ω_{j1j}	50		
	环向剪力键数量	n	15		受弯矩影响不显著的区域中的剪切键的数量
	导管架套管直径	D_{JL}	2800	mm	
	导管架腿的外半径	RJL	1400	mm	23.33333333
	导管架套管壁厚	tJL	60	mm	RJL/tJL应小于30
	钢管桩外半径	Rp	1650	mm	30
	钢管桩壁厚	tp	55	mm	$15\leqslant\frac{R_p}{t_p}\leqslant70$ (G.3.2-5)
	灌浆料弹性模量	Eg	53000	MPA	$E_{cn} = 22\ 000 \cdot (f_{cck}/10)^{0.3}$ MPa for $f_{cck} \le 70$MPa $E_{cn} = 4800 \cdot (f_{cck})^{0.5}$ MPa for $f_{cck} > 70$ MPa
	钢材弹性模量	E	200000	MPA	
	灌浆厚度	tg	195	mm	**考虑施工误差及紧急灌浆口不小于190mm**
	灌浆段弹性刚度 径向刚度参数	kjxg	0.02557406		DNV-0126, C.1.4.3
	灌浆材料试件150*300mm的圆柱体的标准抗压强度	f_{ck}	120	MPa	

注意：灌浆材料的弹性模量计算依据 DNVGL-ST-C502 第 4.3.3.15 节中的规定进行计算，参考如下：

4.3.3.15 The normalized Young's modulus of concrete is controlled by the Young's modulus of its components. Approximate values for the Young's modulus E_{cn}, is taken as the secant value between $\sigma_c = 0$ and 0.4 f_{cck}. Approximate values for quartzite aggregates may be determined from the following equation:

$$E_{cn} = 22\ 000 \cdot (f_{cck}/10)^{0.3} \text{ MPa for } f_{cck} \le 70\text{MPa}$$

$$E_{cn} = 4800 \cdot (f_{cck})^{0.5} \text{ MPa for } f_{cck} > 70 \text{ MPa}$$

For limestone and sandstone aggregates, the value should be reduced by 10% and 30% respectively. For basalt aggregates, the value should be increased by 20%.

2.2 强度计算

灌浆材料 75mm 的立方体抗压强度标准值的依据 APIRP2A-LRFD-2019 中 15.1.4.4 节中相关规定：

由于灌浆料采用高强混凝土，因此此处 $f_{cu,cube75}$ 的强度值可以直接取 110MPa（一般小的立方体抗压强度小于混凝土的标准立方体抗压强度，因此选用 110MPa 已非常保守。）

15.1.4.4 Limitations

The limitation 17 MPa (2500 psi) ≤ f_{cu} ≤ 110 MPa (16,000 psi) should be observed when designing a connection in accordance with 15.1.4.2 or 15.1.4.3.

依据 DNVGL-ST-0126-2018 中 C.1.4.3 节中的相关规定，混凝土的界面抗剪强度值 f_{bk} 计算方法如下：

Pre-installed pile: $$f_{bk} = \left[\frac{800}{D_{JL}} + 140\left(\frac{h}{s}\right)^{0.8}\right] k^{0.6} f_{ck}^{0.3}$$

where

h = height of shear key measured radially from the grout-steel interface

D_P = pile diameter in units of mm

D_{JL} = jacket leg diameter in units of mm

$f_{ck,cube75}$ = characteristic compressive strength of 75 mm cubes in units of MPa

s = vertical centre-to-centre distance between shear keys

k = radial stiffness parameter defined as:

pre-installed pile: $$k = \left[(2R_{JL}/t_{JL}) + (2R_p/t_p)\right]^{-1} + (E_g/E)\left[(2R_p - 2t_p)/t_g\right]^{-1}$$

where:

E_g = Young's modulus for the grout

R_S = outer radius of sleeve

t_S = wall thickness of sleeve

R_P = outer radius of pile

t_P = wall thickness of pile

R_{JL} = outer radius of jacket leg

t_{JL} = wall thickness of jacket leg

灌浆界面抗剪强度的限值可通过下式计算：

However, the interface shear capacity shall not be taken larger than the limit set forth by grout matrix failure:

$$f_{bk} = \left[0.75 - 1.4\left(\frac{h}{s}\right)\right] f_{ck}^{0.5}$$

3.轴向承载力计算

3.1 输入参数

	轴向承载力计算				
	名称	符号	数值	单位	
输入侧	灌浆段轴向荷载	Pa, d(N)	27000	KN	
	材料系数	γm	2.00		DNV-0126, table 6-1

材料系数依据 DNVGL-ST-0126-2018 Support structures for wind turbines 中表 6-1 中取值，剪力键的圆柱体灌浆连接件，材料系数取 2.0。

Table 6-1 Requirements for material factor γ_m for grout depending on type and load case

Type of grouted connection	*Load case*	*Material factor γ_m*
Cylindrical grouted connections with shear keys	ULS	2.0
Conical grouted connections	ULS	1.5
Cylindrical grouted connections with shear keys	FLS	1.5

3.2 单个剪力键承担的荷载

单个剪力键环向单位长度荷载计算方法可依据 DNVGL-ST-0126-2018 Support structures for wind turbines 中 C.1.4.2 中的相关规定进行计算，公式如下：

C.1.4.2 The design load per unit length along the circumference of one shear key shall be taken as:

Pre-installed piles: $F_{V1\,Shk,d} = \dfrac{P_{a,d}}{2\pi R_{JL} n}$ where RJL is the outer radius of the jacket leg

3.3 单个剪力键承载力设计值

（1）标准值

依据 DNVGL-ST-0126-2018 Support structures for wind turbines 中 C.1.4.4 节规定，单个剪力键环向单位长度承载力标准值计算方法如下：

C.1.4.4 The characteristic capacity per unit length of one shear key is:

$$F_{V1\,Shk\,cap} = f_{bk} \cdot s$$

（2）设计值

依据 DNVGL-ST-0126-2018 Support structures for wind turbines 中 C.1.4.5 节规定，单个剪力键环向单位长度承载力设计值计算方法如下：

C.1.4.5 The design capacity per unit length of one shear key is:

$$F_{V1\,Shk\,cap,d} = \frac{F_{V1\,Shk\,cap}}{\gamma_m}$$

3.4 轴向承载力判断

依据 DNVGL-ST-0126-2018 Support structures for wind turbines 中 6.5.3.7 节规定，单个剪力键承担的轴向荷载应小于单个剪力键的轴向承载力设计值：

6.5.3.7 The design criterion for the vertical shear keys is:

$$F_{H1\,Shk,d} \le F_{H1\,Shk\,cap,d}$$

where F_{H1Shk} is the action force per unit length, owing to torque moment and transferred to the shear key and $F_{H1Shk\,cap,d}$ is the design capacity per unit length of one shear key. More details on the verification procedure for tubular grouted connections in monopiles with shear keys are given in [C.1.5].

4.弯曲和水平承载力计算

4.1 输入参数

输入参数如下：

输入参数	设计弯矩	M_0	10000	KN*m	
	水平剪力	Q_0	2000	KN	

4.2 导管架套管的弹性长度

依据 DNVGL-ST-0126-2018 Support structures for wind turbines 中 C.1.4.12 节规定，导管架套管的弹性长度计算方法如下：

C.1.4.13 For connections involving pre-installed piles, the region which is significantly affected by the bending moment is the region of the connection from a level half an elastic length below the top of the connection and upwards.

The elastic length of the pile can be taken as:

Pre-installed pile: $$l_e = \sqrt[4]{\frac{4EI_{JL}}{k_{rD}}}$$

where

I_{JL} = moment of inertia of the jacket leg.

4.3 灌浆段弹性刚度

依据 DNVGL-ST-0126-2018 Support structures for wind turbines 中 C.1.4.14 节规定，灌浆段弹性刚度方法如下：

C.1.4.14 The supporting spring stiffness k_{rD}, defined as the radial spring stiffness times the pile diameter, may be expressed as:

Pre-installed pile:
$$k_{rD} = \frac{4\,ER_{JL}}{\frac{R_p^2}{t_p} + \frac{R_{JL}^2}{t_{JL}} + t_g m}$$

where:

E = Young's modulus for steel

R_p = radius to outer part of pile

R_s = radius to outer part of sleeve

R_{JL} = radius to outer part of jacket leg

t_p = thickness of pile

t_s = thickness of sleeve

t_{JL} = thickness of jacket leg

t_g = nominal thickness of grout

m = ratio of Young's modulus for steel and Young's modulus for grout material; m = 18 can be used if Young's modulus for grout material is not known.

注意：m 为钢材弹性模量和灌浆料弹性模量的比值，不要直接取 18！

4.4 弯矩和剪力引起的最大接触应力

依据 DNVGL-ST-0126-2018 Support structures for wind turbines 中 C.1.4.15 节规定，弯矩和剪力引起的最大接触应力方法如下：

C.1.4.15 Unless data indicate otherwise, the maximum nominal radial contact pressure p_{nom} at the grouted connection, caused by the design horizontal shear force Q_0 and the design bending moment M_0 at the bottom of the sleeve in case of post-installed piles, shall be derived from the following expression:

Pre-installed pile:
$$p_{nom,d} = \frac{l_e^2 k_{rD}}{8EI_{JL}R_{JL}} * (M_d + Q_d * l_e)$$

where:

l_e = elastic length of pile as defined in [C.1.4.12]

k_{rD} = support spring stiffness as defined in [C.1.4.14]

E = Young's modulus for steel

I_P = moment of inertia of the pile

R_p = outer radius of the pile

I_{JL} = moment of inertia of the jacket leg

R_{JL} = outer radius of the jacket leg

依据 DNVGL-ST-0126-2018 Support structures for wind turbines 中 6.5.3.5 节规定，最大接触应力的限值为 1.5MPa：

6.5.3.5 Additionally the following requirement for the maximum nominal radial contact pressure shall be fulfilled:

$$p_{nom,d} \le 1.5\,MPa$$

This requirement for the nominal radial contact pressure can be waived if a detailed FE analysis is performed in accordance with [C.2] and DNVGL-RP-0419.

5 有限元强度计算

5.1 灌浆现场特征强度

依据 DNVGL-ST-0126-2018 Support structures for wind turbines 中 6.3.2.3 节，灌浆材料现场特征强度计算方法如下：

4.3.3.2 The normalized in-situ compression strength, f_{cn}, of normal weight concrete shall be determined from the following formula for concrete with concrete grade between C35 and C90:

$$f_{cn} = f_{cck} \cdot (1 - f_{cck}/600)$$

where:

f_{cck} = characteristic concrete compressive cylinder strength in Table 4-2.

5.2 灌浆疲劳强度设计值

依据 DNVGL-ST-0126-2018 Support structures for wind turbines 中 6.3.2.6 节，灌浆材料现场特征强度计算方法如下：

6.3.2.6 The design strengths of the grout material in compression and tension are found by dividing the characteristic in-situ strengths f_{cn} and f_{tn} by a material factor:

$$f_{cd} = f_{cn} / \gamma_m$$
$$f_{td} = f_{tn} / \gamma_m$$

Requirements for the material factor γ_m are specified with each individual application in [6.4.1].

依据 DNVGL-ST-0126-2018 Support structures for wind turbines 中表 6-1 材料系数γ$_m$的取值方法如下：（强度计算时取 2）

Table 6-1 Requirements for material factor γ_m for grout depending on type and load case

Type of grouted connection	*Load case*	*Material factor γ_m*
Cylindrical grouted connections with shear keys	ULS	2.0
Conical grouted connections	ULS	1.5
Cylindrical grouted connections with shear keys	FLS	1.5

Type of grouted connection	*Load case*	*Material factor γ_m*
Cylindrical grouted connections with shear keys	ALS	1.7
Conical grouted connections	ALS	See Table 5-2 in [5.4.1]
All	SLS	1.0

5.3 有限元强度计算

依据 DNVGL-ST-0126-2018 Support structures for wind turbines 中 C.2.2 的有限元强度计算方法如下：

C.2.2 Ultimate limit states for tubular grouted connections with shear keys

C.2.2.1 The grout material shall be verified against ultimate loads by evaluating a state of equilibrium using a validated material law.

C.2.2.2 The grout material shall be verified against extreme loads using the maximum compression stress $\sigma_{3,FEA}$ (minimum principle) from the finite element calculation (FEA).

Guidance note:

Detailed information on how to apply a FEA is given in DNVGL-RP-0419.

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

C.2.2.3 The design criterion for the grouted connection with shear keys is

$$|\sigma_{3,FEA}| \quad \leq f_{cd}$$

注：灌浆材料的第三主应力（最小主应力）应小于设计抗压强度即可。

6 灌浆连接剪力键疲劳计算

依据 DNVGL-ST-0126-2018 Support structures for wind turbines 中 C.1.6 节规定，剪力键疲劳计算方法如下：

C.1.6 Fatigue limit states for tubular grouted connections with shear keys - general

C.1.6.1 Design against the FLS for the grouted connection is based on the expected long term load history. When the expected long term distribution of load amplitudes has been established, the fatigue design of the grouted connection shall be carried out according to the following procedure:

The S-N curve, which gives number of cycles *N* to failure at a specified relative load level *y*, is represented as:

$$\begin{aligned} \log N &= 5.400 - 8y & & for\ y \geq 0.30 \\ \log N &= 7.286 - 14.286y & & for\ 0.16 < y < 0.30 \\ \log N &= 13.000 - 50y & & for\ y \leq 0.16 \end{aligned}$$

$$y = \frac{F_{V1\,Shk}\gamma_m}{F_{V1\,Shk\,cap}}$$

where $F_{V1\ Shk\ cap}$ is the characteristic shear key capacity as described in [C.1.3.8], $F_{V1\ Shk}$ is the shear key load of the load cycle in question, consisting of the static load and the load amplitude of the load cycle in question, and γ_m is the material factor.

其中，材料参数 γ_m 取 1.5。

其中，$F_{V1\,Shk}$ 和 $F_{V1\,Shk\,cap}$ 的计算与第三章内容一致，材料系数依据 DNVGL-ST-0126-2018 Support structures for wind turbines 中表 6-1，采用 γ_m=1.5。

7 灌浆疲劳强度计算

7.1 灌浆现场特征强度

依据 DNVGL-ST-0126-2018 Support structures for wind turbines 中 6.3.2.3 节，灌浆材料现场特征强度计算方法如下：

4.3.3.2 The normalized in-situ compression strength, f_{cn}, of normal weight concrete shall be determined from the following formula for concrete with concrete grade between C35 and C90:

$$f_{cn} = f_{cck} \cdot (1-f_{cck}/600)$$

where:

f_{cck} = characteristic concrete compressive cylinder strength in Table 4-2.

7.2 灌浆疲劳强度设计值

依据 DNVGL-ST-0126-2018 Support structures for wind turbines 中 6.3.2.6 节，灌浆材料现场特征强度计算方法如下：

6.3.2.6 The design strengths of the grout material in compression and tension are found by dividing the characteristic in-situ strengths f_{cn} and f_{tn} by a material factor:

$$f_{cd} = f_{cn}/\gamma_m$$
$$f_{td} = f_{tn}/\gamma_m$$

Requirements for the material factor γ_m are specified with each individual application in [6.4.1].

依据 DNVGL-ST-0126-2018 Support structures for wind turbines 中表 6-1 材料系数 γ_m 的取值方法如下：

Table 6-1 Requirements for material factor γ_m for grout depending on type and load case

Type of grouted connection	*Load case*	*Material factor γ_m*
Cylindrical grouted connections with shear keys	ULS	2.0
Conical grouted connections	ULS	1.5
Cylindrical grouted connections with shear keys	FLS	1.5
Cylindrical grouted connections with shear keys	ALS	1.7
Conical grouted connections	ALS	See Table 5-2 in [5.4.1]
All	SLS	1.0

计算疲劳时，γ_m 取 1.5。

7.3 灌浆疲劳损伤系数

依据 DNVGL-ST-0126-2018 Support structures for wind turbines 中 C.2.7 的疲劳极限强度计算方法如下：

C.2.7 Fatigue limit states for tubular and conical grouted connections without shear keys

C.2.7.1 Unless data indicate otherwise, the characteristic number of cycles to failure, N, of grout subjected to cyclic stresses can be calculated from:

$$\log_{10} N = C_1 * \left(1 - \frac{\sigma_{max}}{f_{rd}}\right) / \left(1 - \frac{\sigma_{min}}{f_{rd}}\right)$$

where f_{rd} = design reference strength, σ_{max} is the largest value of the maximum principal compressive stress during a stress cycle within the stress block and σ_{min} is the smallest compressive stress in the same direction during this stress cycle. If the direction of the stress is reversed during a stress cycle and the grout is in tension during part of the stress cycle, σ_{min} shall be set equal to zero when the design number of cycles to failure is calculated. If stress cycles occur which keep the grout in tension during the entire cycle, then both σ_{max} and σ_{min} shall be set equal to zero when the design number of cycles to failure is calculated. The factor C_1 shall be taken as:

— 12.0 for structures in air
— 10.0 for structures in water for those stress blocks whose stress variation is in the compression-compression range
— 8.0 for structures in water for those stress blocks whose stress variation is in the compression-tension range.

If the logarithm of the characteristic number of cycles to failure, $\log_{10}N$, calculated according to the expression above, is larger than the value of X given by:

$$X = C_1 / \left(1 - \frac{\sigma_{min}}{f_{rd}} + 0.1 * C_1\right)$$

then the characteristic number of cycles to failure may be increased further by multiplying the calculated value of $\log_{10}N$ by a factor C_2 which is:

$$C_2 = (1 + 0.2 * (\log_{10} N - X))$$

The design reference strength f_{rd} is calculated as:

$$f_{rd} = C_5 * \frac{f_{cn}}{\gamma_m}$$

where:

— f_{cn} is the nominal compression strength, see [6.3.2.3]
— C_5 is an adjustment factor to obtain a best fit of the above expression for $\log_{10}N$ to experimental fatigue test data from fatigue tests on appropriate grout specimens. Reference is made to DNVGL-ST-C502 [6.13]
— γ_m is the material factor, see [6.4.1].

Guidance note:

The fatigue adjustment factor C_5 can take on values above as well as below 1.0, depending on the grout material. In absence of fatigue tests for grout, C_5 may be taken as 0.8.

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

依据 DNVGL-ST-0126-2018 Support structures for wind turbines 中 6.6.3.2 的疲劳损伤系数计算方法如下：

6.6.3.2 The design criterion is:

$$D = DFF \cdot \sum_{j=1}^{k} \sum_{i=1}^{n_0} \frac{n_i}{N_i} \leq 1.0$$

where:

n_0 = total number of stress blocks of constant-amplitude stress

n_i = number of stress cycles in the i^{th} stress block

k = number of lateral environmental load directions

N_i = characteristic number of cycles to failure at the constant stress amplitude of stress block i

The design criterion shall be fulfilled for the following two cases:

— The cumulative damage D is calculated based on the long term distribution of the amplitude of the vertical downward dynamic load on the shear key.
— The cumulative damage D is calculated based on the long term distribution of the amplitude of the vertical upward dynamic load on the shear key.