Grout Volume Loss into Rock Fractures

Rock Socket Grouting — RS Insert Pile Locations

Shinan-Ui Offshore Wind Farm
Based on Rock Characterization Data: TCR, RQD, Fracture, Weathering, Strength
Methods: Lombardi (1985), Priest & Hudson (1976), Houlsby (1990)

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Grout Loss into Rock Fractures — Geometry

1. ROCK SOCKET ZONE — Where Grout Contacts Rock

Grout is exposed to rock ONLY below the driven pile tip:

- TOP: Driven Pile Tip (bottom of driven pile)
- BOTTOM: Insert Pile Tip (bottom of insert pile)

Above this zone, grout is contained between two steel pipes — no rock contact.

KEY DIMENSIONS

Rock Socket Diameter	D	$= 3.2$ m
Insert Pile Outside Dia.	d	$= 3.0$ m
Socket Wall Perimeter	P	$= \pi \times 3.2 = 10.05$ m
Annular Area (socket)	A	$= \pi/4 \times (3.2^2 - 3.0^2) = 0.974$ m^2

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Method A — Joint Geometry (Lombardi 1985, Priest & Hudson 1976)

STEP 1: Fracture Frequency λ from RQD

Priest & Hudson (1976): RQD = 100 × e^(−0.1λ) × (0.1λ + 1)

RQD (%)	λ (frac/m)	Quality
90 – 100	1 – 3	Excellent
75 – 90	4 – 6	Good
50 – 75	6 – 10	Fair
25 – 50	10 – 15	Poor
0 – 25	15 – 25	Very Poor

STEP 2: Base Joint Aperture from Fracture Class

S = 0.3 mm **SF = 0.75 mm** **MF = 2.0 mm**

F = 3.5 mm **HF = 7.0 mm**

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Method A (cont.) — Effective Aperture & Volume Formula

STEP 3: Effective Aperture

$$e_{eff} = e_{base} \times W_{mult} \times S_{factor}$$

Weathering Multiplier (W_mult):

F = 1.0 SW = 1.1 MW = 1.75 HW = 3.0 CW = 4.5

Strength Factor (S_factor):

VS = 1.0 S = 1.0 MS = 1.1 W = 1.25 VW = 1.5

STEP 4: Grout Loss Volume per Layer

$$V_A = 2 \times \pi \times r_{socket} \times R_{pen} \times \lambda \times e_{eff} \times L$$

where:

r_socket = 1.6 m (rock socket radius)
R_pen = 0.75 m (grout penetration radius into rock)
L = layer thickness (m)

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Method B — TCR Void Fraction Method

CONCEPT: Core Loss = Rock Mass Voids

Core loss (100 – TCR) represents voids, cavities, and fractured zones that can accept grout from the rock socket wall.

Void Fraction:

$$V_f = \alpha \times (100 - TCR) / 100$$

where $\alpha = 0.5$ (effectiveness factor — not all voids accept grout)

Grout Loss Volume:

$$V_B = \pi \times [(r + R_{pen})^2 - r^2] \times V_f \times L$$

$$= \pi \times [(1.6 + 0.75)^2 - 1.6^2] \times V_f \times L = 13.22 \times V_f \times L \quad (m^3)$$

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Method C — RQD Empirical Multiplier (Houlsby 1990)

EMPIRICAL MULTIPLIER FROM DAM GROUTING EXPERIENCE

$$V_C = (\text{Multiplier} - 1) \times V_{annular\_per\_layer}$$

RQD (%)	Rock Quality	Multiplier
> 90	Excellent	1.10
75 – 90	Good	1.22
50 – 75	Fair	1.55
25 – 50	Poor	2.40
< 25	Very Poor	4.00

Reference: Houlsby, A.C. (1990) — "Construction and Design of Cement Grouting" — Wiley

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Combined Estimate & Grout Loss Percentage

COMBINED ESTIMATE

Mean Estimate = average of Method A, B, and C

(combines joint geometry + void fraction + empirical dam grouting data)

All values capped at maximum 50%

GROUT LOSS PERCENTAGE

% Loss = Grout Loss / (Overlap Annulus + Socket Annulus) × 100

Total Grout per Pile = Net Annular Volume + Mean Grout Loss

KEY REFERENCES

- Priest & Hudson (1976) — RQD to fracture frequency
- Lombardi (1985) — Joint penetration model for grout flow
- Houlsby (1990) — Empirical grout take from dam grouting
- Ewert (1985) — Rock grouting & Lugeon correlations

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Summary Table — Grout Loss per Location (% of Annulus Volume)

Grout Loss into Rock Fractures — Summary per Location
Shinan-Ui Offshore Wind Farm — RS Insert Pile Locations

% Loss = Grout Loss / (Overlap + Socket Annulus) × 100 | Capped at 50% max
Green <15% | Yellow 15-30% | Orange 30-60% | Red >60%

Location	Overlap Annulus (m³)	Socket Annulus (m³)	Total Annulus (m³)	Method A Joints (m³)	% A	Method B TCR (m³)	% B	Method C RQD (m³)	% C	Mean Loss (m³)	% Mean	Total Grout (net+mean) (m³)
WTG-04	9.33	7.50	16.83	3.11	18%	1.35	8%	5.73	34%	3.40	20%	20.23
WTG-06	9.33	5.75	15.08	2.47	16%	2.12	14%	4.65	31%	3.08	20%	18.16
WTG-07	9.33	7.50	16.83	5.20	31%	2.65	16%	8.41	50%	5.42	32%	22.25
WTG-08	9.33	7.01	16.34	3.03	19%	1.13	7%	6.18	38%	3.45	21%	19.79
WTG-09	9.33	7.30	16.63	8.32	50%	3.21	19%	8.32	50%	6.61	40%	23.25
WTG-10	9.33	5.16	14.49	2.23	15%	2.00	14%	4.60	32%	2.94	20%	17.44
WTG-11	13.14	7.50	20.64	1.14	6%	0.96	5%	1.23	6%	1.11	5%	21.75
WTG-12	9.33	7.79	17.12	8.56	50%	8.56	50%	8.56	50%	8.56	50%	25.68
WTG-13	13.90	10.71	24.61	1.95	8%	0.77	3%	1.65	7%	1.46	6%	26.07
WTG-14	13.90	10.62	24.52	1.49	6%	0.28	1%	1.61	7%	1.13	5%	25.64
WTG-17	13.14	13.83	26.97	0.31	1%	2.79	10%	3.80	14%	2.30	9%	29.27
WTG-18	13.90	8.96	22.86	5.43	24%	7.21	32%	8.62	38%	7.09	31%	29.95
WTG-19	9.33	6.33	15.66	7.83	50%	1.87	12%	7.83	50%	5.84	37%	21.50
WTG-20	9.33	6.04	15.37	6.49	42%	0.00	0%	4.82	31%	3.77	25%	19.14
WTG-21	9.33	5.55	14.88	4.81	32%	1.41	9%	6.41	43%	4.21	28%	19.09
WTG-23	9.33	6.23	15.56	5.33	34%	4.57	29%	6.22	40%	5.37	35%	20.94
WTG-25	9.33	5.75	15.08	0.68	5%	0.00	0%	1.18	8%	0.62	4%	15.70
WTG-26	13.33	12.37	25.70	3.18	12%	2.68	10%	3.94	15%	3.27	13%	28.96
OSS	9.52	8.67	18.19	1.90	10%	0.47	3%	4.82	27%	2.40	13%	20.58

Proposed values

NOTE: All % loss values are capped at maximum 50%

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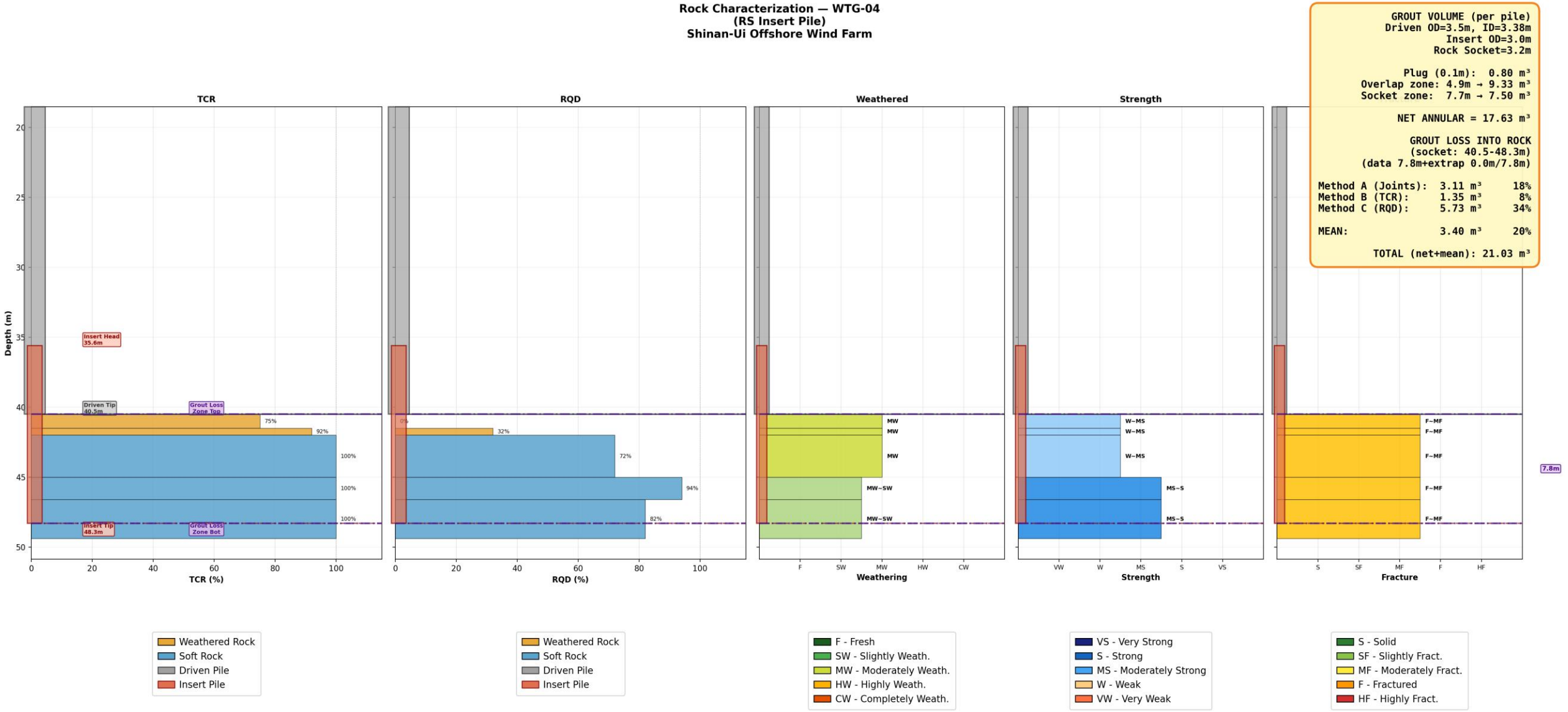
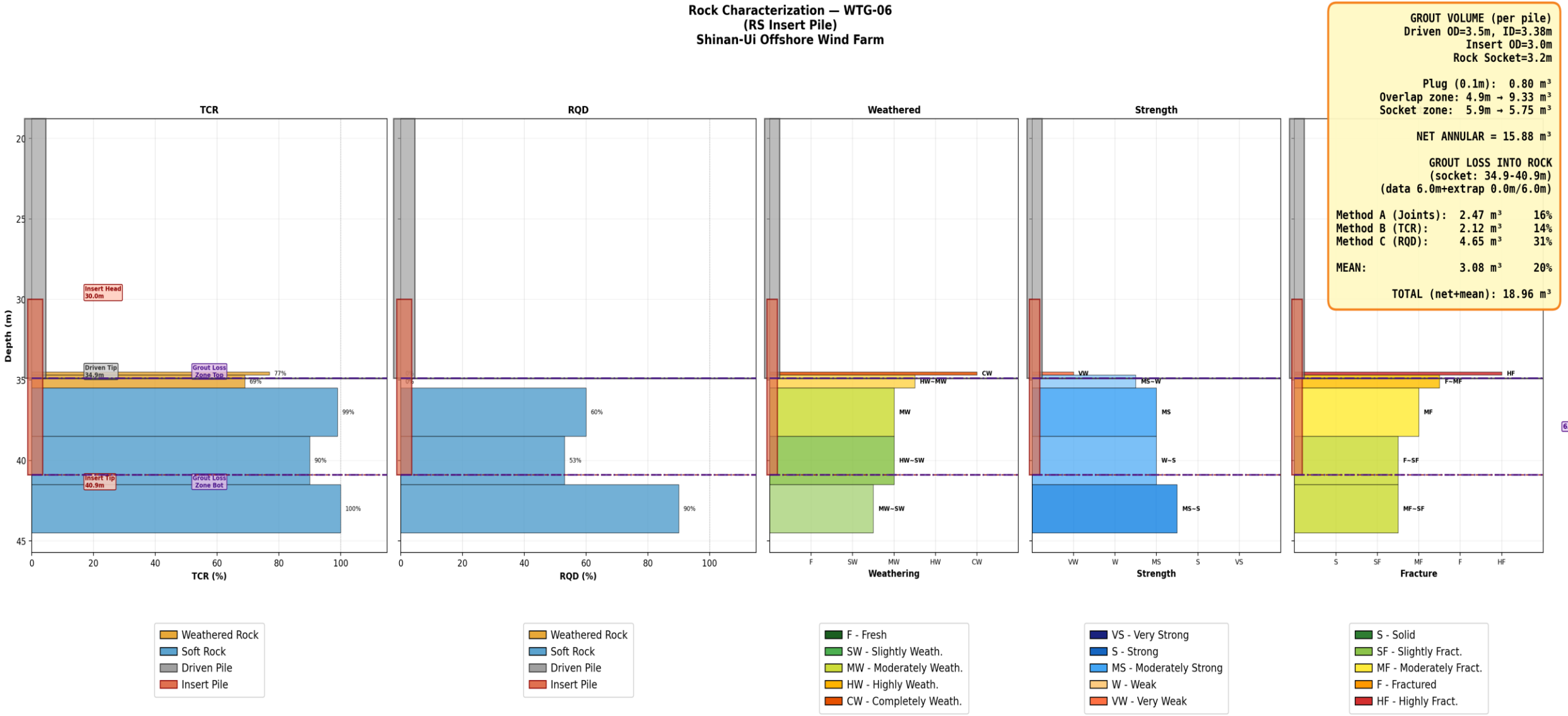
Rock Characterization & Grout Volume — WTG-04



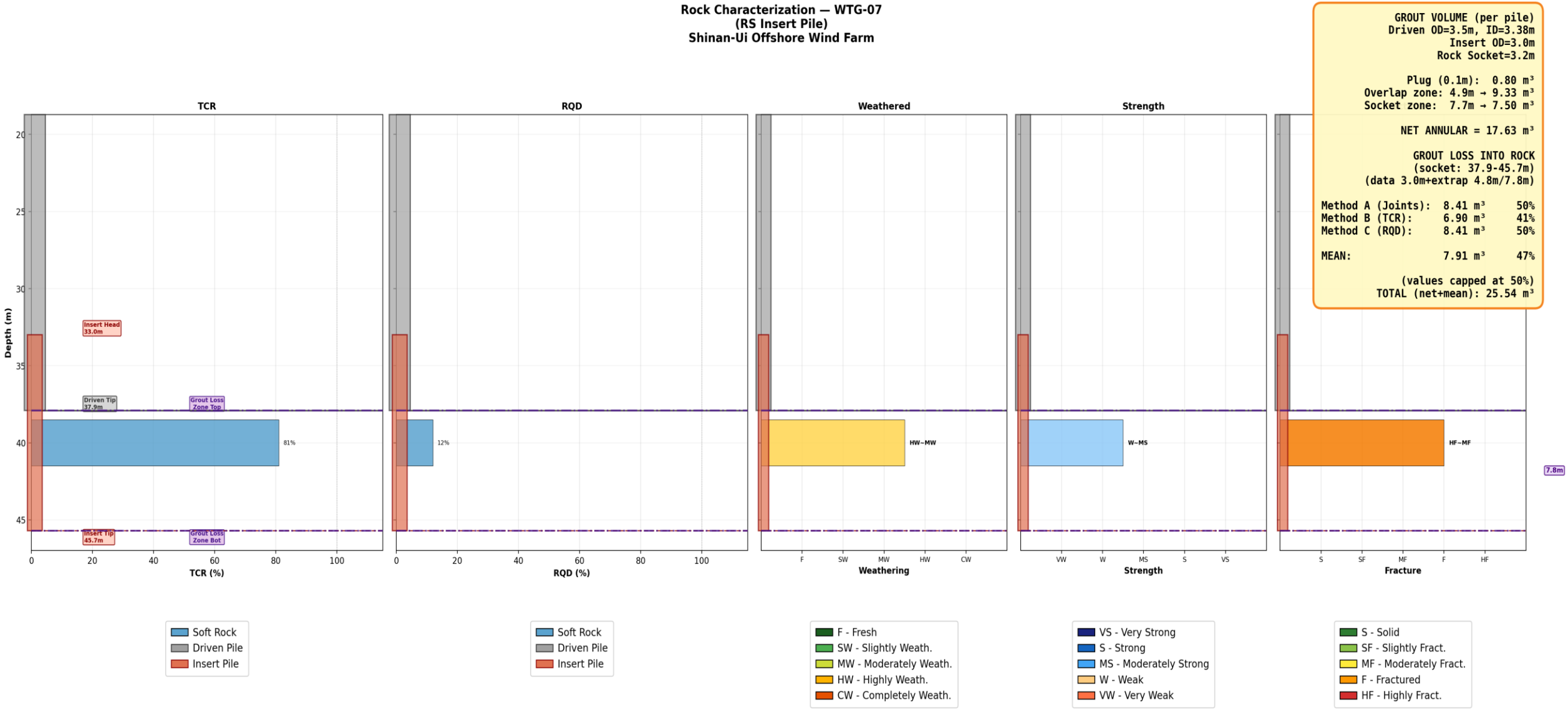
DRAFT — Calculations in Progress | Values capped at 50% max

Rock Characterization & Grout Volume — WTG-06



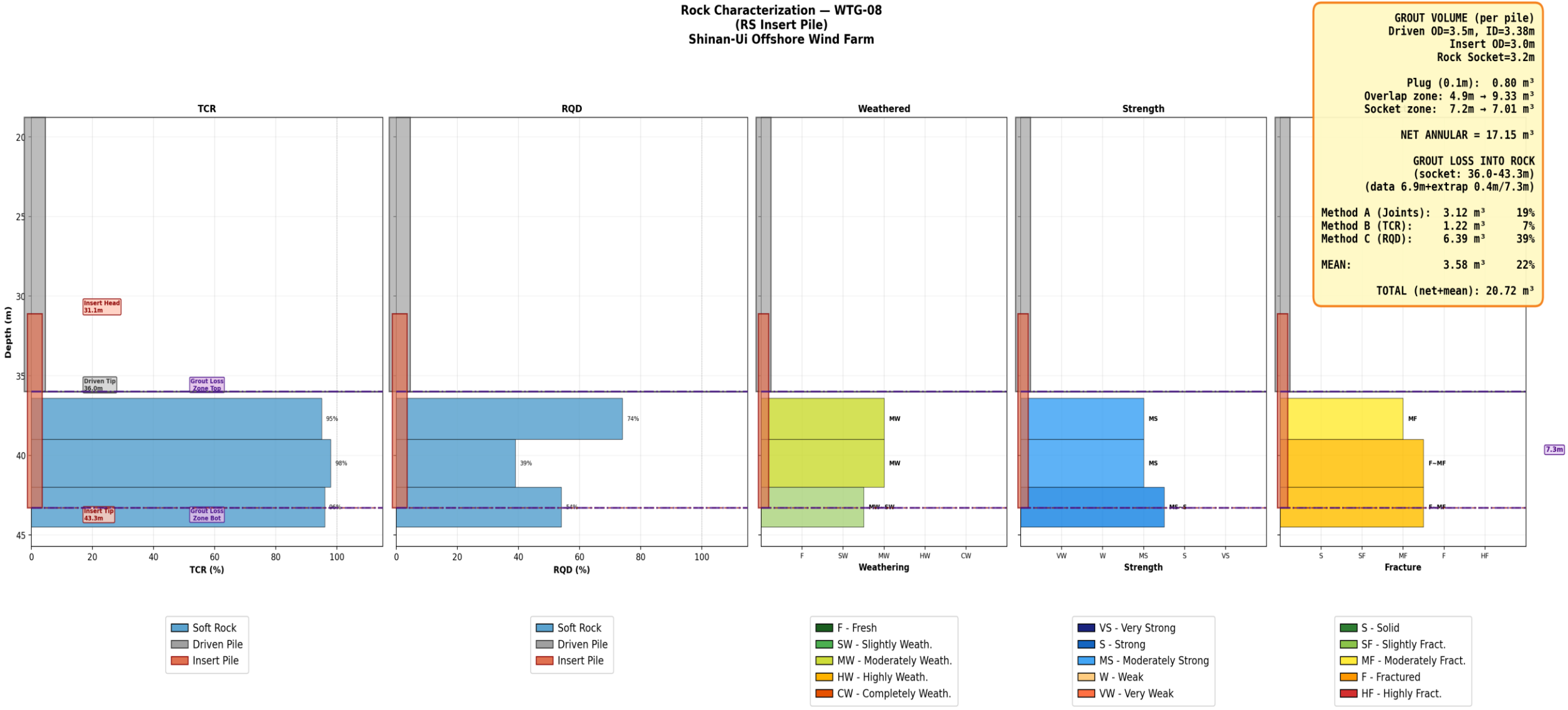
DRAFT — Calculations in Progress | Values capped at 50% max

Rock Characterization & Grout Volume — WTG-07



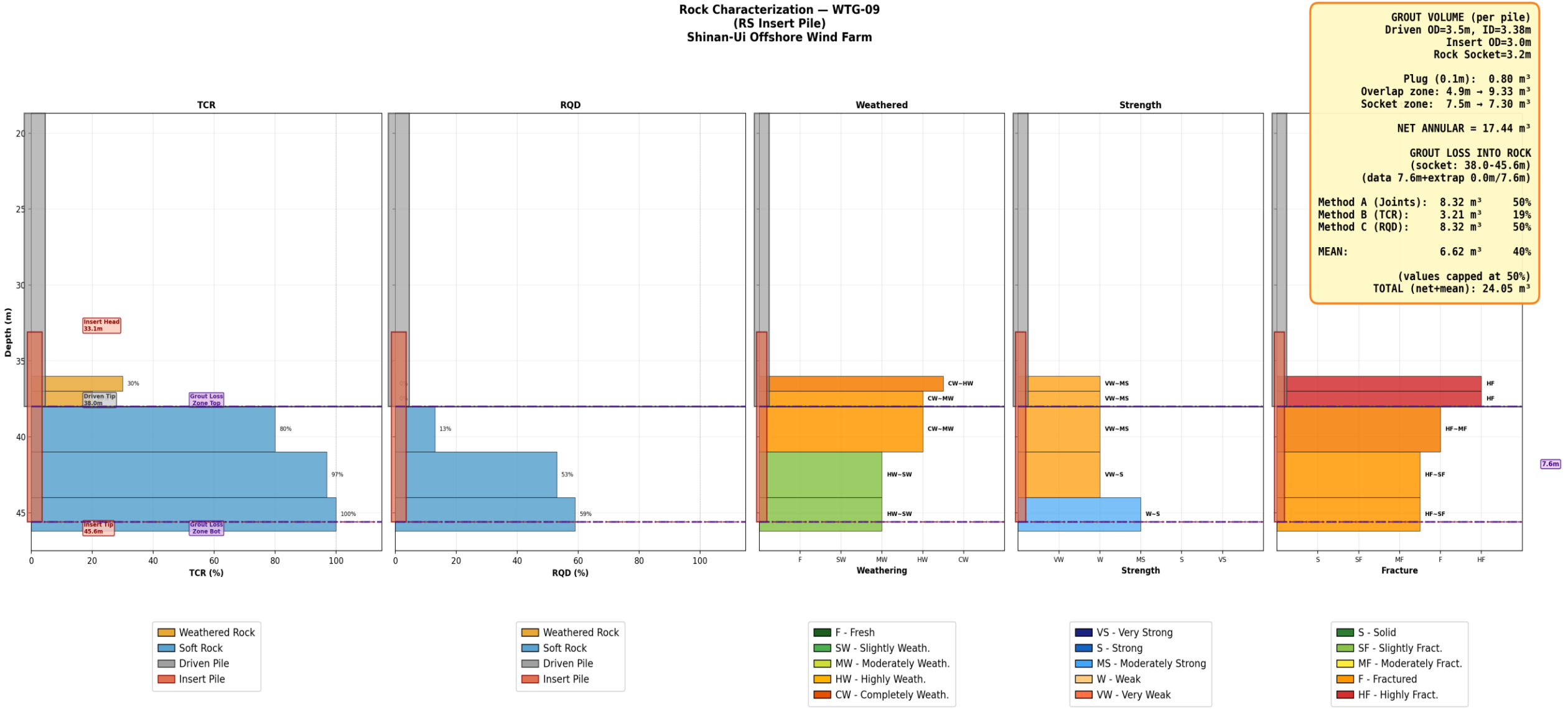
DRAFT — Calculations in Progress | Values capped at 50% max

Rock Characterization & Grout Volume — WTG-08



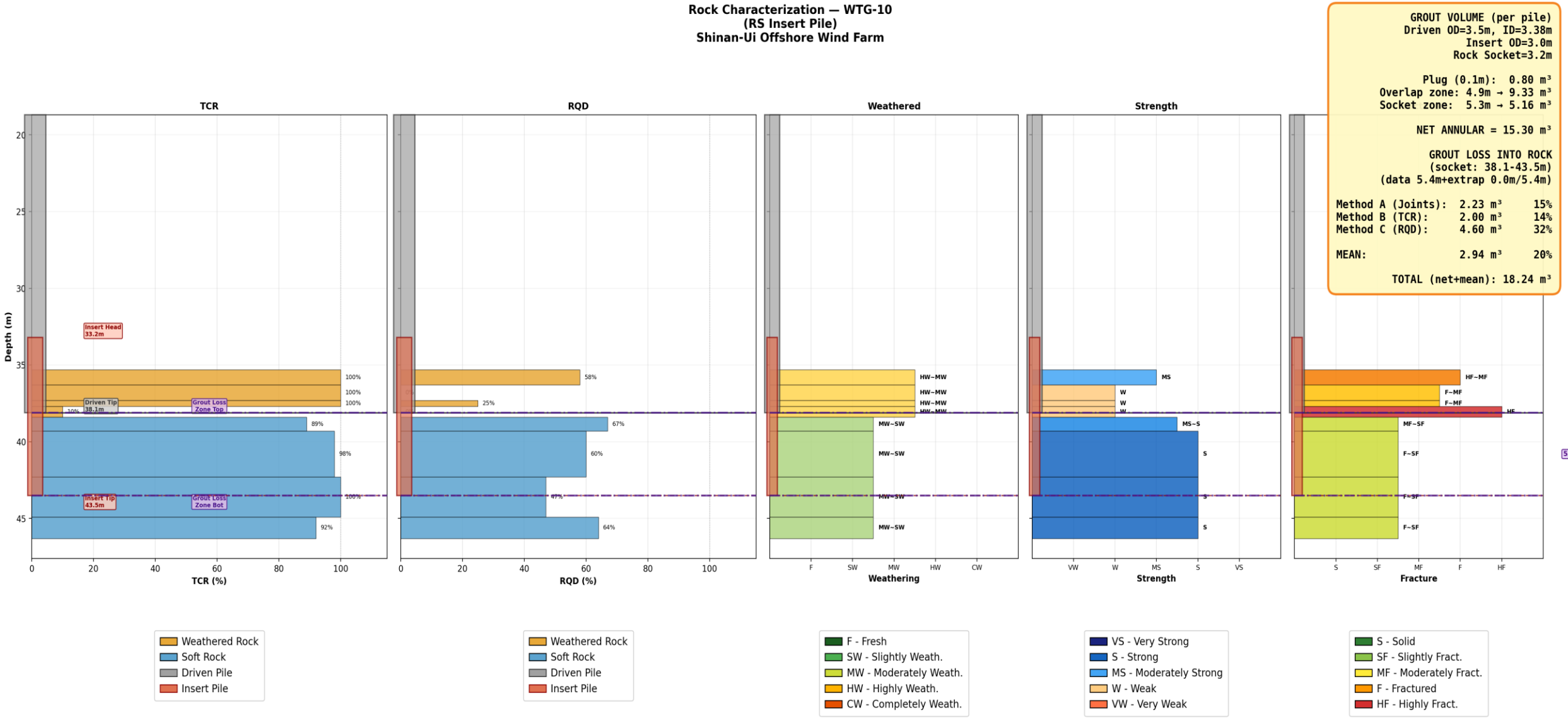
DRAFT — Calculations in Progress | Values capped at 50% max

Rock Characterization & Grout Volume — WTG-09



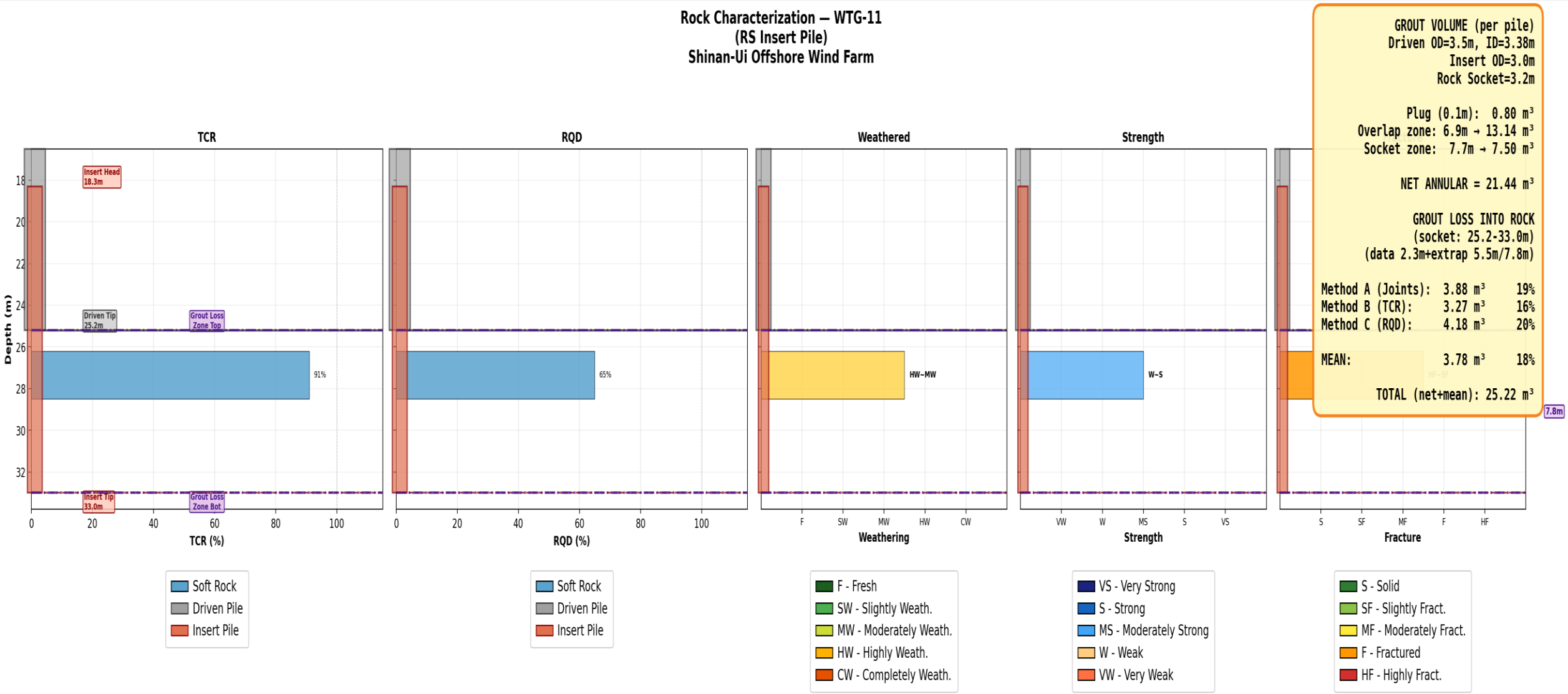
DRAFT — Calculations in Progress | Values capped at 50% max

Rock Characterization & Grout Volume — WTG-10



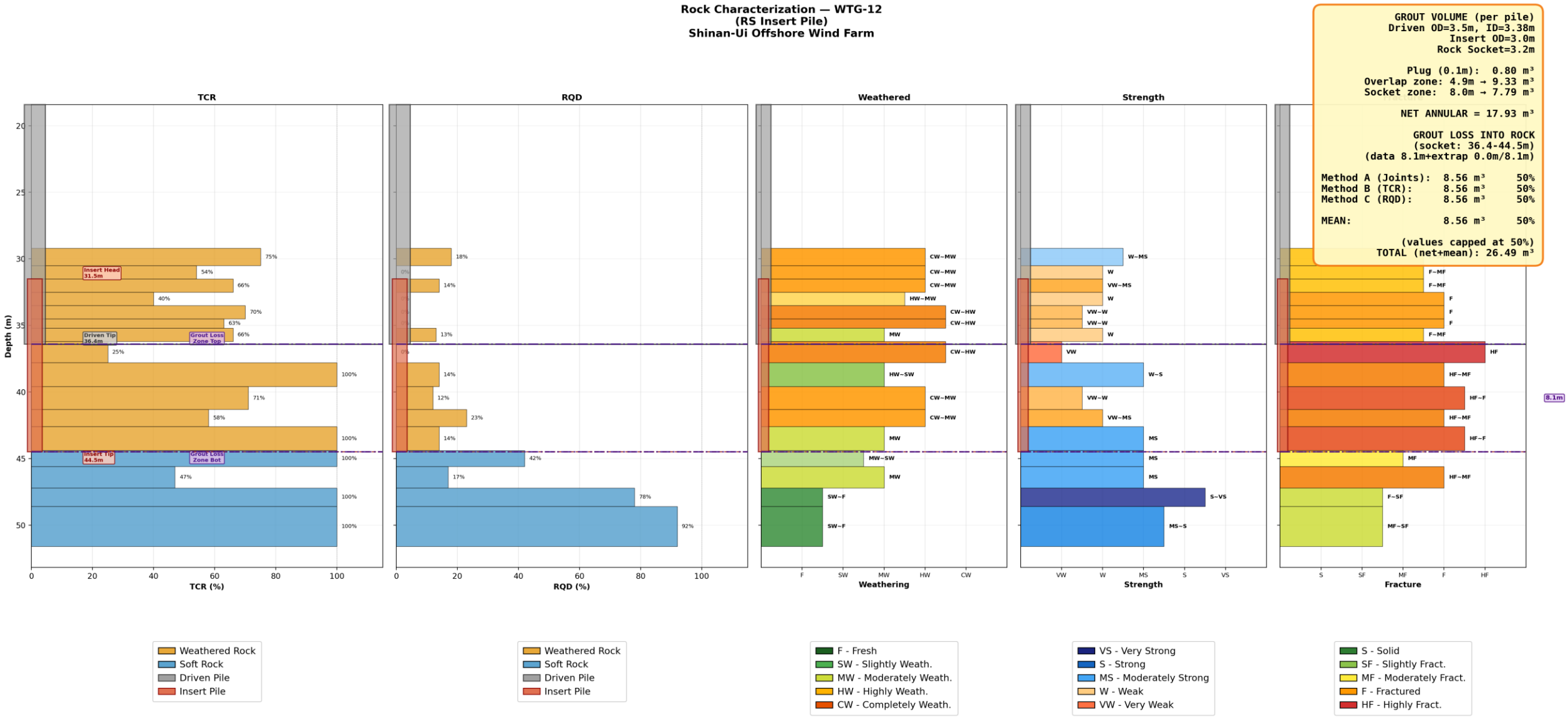
DRAFT — Calculations in Progress | Values capped at 50% max

Rock Characterization & Grout Volume — WTG-11



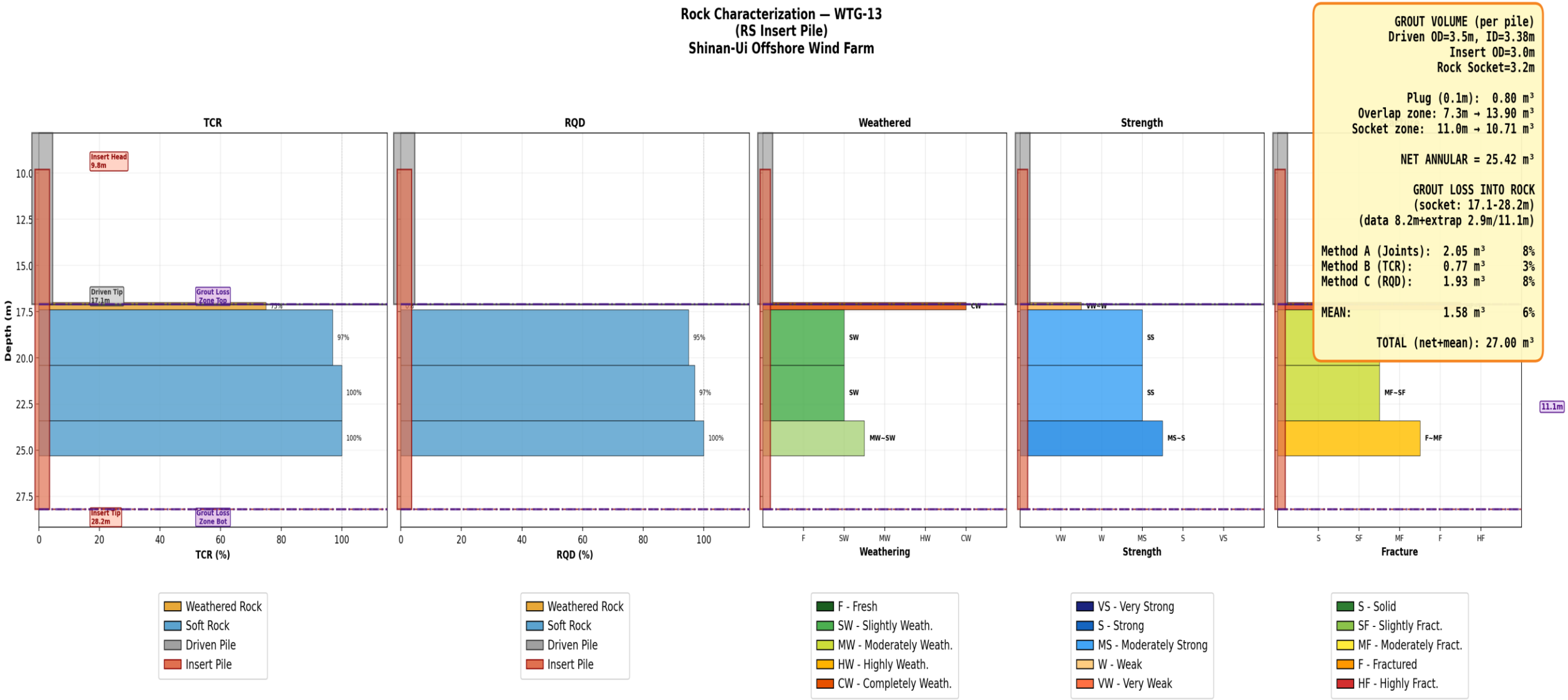
DRAFT — Calculations in Progress | Values capped at 50% max

Rock Characterization & Grout Volume — WTG-12



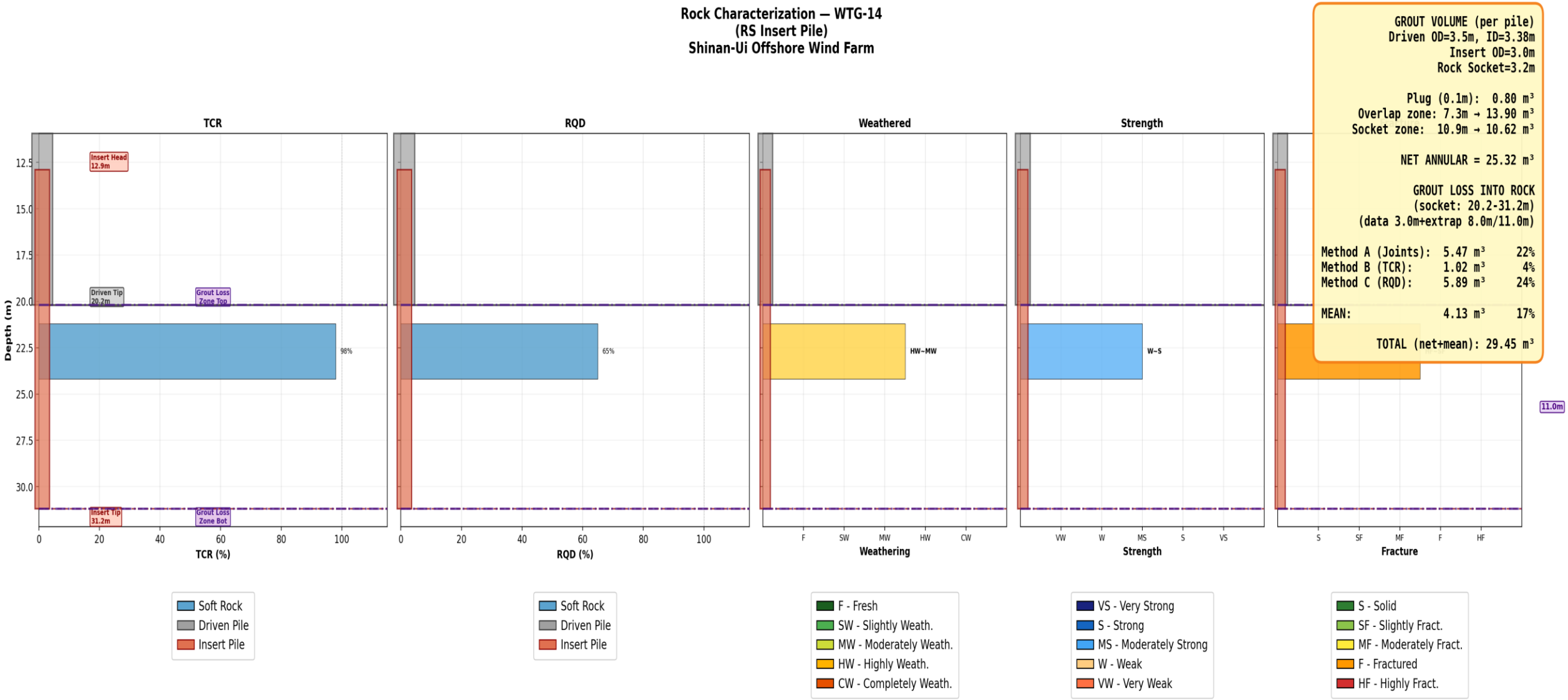
DRAFT — Calculations in Progress | Values capped at 50% max

Rock Characterization & Grout Volume — WTG-13



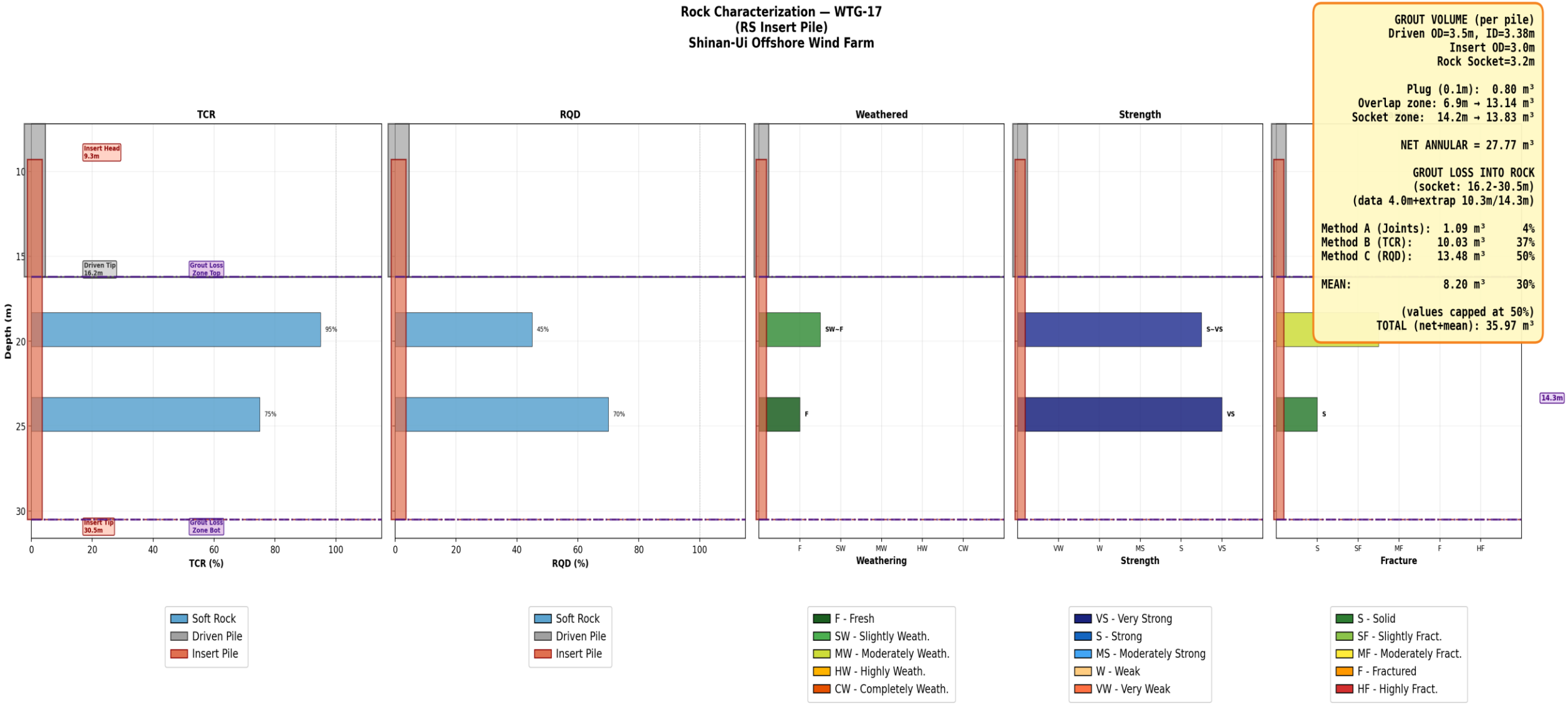
DRAFT — Calculations in Progress | Values capped at 50% max

Rock Characterization & Grout Volume — WTG-14



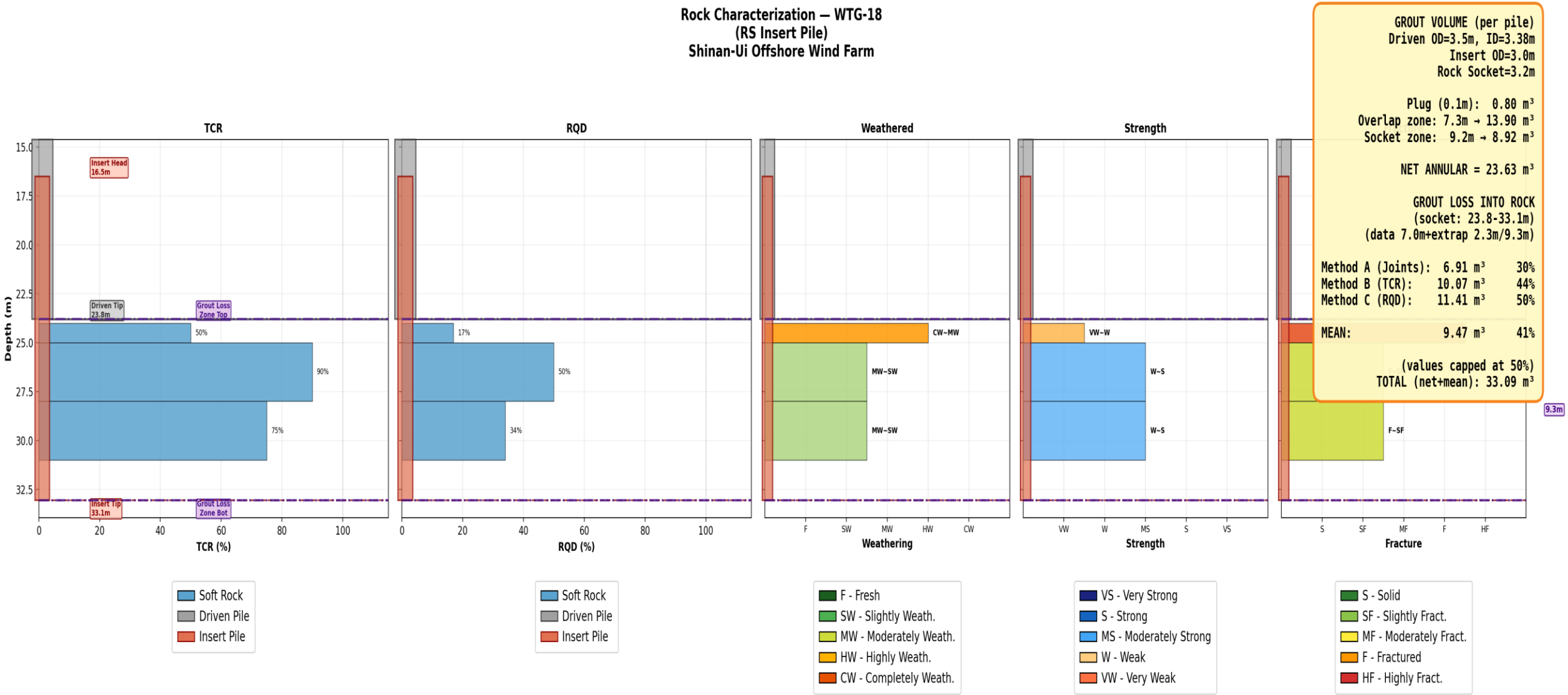
DRAFT — Calculations in Progress | Values capped at 50% max

Rock Characterization & Grout Volume — WTG-17



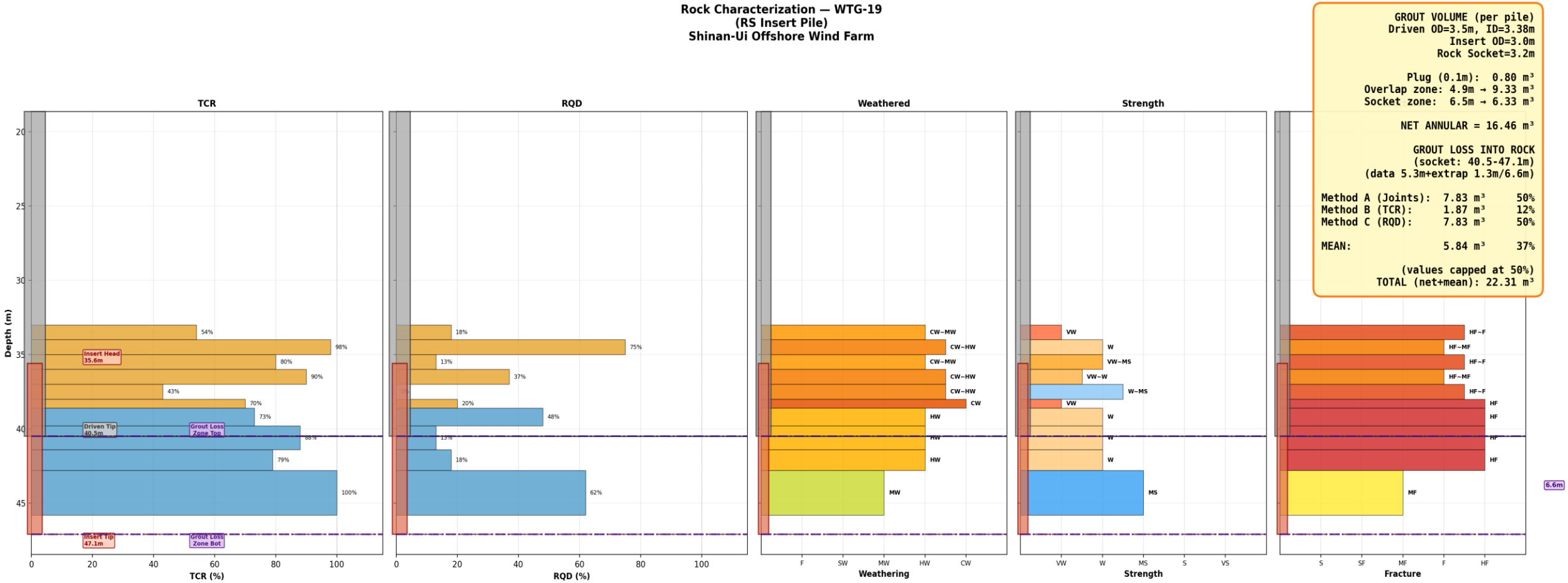
DRAFT — Calculations in Progress | Values capped at 50% max

Rock Characterization & Grout Volume — WTG-18



DRAFT — Calculations in Progress | Values capped at 50% max

Rock Characterization & Grout Volume — WTG-19

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GROUT VOLUME (per pile)
Driven OD=3.5m, ID=3.38m
Insert OD=3.0m
Rock Socket=3.2m

Plug (0.1m):  0.80 m³
Overlap zone: 4.9m → 9.33 m³
Socket zone:  6.5m → 6.33 m³

NET ANNULAR = 16.46 m³

GROUT LOSS INTO ROCK
(socket: 40.5-47.1m)
(data 5.3m+extrap 1.3m/6.6m)

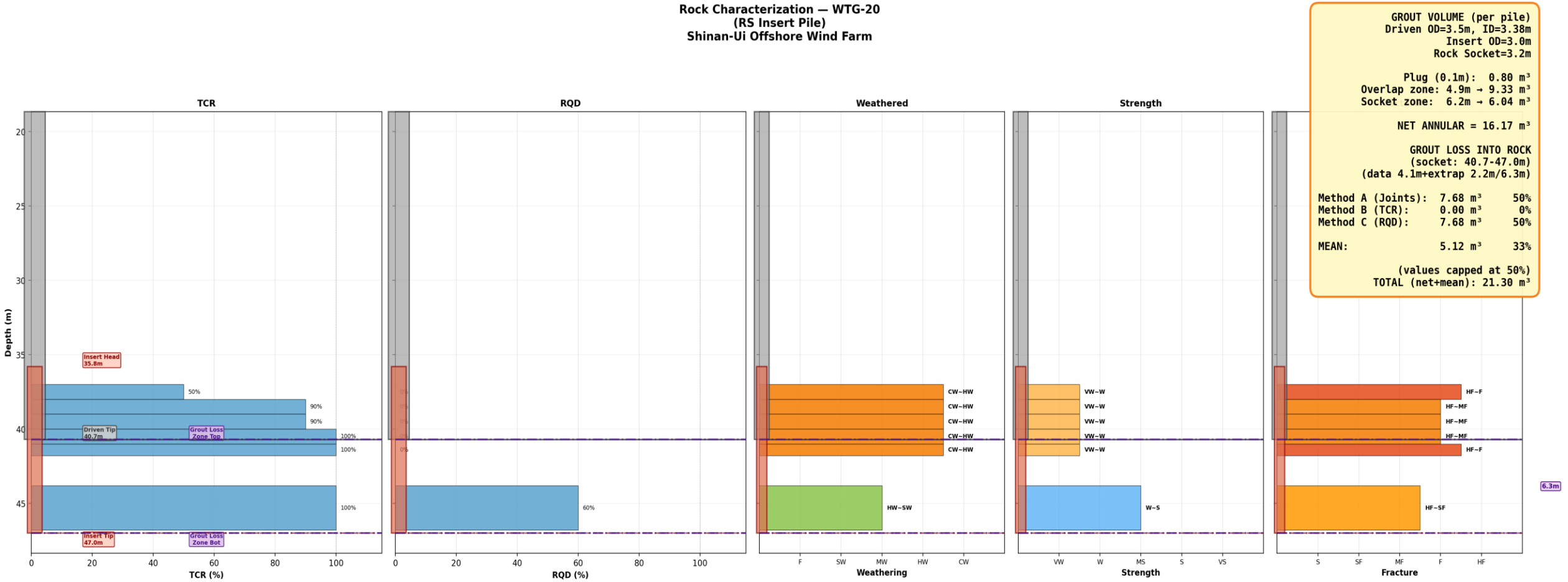
Method A (Joints):  7.83 m³   50%
Method B (TCR):     1.87 m³   12%
Method C (RQD):     7.83 m³   50%

MEAN:               5.84 m³   37%

(values capped at 50%)
TOTAL (net+mean): 22.31 m³
```

DRAFT — Calculations in Progress | Values capped at 50% max

Rock Characterization & Grout Volume — WTG-20




```
GROUT VOLUME (per pile)
Driven OD=3.5m, ID=3.38m
Insert OD=3.0m
Rock Socket=3.2m

Plug (0.1m):  0.80 m³
Overlap zone: 4.9m → 9.33 m³
Socket zone:  6.2m → 6.04 m³

NET ANNULAR = 16.17 m³

GROUT LOSS INTO ROCK
(socket: 40.7-47.0m)
(data 4.1m+extrap 2.2m/6.3m)

Method A (Joints):  7.68 m³    50%
Method B (TCR):     0.00 m³     0%
Method C (RQD):     7.68 m³    50%

MEAN:               5.12 m³    33%

(values capped at 50%)
TOTAL (net+mean): 21.30 m³
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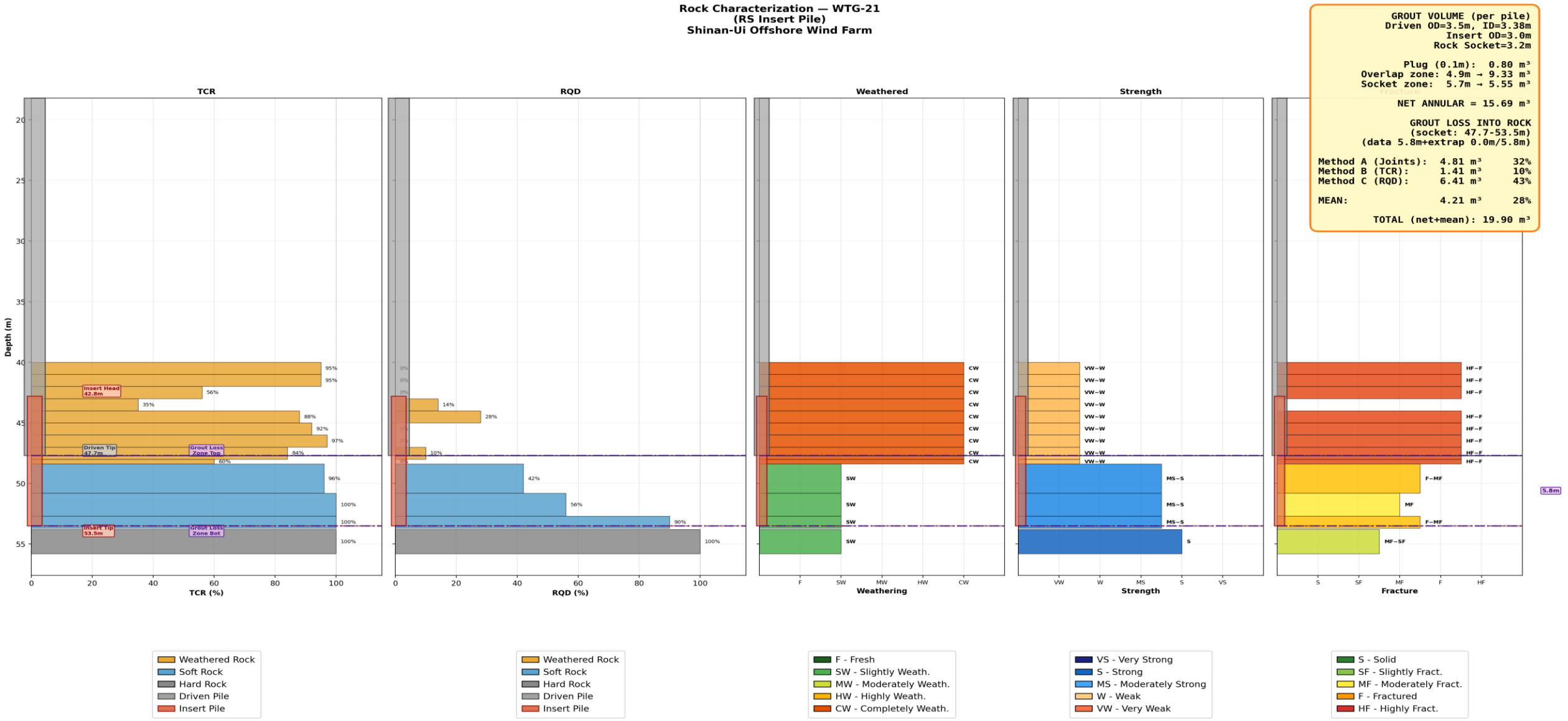
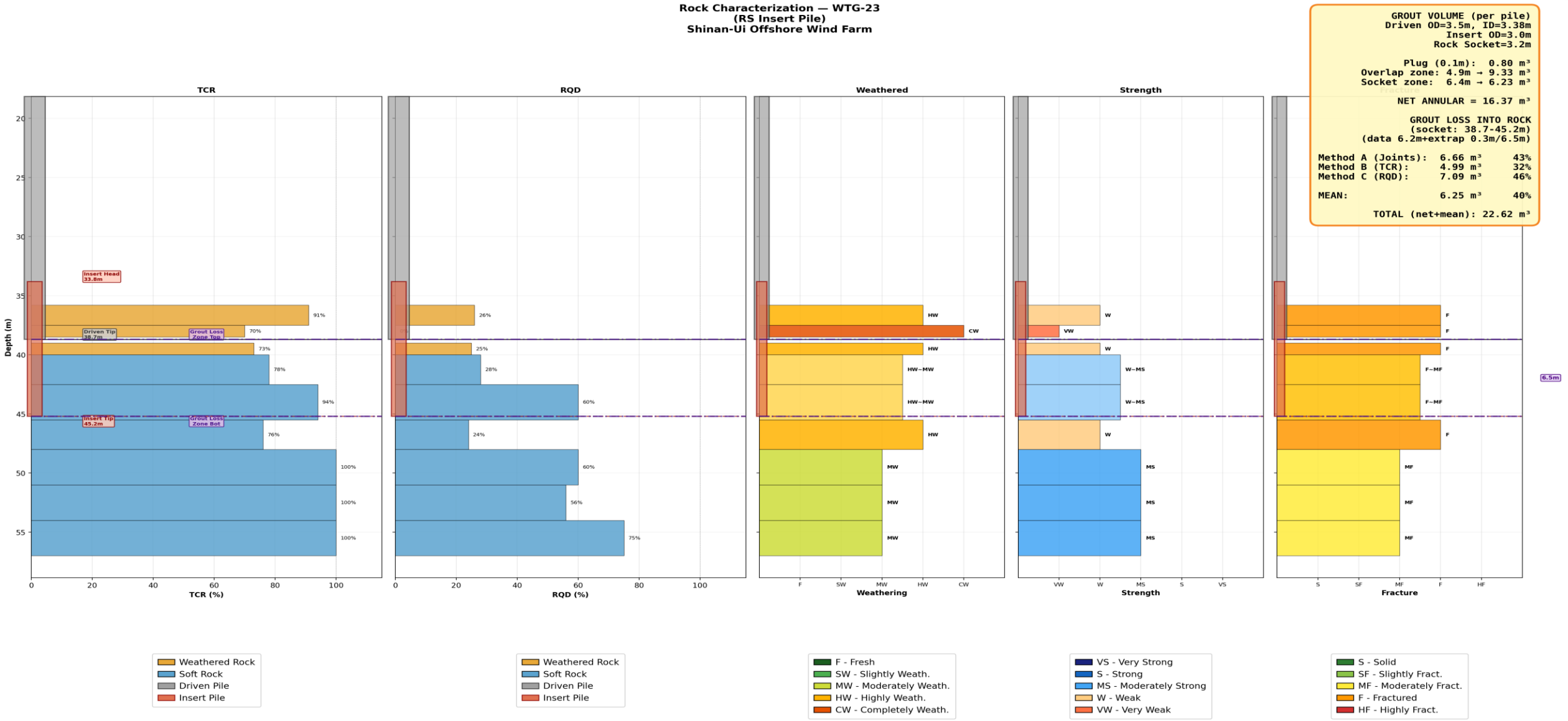
DRAFT — Calculations in Progress | Values capped at 50% max

Rock Characterization & Grout Volume — WTG-21



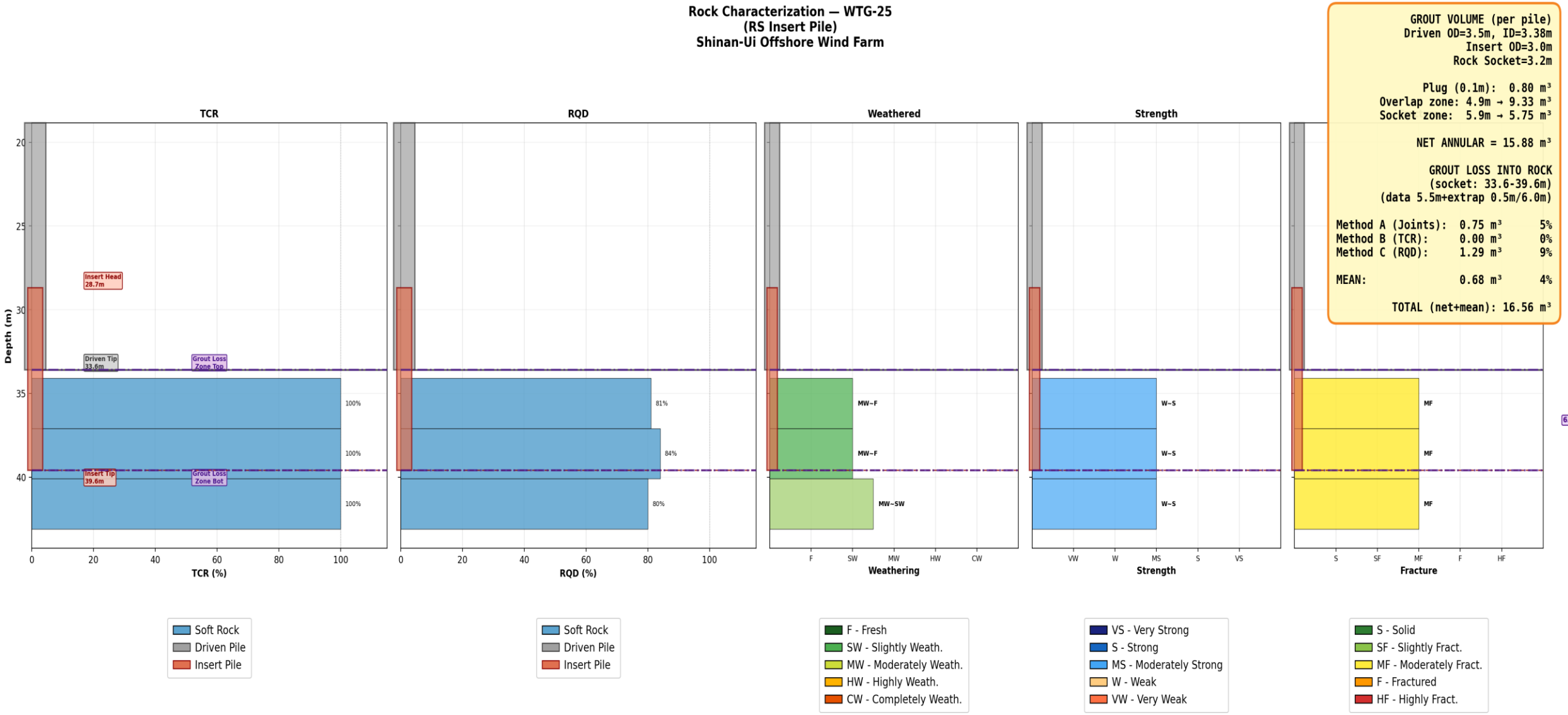
DRAFT — Calculations in Progress | Values capped at 50% max

Rock Characterization & Grout Volume — WTG-23



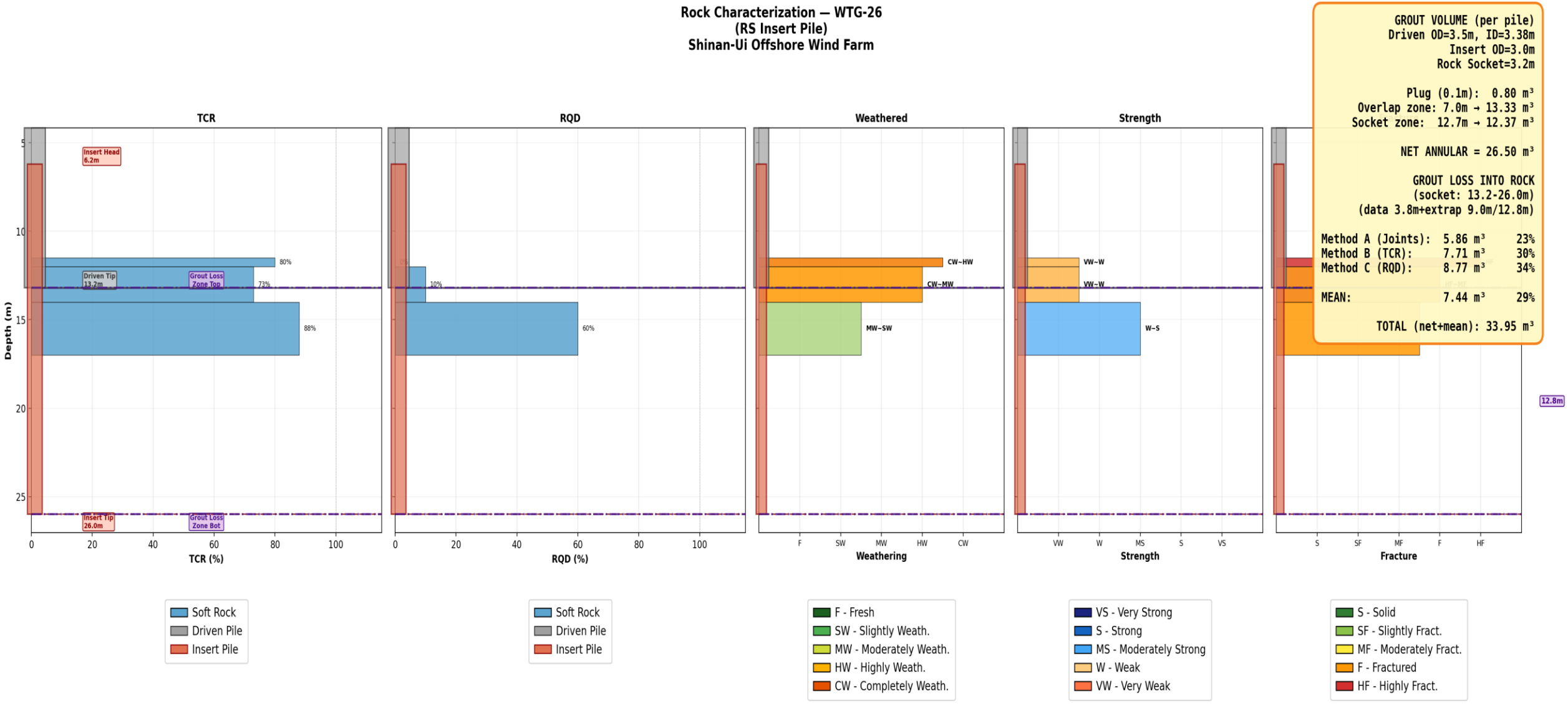
DRAFT — Calculations in Progress | Values capped at 50% max

Rock Characterization & Grout Volume — WTG-25



DRAFT — Calculations in Progress | Values capped at 50% max

Rock Characterization & Grout Volume — WTG-26




```
GROUT VOLUME (per pile)
Driven OD=3.5m, ID=3.38m
Insert OD=3.0m
Rock Socket=3.2m

Plug (0.1m):  0.80 m³
Overlap zone: 7.0m → 13.33 m³
Socket zone:  12.7m → 12.37 m³

NET ANNULAR = 26.50 m³

GROUT LOSS INTO ROCK
(socket: 13.2-26.0m)
(data 3.8m+extrap 9.0m/12.8m)

Method A (Joints):  5.86 m³   23%
Method B (TCR):     7.71 m³   30%
Method C (RQD):     8.77 m³   34%

MEAN:               7.44 m³   29%

TOTAL (net+mean): 33.95 m³
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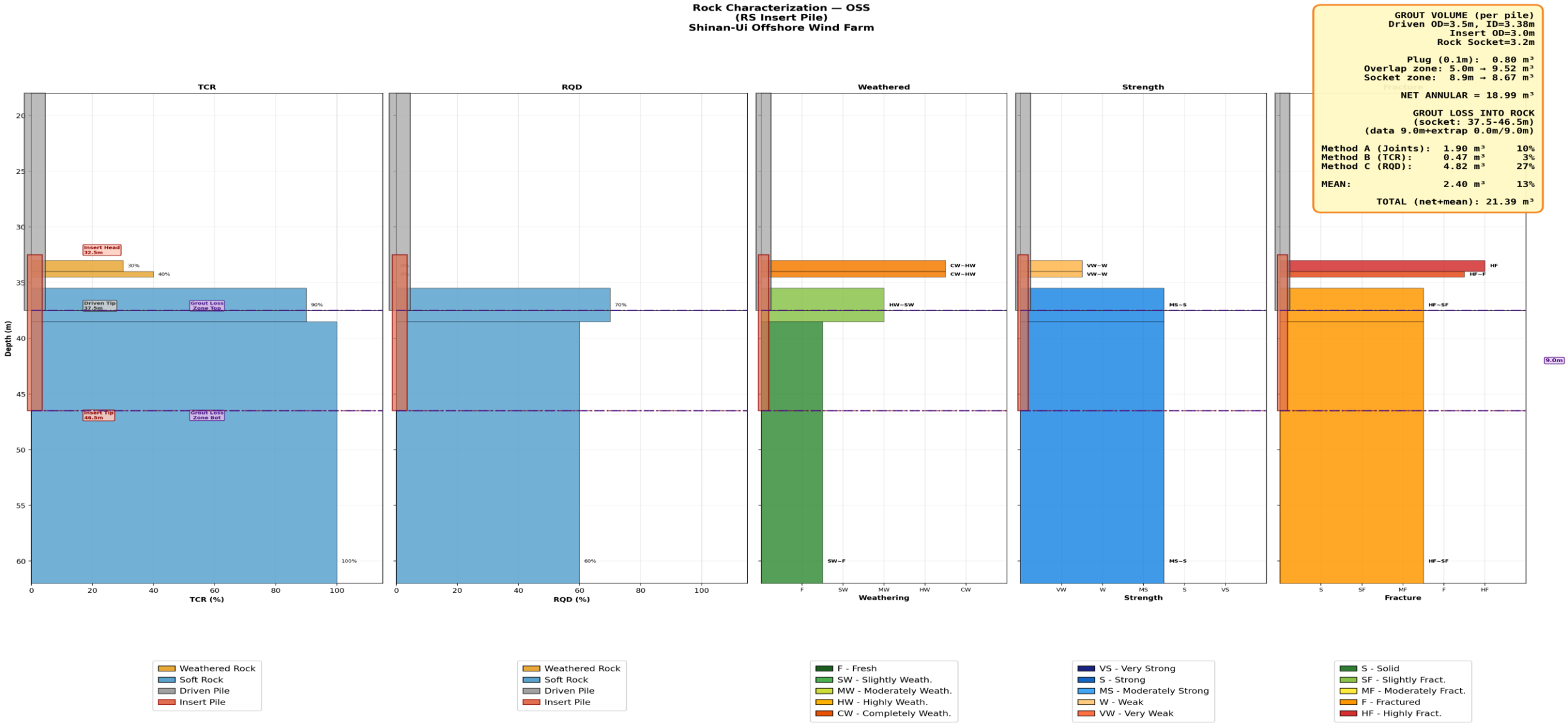
DRAFT — Calculations in Progress | Values capped at 50% max

Rock Characterization & Grout Volume — OSS



DRAFT — Calculations in Progress | Values capped at 50% max