**Q.1.(a) - Cone area ratio from geometry [10%]**

The cone area ratio $a$ is defined as the ratio of the cross-sectional area of the shaft to that of the cone:

$$\begin{aligned} a &= \frac{A_s}{A_c} = \left(\frac{D_s}{D}\right)^2 \\ &= \left(\frac{28.0}{35.7}\right)^2 \\ &= 0.784^2 \\ &= \mathbf{0.615} \end{aligned}$$

[10%]

**[Total 10%]**

**Q.1.(b) - Alternative method for cone area ratio [10%]**

The cone area ratio can be determined experimentally by calibration in a pressure chamber (triaxial cell):

- Place the cone in a sealed chamber filled with water
- Apply a known hydrostatic pressure to the chamber
- Measure the pore pressure response at the $u_2$ position (behind the cone shoulder)
- The area ratio is then: $a = u_{2,measured}/u_{applied}$

This method accounts for the actual geometry and any manufacturing tolerances or imperfections in the cone construction. [10%]

**[Total 10%]**

**Q.1.(c) - Robertson chart classification [40%]**

*Given data:*

- Depth: $z = 20$ m
- Cone resistance: $q_c = 18000$ kPa
- Sleeve friction: $f_s = 120$ kPa
- Pore pressure: $u_2 = 210$ kPa
- Unit weight: $\gamma = 19$ kN m$^{-3}$

[5%]

*Stress calculations:*

$$\begin{aligned} \sigma_{v0} &= \gamma z = 19 \times 20 = 380 \text{ kPa} \\ u_0 &= \gamma_w z = 10 \times 20 = 200 \text{ kPa} \\ \sigma'_{v0} &= \sigma_{v0} - u_0 = 380 - 200 = 180 \text{ kPa} \end{aligned}$$

[5%]

*Corrected cone resistance:*

$$\begin{aligned} q_t &= q_c + u_2(1-a) \\ &= 18000 + 210(1-0.615) \\ &= 18000 + 81 \\ &= 18081 \text{ kPa} \end{aligned}$$

[5%]

*Normalized cone resistance:*

$$Q_t = \frac{q_t - \sigma_{v0}}{\sigma'_{v0}} = \frac{18081 - 380}{180} = \frac{17701}{180} = \mathbf{98.3}$$

[5%]

*Friction ratio:*

$$F_r = \frac{f_s}{q_t - \sigma_{v0}} \times 100\% = \frac{120}{17701} \times 100\% = \mathbf{0.68\%}$$

[5%]

*Pore pressure parameter:*

$$B_q = \frac{u_2 - u_0}{q_t - \sigma_{v0}} = \frac{210 - 200}{17701} = \mathbf{0.001}$$

[5%]

*Classification:*
Plotting $Q_t \approx 98$ and $F_r \approx 0.7\%$ on the Robertson chart places the soil in **Zone 6**: Clean sand to silty sand. [5%]

The high normalized cone resistance with low friction ratio and near-zero $B_q$ (confirming drained behaviour) are characteristic of clean, dense sand deposits. Such sands are common in the southern North Sea where extensive sandy sediments were deposited during Quaternary glacial and post-glacial periods. [5%]

**[Total 40%]**

### Q.1.(d) - Additional tests for $N_{kt}$ [10%]

To determine the appropriate cone factor $N_{kt}$ for deriving undrained shear strength from CPT data:

- Retrieve high-quality soil samples (e.g., using piston samplers or Sherbrooke sampler)
- Perform laboratory strength tests: triaxial compression (CU or UU) or laboratory vane tests
- Compare measured $s_u$ with net cone resistance: $N_{kt} = (q_t - \sigma_{v0})/s_u$
- Alternatively, perform in-situ vane tests adjacent to CPT locations for direct field comparison

$N_{kt}$ typically ranges from 10–20 and varies with soil type, plasticity, OCR, and strain rate effects. Site-specific calibration is essential for reliable strength estimates. [10%]

**[Total 10%]**

**Q.1.(e) - North Sea export cable geohazards [30%]**

Three geohazards of concern for a North Sea export cable:

*1. Mobile bedforms (sandwaves and megaripples):*
Large-scale mobile sand features are common in the southern North Sea where sandy sediments predominate. Sandwaves can be 5–15 m high with wavelengths of 200–500 m and can migrate several metres per year. Cable exposure or free-spanning can occur as troughs migrate, leading to fatigue damage or snagging risk. [10%]

*2. Shallow gas and pockmarks:*
Accumulations of biogenic or thermogenic gas in shallow sediments can create pockmarks (crater-like depressions) when gas escapes. Gas-charged sediments have reduced strength and can cause sudden seabed collapse. Drilling or cable installation can trigger gas blowouts, and pockmark edges may be unstable. [10%]

*3. Shipwrecks, debris, and unexploded ordnance (UXO):*
The North Sea has extensive shipping activity and WWII history, resulting in numerous wrecks, lost cargo, and UXO on the seabed. These present physical obstructions to cable routing and installation, and UXO poses safety risks during burial operations. Detailed survey and route planning are essential. [10%]

*Other acceptable answers include: boulder fields from glacial deposits, scour around existing infrastructure, fishing activity (anchor/trawl damage), or seabed erosion/deposition.*

*Answers that should NOT receive credit (not relevant to North Sea):* earthquakes/major seismic activity (stable tectonic region), tsunamis, volcanic activity, tropical cyclones, coral reefs, gas hydrates (too warm/shallow for hydrate stability), submarine canyons, iceberg scour (not in modern era), turbidity currents.

**[Total 30%]**

**Q.2.(a) - Pipeline overload ratio [35%]**

*Given data:*

- Outer diameter: $D = 1.0$ m
- Specific gravity: $SG = 1.7$
- Embedment depth: $w = 0.3$ m
- Undrained shear strength: $s_u = 2$ kPa
- Effective unit weight of soil: $\gamma' = 6$ kN m$^{-3}$
- Bearing capacity factors: $N_c = 2 + \pi = 5.14$, $f_b = 1.5$

*Contact geometry:*

$$\theta = \cos^{-1}\left(1 - \frac{2w}{D}\right) = \cos^{-1}\left(1 - \frac{2 \times 0.3}{1.0}\right) = \cos^{-1}(0.4) = 66.4^\circ = 1.159 \text{ rad}$$

[5%]

$$\sin\theta = 0.917, \quad \cos\theta = 0.4$$
$$D' = D\sin\theta = 1.0 \times 0.917 = 0.917 \text{ m}$$

[5%]

$$\begin{aligned} A' &= \frac{D^2}{4}(\theta - \sin\theta\cos\theta) \\ &= \frac{1.0^2}{4}(1.159 - 0.917 \times 0.4) \\ &= 0.25 \times (1.159 - 0.367) \\ &= 0.198 \text{ m}^2 \end{aligned}$$

[5%]

*Bearing capacity:*

$$\begin{aligned} V_{max} &= N_c D' s_u + f_b A' \gamma' \\ &= 5.14 \times 0.917 \times 2 + 1.5 \times 0.198 \times 6 \\ &= 9.43 + 1.78 = 11.2 \text{ kN m}^{-1} \end{aligned}$$

[5%]

*Submerged pipeline weight:*

$$\begin{aligned} W' &= (SG - 1)\gamma_w \frac{\pi D^2}{4} \\ &= (1.7 - 1) \times 10 \times \frac{\pi \times 1.0^2}{4} \\ &= 0.7 \times 10 \times 0.785 = 5.50 \text{ kN m}^{-1} \end{aligned}$$

[5%]

*Overload ratio:*

$$OLR = \frac{V_{max}}{W'} = \frac{11.2}{5.50} = \mathbf{2.0}$$

[5%]

*Interpretation:* An overload ratio of 2.0 means the installation vessel must apply twice the pipeline's submerged weight to achieve the target embedment of 0.3 m. This is a typical value for pipeline installation in soft clay. [5%]

**[Total 35%]**

### Q.2.(b) - Ultimate lateral breakout force [35%]

*Interface roughness:*
Intermediate roughness corresponds to $\alpha = 0.5$. [5%]
*Maximum horizontal resistance ratio:*
Using the Merifield et al. (2008) expression with $w/D = 0.3$ and $\alpha = 0.5$:

$$\begin{aligned}\frac{H_{max}}{V_{max}} &= \left(0.48 - \frac{\alpha}{25}\right)\left(\frac{w}{D}\right)^{0.46-\alpha/25} \\ &= \left(0.48 - \frac{0.5}{25}\right)(0.3)^{0.46-0.5/25} \\ &= 0.46 \times (0.3)^{0.44} \\ &= 0.46 \times 0.584 \\ &= 0.269\end{aligned}$$

[5%]

$$H_{max} = 0.269 \times V_{max} = 0.269 \times 11.2 = 3.01 \text{ kN m}^{-1}$$

[5%]

*Shape parameters for failure envelope:*

$$\begin{aligned}\beta_1 &= (0.8 - 0.15\alpha)(1.2 - w/D) \\ &= (0.8 - 0.15 \times 0.5)(1.2 - 0.3) \\ &= 0.725 \times 0.9 = 0.653\end{aligned}$$

[5%]

$$\beta_2 = 0.35(2.5 - w/D) = 0.35(2.5 - 0.3) = 0.35 \times 2.2 = 0.77$$

[5%]

$$\beta = \frac{(\beta_1 + \beta_2)^{\beta_1+\beta_2}}{\beta_1^{\beta_1}\beta_2^{\beta_2}} = \frac{(1.42)^{1.42}}{(0.653)^{0.653}(0.77)^{0.77}} = \frac{1.65}{0.757 \times 0.818} = 2.67$$

[5%]

*Lateral resistance at operating load:*
Under operating conditions, the vertical load is the submerged pipe weight:

$$\frac{V}{V_{max}} = \frac{W'}{V_{max}} = \frac{5.50}{11.2} = 0.491$$

Using the failure envelope:

$$\begin{aligned}\frac{H}{H_{max}} &= \beta\left(\frac{V}{V_{max}}\right)^{\beta_1}\left(1-\frac{V}{V_{max}}\right)^{\beta_2} \\ &= 2.67 \times (0.491)^{0.653} \times (0.509)^{0.77} \\ &= 2.67 \times 0.628 \times 0.595 \\ &= 0.997 \approx 1.0\end{aligned}$$

[5%]

Therefore the ultimate lateral breakout force is:

$H = 1.0 \times H_{max} = \mathbf{3.0\ kN\ m^{-1}}$

*Note:* The lateral resistance is at its maximum because the pipe is operating at $V/V_{max} \approx 0.5$, which corresponds to the peak of the failure envelope. This is a direct consequence of the overload ratio of 2.0 used during installation.

**[Total 35%]**

### Q.2.(c) - Pipeline laying process [30%]

Award 5% for each correct statement (max 30%). Acceptable answers include:

*Vessel types:*

- **S-lay vessels**: Most common method. Pipe is welded horizontally on deck and departs over a curved stinger, forming an S-shape through the water column. Suitable for shallow to moderate water depths.
- **J-lay vessels**: Pipe is welded in a near-vertical tower and departs vertically, forming a J-shape. Better suited for deep water as it reduces bending stresses.
- **Reel-lay vessels**: Pipe is pre-fabricated and welded onshore, then spooled onto a large reel on the vessel. Fast installation but limited to smaller diameter pipes that can tolerate plastic bending.

*Laying process:*

- Pipe joints (typically 12 m) are welded together on the vessel in a firing line/welding stations.
- Each weld undergoes non-destructive testing (NDT) such as radiography or ultrasonic inspection.
- Tensioners grip the pipe and control the departure angle and lay tension.
- A stinger (curved support structure) guides the pipe over the stern and controls the overbend radius.

*Issues and considerations:*

- **Overbend**: The pipe must not exceed allowable bending strain as it passes over the stinger.
- **Touch-down point**: Control of where the pipe contacts the seabed affects embedment, seabed remoulding and residual stress.
- **Free spans**: Uneven seabed may cause unsupported spans leading to vortex-induced vibration (VIV) and fatigue.

- **On-bottom stability**: Hydrodynamic loads from currents and waves may cause lateral movement before the pipe is stabilised.
- **Trenching/burial**: Pipelines may require post-lay trenching or rock dumping for protection and stability.
- **Weather windows**: Laying operations are weather-sensitive; vessel motions affect weld quality and pipe stresses.
- **Water depth limitations**: S-lay is limited to moderate depths; J-lay or reel-lay preferred for deep water.

**[Total 30%]**

**Q.3.(a) - Show that: mudline holding capacity expression [25%]**

*Submerged anchor weight:*

$$W' = mg\left(1 - \frac{\rho_w}{\rho_s}\right)$$

[5%]

*Force parallel to fluke and padeye tension:*
The bearing capacity parallel to the fluke at depth $z_f$:

$$T_p = fA_pN_cs_u(z_f) = fA_pN_ckz_f$$

The padeye tension accounting for anchor weight:

$$T_a = \frac{T_p}{\cos\theta'_w} = \frac{fA_pN_ckz_f}{\cos\theta'_w}$$

[5%]

*Adjusted fluke angle for weighty anchor:*

$$\theta'_w = \tan^{-1}\left(\frac{W' + T_p\tan\theta_w}{T_p}\right) = \tan^{-1}\left(\frac{W'}{fA_pN_ckz_f} + \tan\theta_w\right)$$

[5%]

*Chain bearing resistance and chain angle at padeye:*
The padeye depth is $z_a = z_f - d$. The integrated bearing resistance:

$$z_aQ_{av} = bN_{c,chain}\int_0^{z_a} kz\,dz = \frac{bN_{c,chain}kz_a^2}{2}$$

From chain equilibrium with $\theta_m = 0$: $T_a = \frac{2z_aQ_{av}}{\theta_a^2}$, giving:

$$\theta_a = (z_f - d)\sqrt{\frac{bN_{c,chain}k}{T_a}} = (z_f - d)\sqrt{\frac{bN_{c,chain}\cos\theta'_w}{fA_pN_cz_f}}$$

[5%]

*Ultimate mudline holding capacity:*
Using $T_m = T_a\,e^{\mu\theta_a}$ and substituting:

$$T_m = \frac{fA_pN_ckz_f}{\cos\theta'_w}\exp\left[\mu(z_f - d)\sqrt{\frac{bN_{c,chain}\cos\theta'_w}{fA_pN_cz_f}}\right] \quad \text{Q.E.D.}$$

*Assumptions:* Chain is horizontal at mudline ($\theta_m = 0$). Linear strength profile for neat integration of chain resistance. [5%]

**[Total 25%]**

**Q.3.(b) - Ultimate holding capacity and performance ratio [45%]**

*Submerged anchor weight:*

$$V = \frac{m}{\rho_s} = \frac{35000}{7850} = 4.46 \text{ m}^3$$
$$W' = (\rho_s - \rho_w)Vg = (7850 - 1025) \times 4.46 \times 9.81 = 299 \text{ kN}$$

[5%]

*Adjusted fluke angle:*

$$\theta'_w = \tan^{-1}\left(\frac{W'}{fA_pN_ckz_f} + \tan\theta_w\right)$$
$$= \tan^{-1}\left(\frac{299}{1.25 \times 14 \times 9 \times 1.5 \times 8} + \tan 28°\right)$$
$$= \tan^{-1}(0.158 + 0.532) = \tan^{-1}(0.690) = 34.6°$$

[5%]

*Ultimate mudline holding capacity using given expression:*
With $k = 1.5$ kPa/m, $z_f = 8$ m, $d = 5$ m, $b = 2.5 \times 0.12 = 0.3$ m, $\mu = 0.4$:

$$T_m = \frac{fA_pN_ckz_f}{\cos\theta'_w} \exp\left[\mu(z_f - d)\sqrt{\frac{bN_{c,chain}\cos\theta'_w}{fA_pN_cz_f}}\right]$$
$$= \frac{1.25 \times 14 \times 9 \times 1.5 \times 8}{\cos 34.6°} \exp\left[0.4 \times 3 \times \sqrt{\frac{0.3 \times 7.5 \times 0.823}{1.25 \times 14 \times 9 \times 8}}\right]$$
$$= \frac{1890}{0.823} \exp\left[1.2 \times \sqrt{0.00147}\right]$$
$$= 2297 \times \exp(0.046) = 2297 \times 1.047 = \mathbf{2405 \text{ kN}}$$

[10%]

*Performance ratio:*

$$W = mg = 35000 \times 9.81 = 343 \text{ kN}$$
$$\eta = \frac{T_m}{W} = \frac{2405}{343} = \mathbf{7.0}$$

[5%]

*Comment:* A performance ratio of 7.0 is typical for drag anchors in soft NC clay. Performance ratios typically range from 5–15, with higher values achieved in softer soils where the anchor can penetrate deeper. [5%]

*Discussion of assumptions:*
Award 5% each for discussion of any three of the following assumptions and their implications:

- **Chain horizontal at mudline ($\theta_m = 0$):** This assumes a catenary mooring system. For taut-leg moorings where $\theta_m > 0$, the chain friction contribution would be reduced, lowering $T_m$.
- **Idealised chain resistance:** The analysis uses an average bearing resistance ($z_aQ_{av}$) which relies on the linear strength profile integrating neatly. Real soil profiles with layers, crusts, or spatial variability would require numerical integration or more sophisticated analysis.
- **Undrained soil response:** Assumes rapid loading. Under sustained or cyclic loading, partial drainage may occur, potentially reducing capacity in contractive soils or increasing it in dilative soils.

– **Linear strength profile:** Appropriate for normally consolidated clay. Layered soils, crusts, or overconsolidated conditions would require modified analysis.

– **No soil remoulding:** The analysis assumes intact soil strength. During drag installation, soil is remoulded and may have reduced strength (sensitivity effects), though reconsolidation can recover some capacity over time.

[15%]

**[Total 45%]**

**Q.3.(c) - Alternative anchor types [30%]**

Award 5% for each appropriately stated description, advantage, or disadvantage.

*Suction Caisson:*
A large-diameter, open-ended steel cylinder embedded into the seabed using suction (pumping water from inside creates a pressure differential that drives penetration).
*Advantages:* Precise positioning; retrievable and reusable; predictable capacity; no heavy tensioning equipment required.
*Disadvantages:* Requires specialist pumping equipment; sensitive to sand layers breaking suction seal; limited penetration in strong soils.

*Suction Embedded Plate Anchor (SEPLA):*
A vertically oriented plate anchor installed at the tip of a suction caisson follower, which is then retrieved. The plate is keyed (rotated) to the loading direction by tensioning the mooring line.
*Advantages:* High holding capacity relative to weight; precise positioning; efficient for soft NC clays; lower fabrication cost than suction caissons.
*Disadvantages:* Requires keying process which disturbs soil; capacity depends on successful rotation; not retrievable once keyed; sensitive to installation tolerances.

**[Total 30%]**

**Q.4.(a) - Terminal velocity through water [20%]**

*End area:*

$$A_{end} = \frac{\pi D^2}{4} = \frac{\pi \times 1.0^2}{4} = 0.785 \text{ m}^2$$

[5%]

*Drag coefficient:*

$$C_{drag} = 0.035 + 0.01\frac{L}{D} = 0.035 + 0.01 \times \frac{12}{1.0} = 0.035 + 0.12 = 0.155$$

[5%]

*Terminal velocity:*

$$\begin{aligned} V_{terminal} &= \sqrt{\frac{2mg}{C_{drag}A_{end}\rho_w}} \\ &= \sqrt{\frac{2 \times 60000 \times 9.81}{0.155 \times 0.785 \times 1025}} \\ &= \sqrt{\frac{1,177,200}{124.7}} = \sqrt{9439} = \mathbf{97 \text{ m s}^{-1}} \end{aligned}$$

[10%]

*Note:* This theoretical terminal velocity is high ( 350 km/hr). In practice, anchors are dropped from heights of 30–50 m and do not reach terminal velocity. Field impact velocities are typically 15–25 m $s^{-1}$.

**[Total 20%]**

**Q.4.(b) - Final embedment depth [35%]**

*Submerged anchor weight:*

$$\begin{aligned} W_s &= mg\left(1 - \frac{\rho_w}{\rho_s}\right) = 60000 \times 9.81 \times \left(1 - \frac{1025}{7850}\right) \\ &= 588,600 \times 0.869 = 512 \text{ kN} \end{aligned}$$

[5%]

*Geometric parameters:*

$$\begin{aligned} A_{shaft} &= \pi DL = \pi \times 1.0 \times 12 = 37.7 \text{ m}^2 \\ A_{tip} &= 0.785 \text{ m}^2 \text{ (from part a)} \end{aligned}$$

[5%]

*Resistance parameter:*

$$\begin{aligned} k_{su}(\alpha A_{shaft} + 2N_c A_{tip}) &= 2 \times (0.4 \times 37.7 + 2 \times 12 \times 0.785) \\ &= 2 \times (15.1 + 18.8) = 2 \times 33.9 = 67.8 \text{ kN m}^{-1} \end{aligned}$$

[10%]

*Final embedment depth:*

$$z_{final} = \frac{W_s + \sqrt{W_s^2 + mv_{impact}^2\, k_{su}(\alpha A_{shaft} + 2N_c A_{tip})}}{k_{su}(\alpha A_{shaft} + 2N_c A_{tip})}$$

Numerator terms:

$$W_s^2 = 512^2 = 262,100 \text{ kN}^2$$
$$mv_{impact}^2 \times 67.8 = 60 \times 20^2 \times 67.8 = 60 \times 400 \times 67.8 = 1,627,000 \text{ kN}^2$$

[5%]

$$z_{final} = \frac{512 + \sqrt{262,100 + 1,627,000}}{67.8} = \frac{512 + \sqrt{1,889,000}}{67.8}$$
$$= \frac{512 + 1374}{67.8} = \frac{1886}{67.8} = \mathbf{27.8\ m}$$

[10%]

*Check:* Embedment of 28 m is 2.3 times the anchor length (12 m), which is consistent with field experience in soft NC clays where penetrations of 1.5–2.5 times anchor length are typical.

**[Total 35%]**

**Q.4.(c) - Axial holding capacity [30%]**

*Depth to anchor centroid:*

$$z_{avg} = z_{final} - \frac{L}{2} = 27.8 - 6 = 21.8 \text{ m}$$

*Average and tip shear strength:*

$$s_{u,avg} = k \times z_{avg} = 2 \times 21.8 = 43.6 \text{ kPa}$$
$$s_{u,tip} = k \times z_{final} = 2 \times 27.8 = 55.6 \text{ kPa}$$

[5%]

*Shaft friction capacity:*

$$Q_{shaft} = \alpha \times s_{u,avg} \times A_{shaft} = 0.4 \times 43.6 \times 37.7 = 658 \text{ kN}$$

[5%]

*End bearing capacity (tip and reverse end bearing):*
For deep embedment, bearing resistance develops at both ends of the anchor:

$$s_{u,top} = k \times (z_{final} - L) = 2 \times (27.8 - 12) = 31.6 \text{ kPa}$$
$$Q_{bearing} = N_c \times A_{tip} \times (s_{u,tip} + s_{u,top})$$
$$= 12 \times 0.785 \times (55.6 + 31.6) = 12 \times 0.785 \times 87.2 = 821 \text{ kN}$$

[5%]

*Total axial capacity:*

$Q = Q_{shaft} + Q_{bearing} = 658 + 821 = \mathbf{1479\ kN}$

[5%]

*Holding capacity ratio:*

$W = mg = 60000 \times 9.81 = 589$ kN

$$\eta = \frac{Q}{W} = \frac{1479}{589} = \mathbf{2.5}$$

[5%]

*Comment:* A holding capacity ratio of 2.5 is typical for torpedo anchors in soft NC clay. Higher ratios (3–5) are achieved with deeper embedment or inclined loading where lateral soil resistance contributes. [5%]

**[Total 30%]**

**Q.4.(d) - Uncertainties in holding capacity prediction [15%]**

Award 5% each for discussion of any three of the following:

- **Strain rate effects:** During penetration, the soil is loaded at strain rates orders of magnitude higher than in laboratory tests or static loading. This strain rate hardening increases penetration resistance, potentially leading to shallower embedment than predicted. However, under static holding loads, normal strain rates apply and the capacity is based on conventional shear strength.
- **Anchor orientation:** The anchor may not penetrate vertically. Tilting during free-fall or soil contact can result in an inclined final orientation. This affects load transfer to the soil: an inclined anchor under vertical mooring load will experience combined axial and lateral loading, altering the failure mechanism and capacity.
- **Soil remoulding and setup:** High-velocity penetration severely remoulds the soil around the anchor, reducing its strength (sensitivity effects). Over time, reconsolidation (setup) recovers capacity. The design must account for whether short-term (remoulded) or long-term (recovered) strength governs.
- **Layered or variable soil conditions:** The analysis assumes a uniform linear strength profile. Sand layers, crusts, or spatial variability would affect both penetration (harder layers reduce depth) and capacity (different failure mechanisms).

[15%]

**[Total 15%]**