Comparison of Performance of CFA Piles in Weak Rock with Eurocode Design Predictions

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Topics of Discussion

- Outline project description with details of ground conditions
- Review of pile design to EN 1997-1:2004 Eurocode Design Standards (EC7) and Irish National Annex
  - Demonstrate benefit of carrying out pile load testing
- Example of model pile design calculations used in piling specification
- Present interpreted results of instrumented pile load tests
- Compare performance of instrumented CFA test piles with predicted capacity based on preliminary pile designs to EC7
- Discuss how load tests were used to adapt pile design to account for construction difficulties associated with CFA piling
Project Description

- Windfarm consists of 18 No. 1.5 Mega Watt Turbines located on reclaimed tidal mudflats, in the south east of Ireland
  - Hub Height of 70 m and Rotor Diameter of 72 m

- Supported on 12 No. 600 mm diameter reinforced concrete continuous flight auger (CFA) piles
  - Outer Pile Characteristic Load
    - compression 1248 kN
    - uplift load of 568 kN
  - Inner Pile Load
    - Compression 568 kN
Ground Conditions – Overburden

- Overburden: Complex Stratigraphy
  - Recent estuarine deposits
    - very soft & soft silts,
    - loose to medium dense sands & gravels
    - N_{spt} : 5 – 7 from 0 – 5 mBGL
    - \omega_n 21 - 90\%, mean 47%  

  - Underlain by firm, stiff & v. stiff boulder clay and dense gravel
    - N_{spt} : 8 – 50 (ref)
    - \omega_n 7.2 – 52\%, mean 22%
Ground Conditions – Bedrock Geology

- Windfarm located on fault line between major geological groups
  - Pale grey limestones of the Wexford Formation
  - Conglomerates of silt and sandstone of the Kilag Formation

- Turbine locations could be divided into two groups based on the depth to rock in coreholes:
  - Group 1: Depth to rock was between 16 m - 22 m
  - Group 2: No competent rock was recorded in the rotary coreholes to depths of 31m to 45m
    - Poor quality rock, very little recovered core
    - Described as fragments of conglomerate or fault breccia
Ground Investigation - The Problem

- Limitations in the ground investigation left an unknown zone in the soil stratigraphy at 16 No. turbine locations
  - From 9.7 – 18.7 mBGL, 1 – 11.5 m in thickness
  - Highly weathered and highly fractured fault breccia / conglomerate rock? Or very dense gravel/stiff to hard boulder clay with boulders?

- Difficulty in classification & assignment of material properties to soil in unknown zone
  - Would it behave as a granular soil or as a very weak rock?
  - Would CFA piles be capable of penetrating the deposit to the required design depth?
Review of Pile Design to Eurocode 7 (EC7)

- Piling specification required pile design to be carried out in accordance with Eurocode 7 EN-1997:2004
  - Model calculations included with specification

- Limit State Design Philosophy
  - Combinations of partial factors applied to actions, soil parameters & resistances

- EC7 proposes 3 Design Approaches (DA)
  - DA specify combination of partial factors applied
  - RFA vs MFA
  - Required DA for design specified in National Annex (NA)

- Overall margin of safety determined from
  - Ratio of variable to permanent action
  - Method used to determine characteristic value of shaft friction and base resistance
Characteristics Pile Resistance

- Under EC7 values of characteristic resistance ($R_{c;k}$) derived from:
  - **Insitu testing:**
    - Static / dynamic pile load tests
    - Insitu tests (CPT or Nspt profiles)
    - $R_{c;k} = \min\{(R_c)_{\text{mean}} / \xi_1, (R_c)_{\text{min}} / \xi_2\}$
      - $\xi$ is a correlation factor, value varies according to number of tests
  - Or by calculation alone:
    - $R_{c;k} = A_b q_{b;k} + \sum A_{s;i} \times q_{s;i;k}$

- Design resistances (and actions) derived by applying partial factors to characteristic resistances and actions

- Values of correlation factors, and partial factors depend upon pile type & design approach adopted
  - Vary for a country’s National Annex
Irish NA permits any of the 3 Design Approaches to be adopted:
- Unique
- Design Approach at the discretion of designer / client

- Pile design from static and dynamic pile load tests
  - Adopts recommended correlation factor ($\xi$)
  - Adopts recommended partial factors

- Pile design from Nspt or CPT profiles
  - Recommended correlation factors increased by a factor of 1.5
  - Adopts recommended partial factors

- Piles designed by calculation alone
  - Partial factors increased by a factor of 1.75
Comparison of F.O.S. under Irish National Annex

- Adopting Design Approach 1 for CFA piles, with load considered entirely as a variable load:
  - Characteristic Pile resistance verified by 2 pile load tests
    - Equivalent F.O.S. in compression = 2.4, in tension = 2.7

- Characteristic pile resistance from 10 profiles from CPT or $N_{spt}$
  - Equivalent F.O.S. in compression = 3.4

- Characteristic pile resistance from calculation alone
  - Equivalent F.O.S. in compression = 3.2

- Under EC7 carrying out a small No. of pile load test allows the adoption of significantly more favourable correlation and partial factors
Calculation of Pile Resistance for Preliminary Pile Designs

- **Fine grained soils:**
  - Shaft resistance: \( R_s = \alpha \cdot c_u \) kPa
    - \( \alpha \) = adhesion factor
  - End bearing: \( = 9 \times c_u \)

- **Granular soils:**
  - Shaft resistance: \( R_s = K_0 \cdot \sigma_v' \cdot \tan \delta \)
    - \( K_0 = 1 - \sin \phi_k' \)
    - \( \sigma_v' = \) vertical effective stress
    - \( \delta = \) angle of shearing resistance between pile and the granular material. (\( \delta = \phi_k' \) used in design)
  - End bearing resistance on granular soils conservatively limited to bearing resistance of weak rock UCS = 1000 kN/m²

- **Rock:**
  - Shaft resistance: \( R_s = \alpha_R \cdot \sigma_C \)
    - \( \alpha_R = 0.1 \) to \( 0.15 \) for highly fractured to weak rock
    - \( \sigma_C = \) unconfined compressive strength of rock
  - Ultimate End bearing in rock taken as \( 9 \left( \sigma_C / 2 \right) \) kPa for competent rock
Piling Contractor Proposed Design

- 2 preliminary model pile designs submitted with specification
  - T9: Full soil stratigraphy known, pile length = 22.5 m
  - T17: Zone of unknown material, pile length = 20.1 m to 23.0 m
    - No information on ground conditions from 11.0 – 18 m

- Piling contractor opted to adopt an equivalent factor of safety in design

- Proposed shorter pile lengths
  - Based on previous experience used higher values
    - Skin friction in granular soils
    - Adhesion in cohesive soils
    - End bearing

- Contractor design assumption to be verified by preliminary load tests at T9 and T17
Test Pile Details – Strain Gauges

- Test piles fitted with vibrating wire strain gauges
  - Strain gauges attached to reinforcing cage and centralised bar
  - 3 strain gauges at 6 No intervals, welded to cage and bar
    - Gauges positioned at 120 Degrees
    - Determine the distribution of axial load with depth & at the pile tip
Instrumented Test Pile Results

- **T9 Compression Test**
  - Loaded to 3,770 kN
    - 2,792 kN in shaft resistance
    - 578 kN tip resistance
  - Load profile untypical of expected results
    - Strain gauge malfunction

- **T17 Compression Test**
  - Loaded to 3,770 kN
    - 2,985 kN in shaft resistance
    - 385 kN tip resistance
  - Profile consistent with anticipated results
Comparison with Calculated Preliminary Pile Resistances

- T9 measured shaft resistance in overburden unrealistic
  - Strain gauge malfunction
  - Disregard results

- T17 preliminary design assumptions significantly underestimated shaft resistance
  - Mobilised shaft resistance
    - 0 – 4 m 30 kPa
    - 4 – 10 m 56 kPa
    - 10 – 18 m 160 kPa

- Mobilised shaft resistance most closely estimated in cohesive soils

- Least accurately estimated in sand & gravel
  - $K_o = 1.7$ reasonable approx. of mobilised resistance

- Assigning properties of very weak rock to unknown zone appropriate
**Construction Difficulties**

- CFA rig had difficulty in penetrating the fault breccia / dense gravel
  - Installed piles up to 4.5m shallower than design lengths
  - In shorter piles uplift was satisfied by verified increased adhesion factors
  - Necessary to justify increased end bearing resistance in granular soils
    - Originally conservatively limited to bearing resistance of weak rock with UCS = 1000 kN/m²
    - \( R_{bcal} = A_b \sigma'_v N_q' \)
    - Published values of \( N_q' \) ranging from 123.5 - 325

- Where uplift or compression was not satisfied in individual piles in some cases sufficient capacity could be justified through pile group behaviour

- Where the installed lengths could not be justified necessary to carry out additional pile tests
Conclusions

- Design to EN 1997-1:2004 Eurocode 7 (EC7) adopts limit state design philosophy in which overall factor of safety determined by
  - Ratio of variable to permanent action
  - Method used to calculate pile characteristic pile resistance

- Assuming $K_s = K_0$ significantly underestimated the shaft resistance of the pile in the granular soils
  - A value of $K_s = 1.7$ gives close approximation

- Published values of $\alpha$ give reasonable estimates of pile resistance

- Material property most appropriate to soil in unknown zone was that of a highly weathered weak rock

- The resulting practical benefits to carrying out pile load testing which the Irish National Annex allow have been demonstrated
  - Lower correlation & partial factors
Summary

- Outlined geotechnical issues relating to the Richfield Windfarm
  - Difficult ground conditions
  - Limited ground investigations
- Reviewed pile design to EN 1997-1:2004 Eurocode Design Standards (EC7)
  - Irish National Annex
  - Demonstrate benefit of carrying out pile load testing
- Provided example of model pile design calculations used in piling specification
- Presented interpreted results of instrumented pile load tests
- Compared performance of instrumented CFA test piles with predicted capacity based on preliminary pile designs
  - Discussed the accuracy of methods of calculating pile resistances in granular & cohesive soils
- Discussed how load tests were used to adapt pile design to account for construction difficulties associated with CFA piling