

DESIGN OF STEEL STRUCTURES
ANNEX K
SPECIAL DESIGN PROVISIONS FOR JACKETS

K.5.3 Grouted connection

K.5.3.1 General

Grouted pile connections shall be designed to satisfactorily transfer the design loads from the pile sleeve to the pile as shown in Figure K.5-1. The grout packer may be placed above or below the lower yoke plate as indicated in Figure K.5-2. The connection may be analysed by using a load model as shown in Figure K.5-3. The following failure modes of grouted pile to sleeve connections need to be considered:

- Failure of grout to pile interface shear due to axial load and torsional moment (ULS and ALS).
- Failure of the grout due to compressive stresses at the lower end of the grout due to bending moment and shear in the pile (ULS and ALS).
- Fatigue of the grouted connection for alternating interface shear stress due to axial load and bending moment in the pile (FLS).
- Fatigue of the grout due to compression and shear stresses at the lower end from bending moment and shear in the pile (FLS).

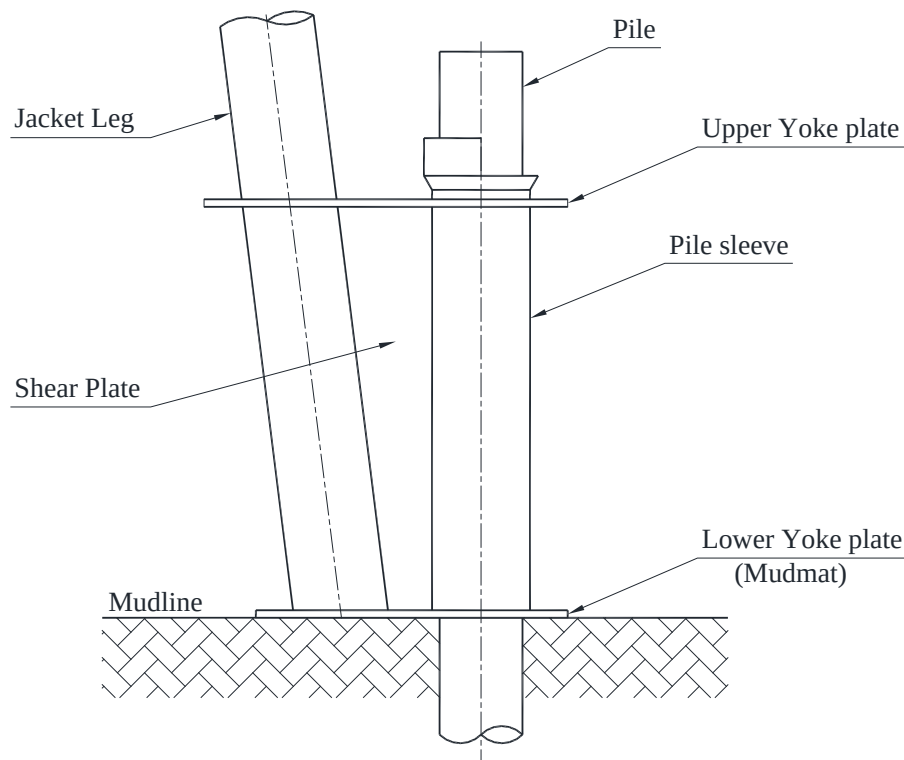


Figure K.5-1 Terms for typical pile-sleeve connections

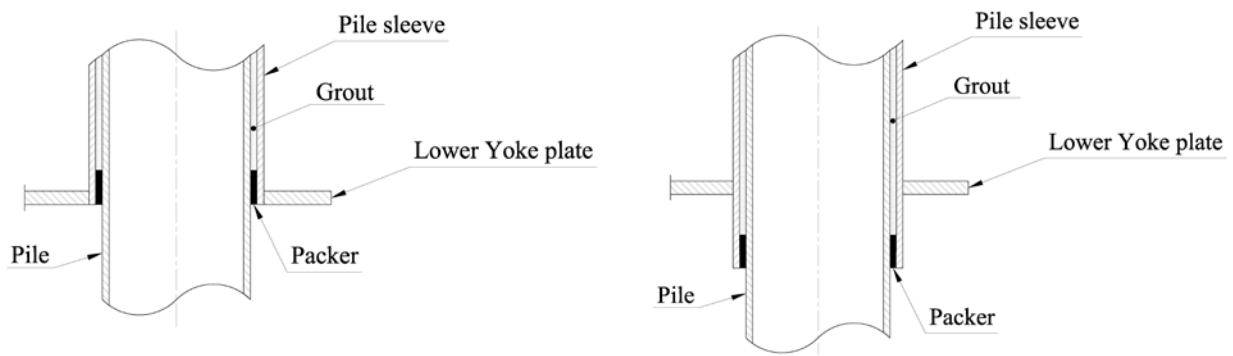


Figure K.5-2 The left figure shows grout termination above Lower Yoke plate and the right figure shows grout termination below Lower Yoke plate

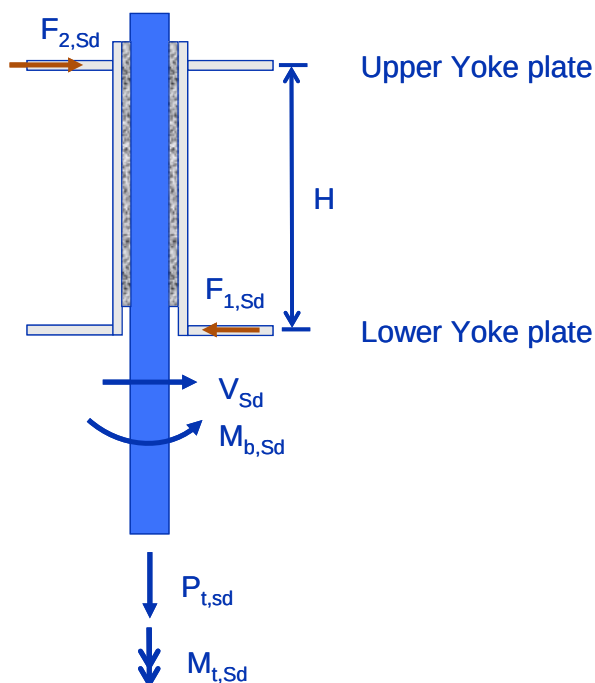


Figure K.5-3 Model for calculation of forces in grouted pile-sleeve connections

The recommendations for check of the above failure modes for pile sleeve connections with circular hoop or helix curved strings of weld beads or bars denoted shear keys are described in Section K.5.3.2 to K.5.3.5

K.5.3.2 Failure of grout to pile interface shear due to axial load and torsional moment (ULS and ALS)

When a grouted connection is subjected to combined axial force and torsional moment, the interface transfer stress shall be taken as the result of the component stresses caused by axial force and torsional moment at the inner member.

The design interface transfer stress due to axial force, $\tau_{ba,Sd}$, is defined by:

$$\tau_{ba,Sd} = \frac{N_{Sd}}{\pi \cdot D_p \cdot L_e} \quad (\text{K.5.1})$$

where

$$\begin{aligned} N_{Sd} &= \text{design axial force [N]} \\ D_p &= \text{outside diameter of pile [mm]} \\ L_e &= \text{effective grouted connection length [mm]} \end{aligned}$$

In calculating the effective grouted connection length, L_e , the following non-structural lengths shall be subtracted from the connection's nominal gross grouted length:

1. Where setting of a grout plug is the primary means of sealing, or is the contingency sealing method in the event of packer failure, the grout plug length shall be considered as non-structural.
2. To allow for potential weak interface zones, grout slump, etc. at each end of the connection, the greater of the following grouted lengths shall be considered as non-structural:
 - two thickness of the grout annulus, $2t_g$
 - one shear key spacing, s , if shear keys are used.
3. Any grouted length that is not certain to contribute effectively to the connection capacity, shall be considered as non-structural (e.g. when shear keys are used, the implications of possible over and under driving of piles shall be considered in relation to the number of shear keys present in the grouted length).

The design interface transfer stress due to torsional moment, $\tau_{bt,Sd}$, is defined by:

$$\tau_{bt,Sd} = \frac{2M_{t,Sd}}{\pi \cdot D_p^2 \cdot L_e} \quad (\text{K.5.2})$$

where

$M_{t,Sd}$ = design torsional moment on the connection.

The combined axial and torsional design interface shear is calculated as:

$$\tau_{b,Sd} = \sqrt{\tau_{ba,Sd}^2 + \tau_{bt,Sd}^2} \quad (\text{K.5.3})$$

The inherent variability in the test data should be considered when calculating the characteristic strength if the capacity is based on test results.

The characteristic interface transfer strength for grout steel interface sliding with shear keys is given by:

$$f_{bks} = \frac{C_I \cdot E}{C_f \cdot D_p} + C_p \cdot 140 \cdot \left(\frac{h}{s}\right)^{0.8} \cdot C_s^{0.6} \cdot f_{ck}^{0.3} \quad (\text{K.5.4})$$

The characteristic interface transfer strength for grout steel interface sliding without shear keys is given by:

$$f_{bkf} = \frac{C_I \cdot E}{C_f \cdot D_p} \quad (\text{K.5.5})$$

The characteristic interface transfer strength for grout matrix shear failure is given by:

$$f_{bkg} = \left[0.75 - 1.4 \cdot \left(\frac{h}{s} \right) \right] \cdot f_{ck}^{0.5} \quad (\text{K.5.6})$$

where

s	=	shear key spacing
h	=	shear key height
C _I	=	surface irregularity coefficient = 0.084 mm
C _p	=	pile diameter scale factor
	=	1.5 for D _p < 300 mm
	=	(D _p /D _{ref}) ² - (2·D _p /D _{ref}) + 2 for 300 < D _p < 1000 mm
	=	1.0 for D _p ≥ 1000 mm
C _s	=	radial stiffness factor
	=	[(D _p /t _p) + (D _s /t _s)] ⁻¹ + (1/m)·(D _g /t _g) ⁻¹
C _f	=	radial flexibility factor
	=	D _p /2t _p + 2m t _g /D _p + D _s /2t _s
f _{ck}	=	characteristic cube strength [MPa]
D _p	=	outside diameter of pile
D _{ref}	=	reference diameter of pile = 1000 mm
t _p	=	wall thickness of pile
D _s	=	outside diameter of pile sleeve
t _s	=	wall thickness of pile sleeve
D _g	=	outside diameter of grout annulus
t _g	=	thickness of grout annulus
E	=	Young's modulus of elasticity for steel
m	=	steel-grout elastic modular ratio (to be taken as 18 in lieu of actual data)

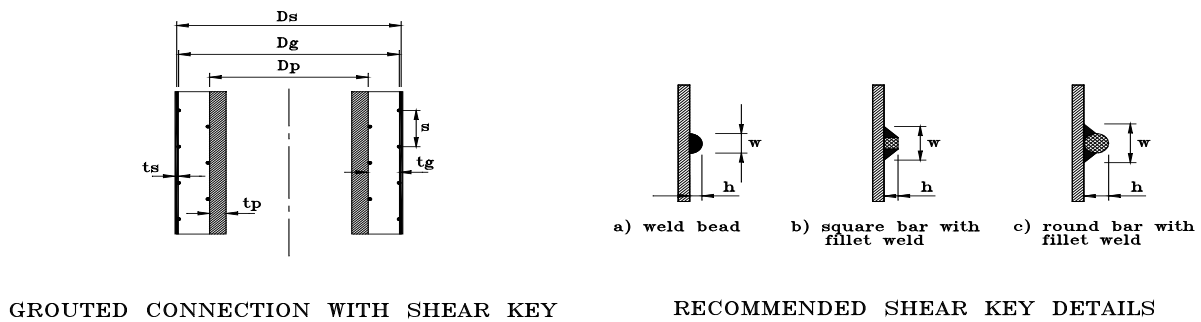


Figure K.5-4 Grouted connection with recommended shear key details

Equation (K.5.4), (K.5.5) and (K.5.6) are valid for uncoated tubulars with normal fabrication tolerances, where mill scale has been fully removed. The recommendations are valid for the following range:

80 MPa	≥	f_{ck}	≥	20 MPa
0.10	≥	h/s	≥	0.0
40	≥	D_p/t_p	≥	20
140	≥	D_s/t_s	≥	30
45	≥	D_g/t_g	≥	10
0.02	≥	C_s		
0.012	≥	h/D_p		
16	≥	D_p/s		
10	≥	L_e/D_p	≥	1

Connection with circular hoop shear keys should be checked as follows:

$$\tau_{ba,Sd} \leq \frac{f_{bks}}{\gamma_M} \quad (K.5.7)$$

$$\tau_{bt,Sd} \leq \frac{f_{bkf}}{\gamma_M} \quad (K.5.8)$$

$$\tau_{b,Sd} \leq \frac{f_{bkg}}{\gamma_M} \quad (K.5.9)$$

where

γ_M = material factor for interface transfer strength equal to 2.0 for ULS and 1.5 for ALS

If the check of torsion stresses according to (K.5.8) is not fulfilled the ULS checks can be made assuming redistribution of the pile torsion moment. This can be done by releasing the corresponding degree of freedom for the pile in the model. In addition a FLS check according to K.5.3.6 need to be satisfied.

A shear key shall be a continuous hoop or a continuous helix. Where hoop shear keys are used, they shall be uniformly spaced, oriented perpendicular to the axis of the tube, and be of the same form, height and spacing on both the inner and outer tubes.

Where helical shear keys are used, the following additional limitation shall be applied:

$$2.5 \geq D_p/s$$

and the characteristic interface transfer strength given by equations (K.5.4) and (K.5.6) shall be reduced by a factor of 0.75.

The possible movements between the inner and the outer steel tubular member during the 24 hour period after grouting shall be determined for the maximum expected sea states during that time, assuming that the does not contribute to the stiffness of the system. For foundation pile-to-sleeve connections, this analysis shall be an on-bottom analysis of the structure with ungrouted piles.

If the expected relative axial movement at the grout steel interface exceeds $0.035\%D_p$ during this period, the movements should be limited by e.g. installation of pile grippers.

K.5.3.3 Check of compressive stresses at the lower end of the grout due to bending moment and shear in the pile (ULS and ALS)

The compressive capacity of the grout shall be checked for forces in the Ultimate Limit States (ULS) and the Accidental limit States (ALS).

The compressive contact stress between the steel and the grout will create tensile stresses in the grout. It is considered acceptable that the grout cracks for tensile stresses during these limit states; however, the grout needs to transfer the forces from the sleeve to the pile throughout the storm that includes the dimensioning environmental load.

The design contact pressure between steel and grout can be obtained from

$$\sigma_{p, Sd} = C_A \frac{F_{1, Sd}}{D_p^{\frac{3}{2}} \cdot \sqrt{t_p}} \quad (\text{K.5.10})$$

where

$$F_{1, Sd} = V_{Sd} + M_{b, Sd} / H \quad (\text{See Figure K.5-3})$$

C_A = 2 for grout ending above lower yoke plate and without reinforcement steel (See Figure K.5-2)

= 1 for grout ending a minimum distance = $\sqrt{D_p \cdot t_p}$ below lower yoke plate and without reinforcement steel

= 1 for grout ending above lower yoke plate and with longitudinal reinforcement steel

= 0.5 for grout ending a minimum distance = $\sqrt{D_p \cdot t_p}$ below lower yoke plate and with reinforcement steel.

The largest principal design stress can be calculated as

$$\sigma_{I, Sd} = \frac{\sigma_{p, Sd}}{2} \left(1 + \sqrt{1 + 4\mu^2} \right) \quad (\text{K.5.11})$$

where a friction coefficient between pile and grout (upper bond value) should be taken as: $\mu = 1.0$. It should be checked that:

$$\sigma_{I, Sd} \leq \frac{f_{cN}}{\gamma_M} \quad (\text{K.5.12})$$

where

$$f_{cN} = 0.85 \cdot f_{ck} \left(1 - \frac{f_{ck} \cdot 0.85}{600} \right) \quad (\text{K.5.13})$$

f_{ck} = characteristic cube strength of grout in MPa

γ_M = 1.5 for ULS and 1.25 for ALS

When steel reinforcements are prescribed, the reinforcements should meet requirement given in K.5.4.

K.5.3.4 Fatigue of the grouted connection for alternating interface shear stress due to axial load and bending moment in the pile (FLS)

General

The principle for assuring fatigue capacity of grouted connections due to axial loads and bending moment is to avoid sliding of the pile in the sleeve during a loading cycle. A way to document fatigue is to limit the reversed interface shear stress caused by axial force and bending moment to the capacity of the grouted connection without including the capacity from the shear keys.

The maximum axial loads in piles of jacket platforms will normally be in compression due to addition of permanent and variable loads. Sliding of the pile at the grout interface should then be checked in case the pile experiences tension. Similarly it is necessary to calculate if the bending stresses in the pile changes to the opposite direction when all loads (permanent and variable) are considered.

As research data on the long-term capacity of grouted connections is scarce especially on effects from moment, there are no established methods for capacity assessment available for moment loading. However, the following checks are proposed based on the assumption that the shear keys should not be activated for the cases where the axial force or the bending moment changes direction. For simplicity the effects from axial tension and bending moment are treated separately neglecting any detrimental interaction effects from these.

The checks are based on that sliding should not take place for environmental loads with a 10 year return period.

The stiffness representation of the soil should represent the best estimate for cyclic loading.

Check of change of direction for interface stress due to axial load

Calculate the maximum pile axial tension load ($P_{t, Sd}$) for 10 year loading with load factor $\gamma_f = 1.0$.

Assess axial capacity without shear keys as follows:

Derive f_{bkf} without shear keys from equation (K.5.5).

Assess the design axial capacity without shear keys as:

$$P_{f, Rd} = f_{bkf} A_{OP} \quad (\text{K.5.14})$$

where:

A_{OP} = pile outer area in contact with grout using the effective grout length L_e as described in K.5.3.2.

Material factor $\gamma_M = 1.0$

Check if

$$P_{t,Sd} \leq P_{f,Rd} \quad (\text{K.5.15})$$

If equation (K.5.15) is not fulfilled, the capacity from friction created by the forces from the minimum corresponding bending moment and shear force in the pile according to the calculation model shown in Figure K.5-3 can be added to obtain larger capacity. The reaction forces can be calculated as:

$$F_{1,Sd} = V_{Sd} + M_{b,Sd} / H \quad (\text{K.5.16})$$

$$F_{2,Sd} = M_{b,Sd} / H$$

$$F_{3,Sd} = 2M_{t,Sd} / D_p$$

Then the net friction force can be derived as

$$F_{\mu,Rd} = (F_{1,Sd} + F_{2,Sd} - F_{3,Sd}) \mu \quad (\text{K.5.17})$$

where

μ = coefficient of friction between pile and grout for the contact area at the upper and lower yoke plates = 0.6 for this assessment

γ_M = material factor = 1.0

Check if

$$P_{t,Sd} \leq F_{\mu,Rd} + P_{f,Rd} \quad (\text{K.5.18})$$

Check of change of direction for interface stress due to bending moment

If there exist combinations of permanent, variable and environmental loads that will lead to change of direction of the bending stress in the pile (at the lower end of the pile sleeve connection) the following check should be fulfilled:

Calculate the largest absolute values of the pile bending moment from permanent loads and minimum variable loads setting all load factors equal 1.0. If the absolute value of the moment from environmental loads with 10 years return period is larger than the moment from permanent and minimum variable load, the following check should be made:

$$M_{Env10,Sd} < f_{bkf} D_p^2 L_{eM} \quad (\text{K.5.19})$$

where:

$M_{Env,10,Sd}$ = Bending moment from 10 year environmental load

L_{eM} = Minimum of L_e and $3 \cdot D_p$

If this simplified check is not satisfied an analysis of the actual wear based on the sliding length and the corresponding contact pressure to better determine the risk of deterioration of the connection that may lead to loss of structural integrity may be carried out.

K.5.3.5 *Fatigue of the grout due compression and shear stresses at the lower end of the grout due to bending moment and shear in the pile (FLS)*

The stress variations in the grout at the lower end is caused by cyclic bending moment and shear force in the pile giving compression stress in the grout and shear stress due to the friction caused by the sliding between the pile and the grout. For a grouted connection without steel reinforcement one should limit these friction stresses such that they will not exceed the tensile capacity more than once during the life of the platform. This is considered to be achieved if the following requirements are met based on calculation of 10 year return period environmental loads.

For fatigue the action effects are derived with a load factor $\gamma_f = 1.0$.

The tensile stress in the grout can be calculated as

$$\sigma_{II, Sd} = \frac{\sigma_{p, Sd}}{2} \left(1 - \sqrt{1 + 4\mu^2} \right) \quad (\text{K.5.20})$$

where a friction coefficient between pile and grout (upper bond value) should be taken as $\mu = 1.0$.

The design criterion reads:

$$|\sigma_{II, Sd}| \leq \frac{f_{tk}}{\gamma_M} \quad (\text{K.5.21})$$

where

f_{tk} = the characteristic tensile strength according to DNV-OS-C502 determined from splitting tensile testing of the actual grout.

$\gamma_M = 1.25$ = material factor used in fatigue assessment for the grout.

If equation (K.5.21) is not fulfilled, the capacity can be increased by introduction of longitudinal reinforcements. The fatigue capacity of the reinforced grouted section is for ordinary jacket pile-sleeve connections judged to be acceptable if the requirements stated in K.5.4 are met.

K.5.3.6 *Fatigue check due to torsion*

In cases where the ULS check according to K.5.3.2 fails in the check for interface shear stresses due to torsional moments and redistribution of the moment is assumed, the following check need to be carried out. The return period for the load should be taken as 10 year and the load factor $\gamma_f = 1.0$.

$$\tau_{btEnv10, Sd} \leq f_{bkf} \quad (\text{K.5.22})$$

where

$$\tau_{btEnv10, Sd} = \frac{2M_{tEnv10, Sd}}{\pi \cdot D_p^2 \cdot L_e} \quad (\text{K.5.23})$$

If this check is not satisfied it is recommended to increase the capacity against torsional moments e.g. by introduction of shear keys transverse to the direction of the interfaces shear stresses.

K.5.4 Requirements to ribbed steel reinforcement

If the grout strength and durability is increased by introduction of ribbed steel reinforcement bars, the following requirements to the steel reinforcement are assumed for the formulas given in this Annex:

- The steel reinforcements should be arranged in the longitudinal direction of the sleeve starting from the lower end of the grout over a length of $2.5 \sqrt{D_p \cdot t_p}$ in case for grout ending above lower yoke plate and $5.0 \sqrt{D_p \cdot t_p}$ for the case when the grout extend below the lower yoke plate.
- The longitudinal reinforcements should be placed as close as possible to the pile wall.
- Each reinforcement bar should be bent and welded to the sleeve at the top and bottom for the full yield capacity of the bar.
- Longitudinal bar spacing should be in the range of 0.5 to 2.0 times the grout thickness.
- Ring bars to be arranged to secure the position of the longitudinal bars throughout all phases and should as a minimum meet ordinary code requirements to reinforcements for shrinkage (e.g. DNV-OS-C502).
- The required area of the reinforcement can be calculated as

$$A_s = 0.5 \frac{\sigma_{p, Sd}}{f_{sd}} \mu t_g s \quad (\text{K.5.24})$$

where

- t_g = thickness of grout
 s = distance between longitudinal reinforcement bars
 f_{sd} = f_{sy} / γ_M = design strength of the reinforcement bars
 f_{sy} = characteristic yield stress of the reinforcement bars
 γ_M = 1.0 = material factor for reinforcement bars
 A_s = area of reinforcement bar
 μ = 0.6 = friction coefficient

K.5.5 Considerations on in-service inspection

Generally the experience with grouted pile-sleeve connections is good and regular in-service inspections have not been considered to be necessary. However, it should be kept in mind that the long term performance of grouted sleeve connections is uncertain. An effective in-service inspection of these connections is usually difficult to execute as there is limited access. Especially if the requirements of this standard are not met it should be considered to implement measures at the design and construction phases that enable easy inspections to check that the connection is functioning as intended.

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