

Advanced modelling and testing for high-precision telescope foundations

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ABSTRACT: The Square Kilometre Array (SKA) project, an international effort to build the world's largest radio telescope array, requires exceptional foundation performance to ensure precise antenna alignment. This paper presents the design methodology, validation, and construction procedures for the SKA telescope foundations in the Meerkat National Park, South Africa. The design was governed by stringent criteria for settlement, stiffness, and residual performance under different loading conditions. From a global geotechnical ground model, five distinct ground models were developed, each representing varying rock depths. Finite Element Modelling using Plaxis 3D was employed to simulate pile group behaviour, with sensitivity analyses confirming small-strain shear stiffness as the dominant factor influencing settlement. Design checks included pile/socket length selection, factor of compliance assessments, and geotechnical capacity evaluations. Full-scale pile load tests validated the finite element modelling predictions, with measured vertical and lateral displacements aligning closely with modelled results. Corrections for seating errors and temperature effects ensured accurate interpretation. An analysis of varying rock head levels within the same base was conducted, and recommended to ensure all piles were the same length. The adaptable design and rigorously validated foundation design ensure the long-term stability of the SKA telescopes, which support reliable telescope performance under all expected loading scenarios.

KEYWORDS: Square Kilometre Array, Finite Element Modelling, Stiffness Compliance, Pile Load Testing, Load-displacement.

1 INTRODUCTION

The Square Kilometre Array (SKA) project is an international scientific initiative to construct the world's largest radio telescope array, with sites in the Northern Cape, South Africa, and Western Australia. The scientific objectives of the SKA demand an unprecedented level of precision in telescope alignment and stability. Even minor settlements or rotations of the antenna's foundation can result in significant misalignments, directly impacting the quality and reliability of the astronomical data.

This paper presents the results of full-scale pile load tests conducted to validate the finite element modelling (FEM) predictions, as detailed in the Square Kilometre Array Pile Foundation Design Methodology (Pitt, Van der Merwe, & Barratt, 2025). As rock head levels differed on site within the same base, additional comparative analysis of pile length strategies, Equal Socket–Unequal Length (ES-UL) versus Unequal Socket–Equal Length (US-EL), was conducted to optimise construction consistency and performance across varying ground conditions.

Figure 1 shows the existing telescopes behind the drilling rig and concrete truck.



Figure 1. Existing telescopes and drilling rig at the Meerkat National Park.

2 BACKGROUND AND IMPORTANCE OF SETTLEMENTS

The design of the SKA telescope foundations is governed by exceptionally stringent settlement and stiffness criteria. The maximum allowable permanent plastic displacement under operational loads is limited to 20% of the total displacement,

and the pile cap must not exceed stringent displacement limits under axial, lateral, tilting, and torsional loading for both operational and survival load cases. Stiffness limits were imposed on all loading scenarios.

3 SITE LOCATION AND GEOTECHNICAL INVESTIGATION

The SKA site is located in the remote Meerkat National Park, Northern Cape, South Africa. Due to the vast area and number of telescope positions, detailed geotechnical investigations at every telescope location were not feasible. Instead, a comprehensive global ground model was developed by Zutari, using rotary core boreholes, percussion holes, test pits, and Continuous Surface Wave (CSW) tests at locations across the greater site.

Based on this data, five generalised ground profiles, referred to as Ground Models (GMs), were defined, each representing a specific range of rock depths. Each telescope base was assigned to an appropriate ground model based on the global ground model. The design heavily depended on the stiffness of the soil and rock layers; therefore, the lowest measured stiffness values within each model were used as the basis for design to ensure a conservative approach.

The approximate rock depths throughout ground models 1 to 5 varied from 2.0 m to 10.5 m, and their respective stiffness values (G_0) are plotted in Figure 2. No groundwater was expected for these ground models.

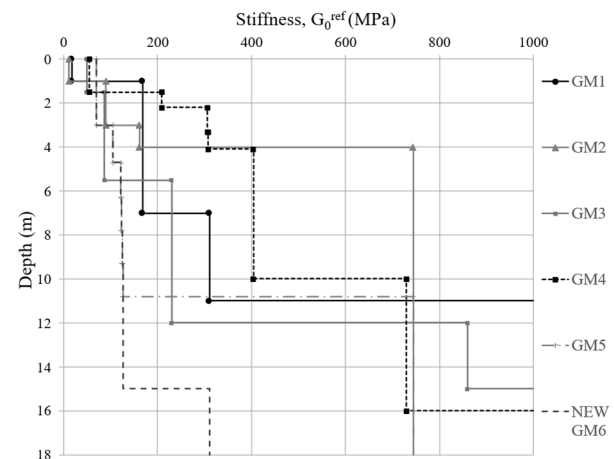


Figure 2. G_0 plot for all ground models.

4 INTRODUCTION OF A NEW GROUND MODEL

A new ground model (GM6) was introduced during construction when unexpected ground conditions were encountered at two telescope positions with bedrock at 15m and groundwater presence. GM6 required temporary cased augers as opposed to the typical open-hole auger pile used on the original 100-plus bases. A revised design was undertaken as more reliance was to be placed on soil-pile side shear capacity compared to other ground models, potentially increasing settlement. The design, which included longer pile lengths, was reviewed and adopted on-site for the two positions.

5 DESIGN REQUIREMENTS AND LOADING

The SKA telescope foundations were required to meet strict design criteria to ensure precise telescope operation and prevent misalignment. The SKA telescope foundations were designed to meet the following key requirements:

- Design Criterion 1 (DC 1): The first criterion was stiffness limits from which factor of compliance (FoC) ratios were calculated.
- Design Criterion 2 (DC 2): Permanent plastic deformations under operational loads were limited to 20% of the total displacement experienced under full operational load.
- Design Criterion 3 (DC 3): Breakdown of the stiffness response after survival load cases had to be negligible.

The design requirements are illustrated on the load-displacement curve in Figure 3.

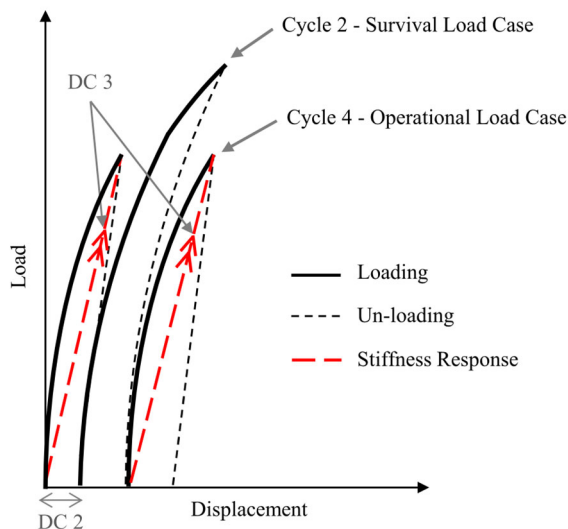


Figure 3. Load-displacement curve with design criteria illustrated.

To address these requirements, the design considered four load types (axial, lateral, torsional and moment), which included four load cases:

1. Operational Load Case: Typical service conditions, including self-weight and live loads.
2. Survival Non-Stow Load Case: Extreme wind or environmental events with the antenna in its most vulnerable position.
3. Survival Stow Load Case: Extreme events with the antenna in a stowed (protected) position.
4. Earthquake Load Case: Factored combinations to ensure structural integrity during seismic events.

6 FINITE ELEMENT MODELLING

Finite element modelling (FEM) was central to the SKA foundation design, enabling precise prediction of the 8-pile group behaviour under complex loading and ground conditions (Pitt, Van der Merwe & Barratt, 2025). Plaxis 3D was used to simulate the pile group, pile cap, and surrounding soil and rock, as shown in Figure 4.

Piles were modelled using embedded beam elements rather than volumetric elements. While volumetric elements offer a more detailed representation, they produce less conservative results and increased modelling time. Embedded beams provided a simplified yet suitably accurate approach for design verification. Hardening Soil model with small strain stiffness (HSS) was adopted to account for stiffness degradation under increasing shear strain. This was critical due to strict displacement tolerances. Rock properties were modelled using Mohr-Coulomb. Sensitivity analysis showed that small-strain shear stiffness (G_0^{ref}) was the dominant factor controlling settlement and shear strain. FEM results were validated against pile load test data discussed in Section 8.

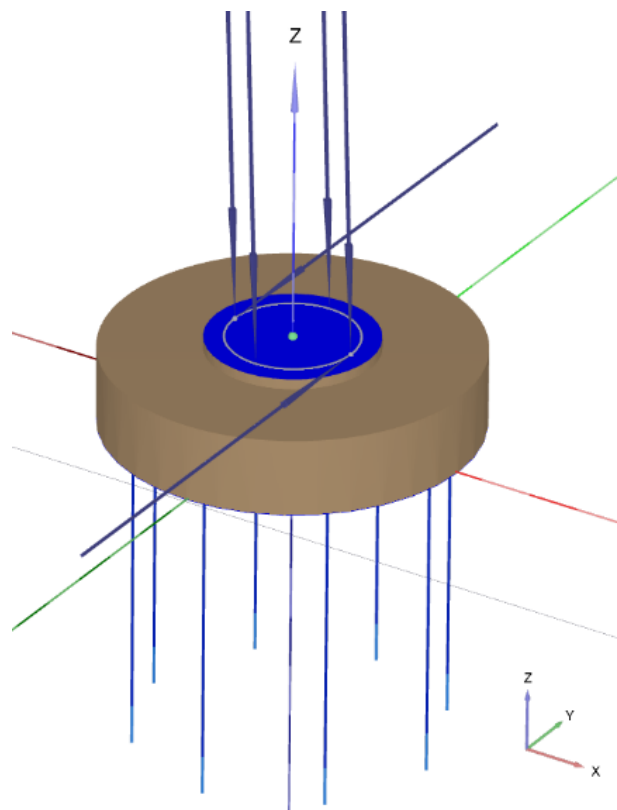


Figure 4. Finite Element Model (Pitt, Van der Merwe & Barratt, 2025).

7 DESIGN STEPS AND METHODOLOGY

The design methodology for the SKA telescope foundations combined analytical hand calculations with advanced numerical modelling and a series of rigorous design checks to ensure compliance with the strict design requirement criteria. The main steps are outlined below:

7.1 Design Checks

A series of design checks was carried out to ensure the SKA foundations met all settlement, stiffness, and capacity requirements. Each check addressed a specific aspect of performance, from pile length selection to structural integration with the telescope.

7.1.1 Check 1: Pile/Socket Lengths

For vertical loading, a single pile was analysed in the FEM to determine settlements and shaft behaviour. For horizontal loading, the full pile group and cap were modelled due to fixed-headed conditions.

A key part of this check was evaluating the shear strain along the pile shaft. The shear strain modulus ratio (G/G_0) was calculated and plotted for each load case on the curve derived by Díaz-Rodríguez (2009). Two thresholds were used, namely:

- A 0.72 ratio to ensure plastic deformation remains below 20% under operational loads, and
- A 0.55 ratio to ensure no significant stiffness breakdown occurs after the survival load case.

Socket lengths and pile diameters were selected to ensure these criteria were met. If the calculated ratios were not achieved, the pile length or diameter was increased accordingly. By meeting these thresholds, both the allowable displacement and the requirement for no stiffness breakdown after survival loading were satisfied in this step (i.e. Design Criteria 2 & 3 were met). The lateral capacity was also analysed using the above ratios.

7.1.2 Hand Calculations

Hand calculations were performed to independently estimate both vertical and horizontal pile displacements, providing a check on the FEM results. For vertical displacements, standard equations were used to calculate elastic shaft compression and socket displacement for piles socketed into rock. Horizontal (lateral) displacements were estimated using established methods that relate pile head movement to applied load and soil stiffness. These calculations ensured that the results from the FEM were within reason.

Settlements from the finite element model were compared to hand calculations for both vertical and horizontal displacements, ensuring the design remained conservative and robust.

7.1.3 Check 2: Factor of Compliance (FoC)

After establishing the required pile length, the full pile group and cap were modelled to check the Factor of Compliance (FoC) for each of the four load cases. The FoC is the ratio of the calculated foundation stiffness to the required stiffness for axial, lateral, tilting, and torsional loading. A minimum FoC of 1.0 was required, with a target of 1.25 to account for any additional movements in the telescope's bolt cage connection. Once all FoCs were adequate, check 3 commenced. Check 1 always governed the design, with all FoCs meeting the requirement with the pile length derived in Check 1.

7.1.4 Check 3: Geotechnical Capacity

Geotechnical capacity was assessed for the required pile length determined in Checks 1 and 2. Capacity was based solely on shaft and socket shaft resistance. Base resistance was intentionally ignored to avoid overestimating performance. End bearing requires significant displacement to develop, or drilling spoil may remain at the base of the socket. Utilisation factors were determined for each pile design, and pile lengths were adjusted for different rock strengths by correlating these utilisation factors. This approach enabled quick, on-site adaptability to varying rock conditions without delay, with simple tables provided to HHO Consulting Engineers' on-site personnel to align different rock strengths to socket lengths.

8 PILE LOAD TESTING: RESULTS AND INTERPRETATION

To validate the accuracy of the FEM assumptions used in the design of the telescope foundations, two pile load tests were undertaken on site. The measured settlements from these tests were compared against the predicted settlements derived from FEM analysis using a single embedded beam element and a point load at the pile head. This section provides an overview of one of the two full-scale pile load tests conducted. Pile Load Test 1 (GM1, 750 mm pile) is discussed; however, the second Pile Load Test 2 (GM3, 1050 mm pile) provided similar conclusions. The testing and interpretation of Pile Load Test 1 (PLT1) are discussed below, which together validate the design.

8.1 Data Quality, Corrections, and Modelling Validation

A key aspect of interpreting pile load test results is understanding the expected shape of the load-displacement curve. For vertical loading, the ideal response is typically hyperbolic: an initial steep (linear) segment representing "elastic" pile and soil behaviour, followed by a gradual flattening of a tangent slope as plastic deformation and soil yielding occur at higher loads. Figure 5 shows a typical load-displacement curve.

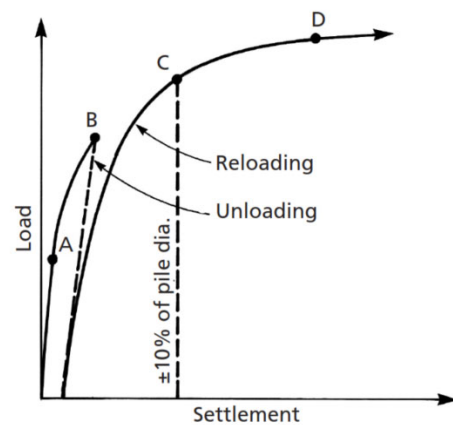


Figure 5. Typical pile load-displacement curve (Byrne et al, 2019).

When any portion of a load-displacement curve shows a shallower tangent slope than that at a higher load, it indicates that there may be minor seating or bedding-in effects, which are not representative of the true pile settlement behaviour. Deviations from this expected curve, such as abrupt changes in gradient or anomalous offsets, can indicate data quality issues, seating errors, or instrumentation effects. Recognising and correcting for these factors is essential for reliable interpretation and for validating the accuracy of the FEM predictions against measured results. With the maximum displacement measured during the testing of only 0.7 mm, seating errors can easily occur.

The following measures were implemented during the review of pile load test data to accurately determine the true pile displacement curve:

- Seating Error Curve Alignment: In some cases, the curve was adjusted to ensure that the tangent slope was never steeper with increased load.
- Temperature Effects: Corrections for elastic shortening and temperature were applied to ensure data accuracy.
- Strain Gauge Usage: When linear variable displacement transducer (LVDT) readings showed seating errors, the strain gauge data was used to validate the displacement using Fellenius' method as discussed in Van der Merwe and Pequeno (2014).

8.2 Test Setup and Instrumentation

The test setup included:

- A test pile (750 mm at Pile Load Test (PLT) 1, 1050 mm at PLT 2) instrumented with seven vibrating wire strain gauges along the shaft and a Durham Geo Slope Indicator (DGSI) inclinometer (Figure 6).
- Four tension (anchor) piles for vertical reaction and a dedicated reaction pile for lateral load testing.
- Calibrated 200-ton jack to apply load.
- Four LVDTs for pile head displacement and dataloggers. The LVDTs were mounted on glass surfaces to ensure high precision and to try to avoid even the smallest seating errors, such as those caused by dust particles or slight misalignments.

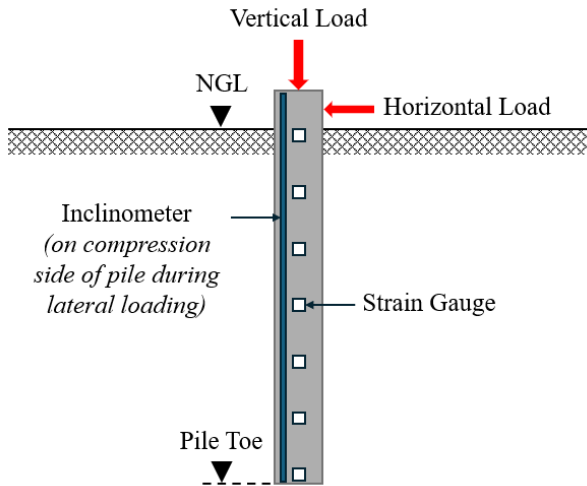


Figure 6. Test setup with instrumentation.

8.3 Test Procedure

Each pile was subjected to a sequence of static maintained load cycles as shown in Table 1:

Table 1. Load Cycles.

Cycle	Load case	Load
1	Vertical operational	350 kN
2	Vertical survival	800 kN
3	Horizontal survival	100 kN
4	Vertical operational repeated	350 kN

LVDTs were zeroed at the start of each cycle; strain gauges and inclinometers were referenced to initial readings. Data was collected for both loading and unloading phases.

8.4 Vertical Load Test

The test pile reviewed in this paper was conducted on a 750 mm diameter pile at a telescope position classified as Ground Model 1. The profile for GM1 is discussed in Pitt, Van der Merwe & Barratt (2025), which shows rock at 7.0 m below ground level. The test pile has a 5.0 m socket in very soft rock, resulting in a 12.0 m pile.

8.4.1 Comparison of Predicted vs Measured Displacements

Figure 7 shows the comparison between the FEM predicted and measured displacements at 350 kN (operational load). The FEM predicted a displacement of 0.235 mm, while the test recorded 0.392 mm (Cycle 1) and 0.417 mm (Cycle 4).

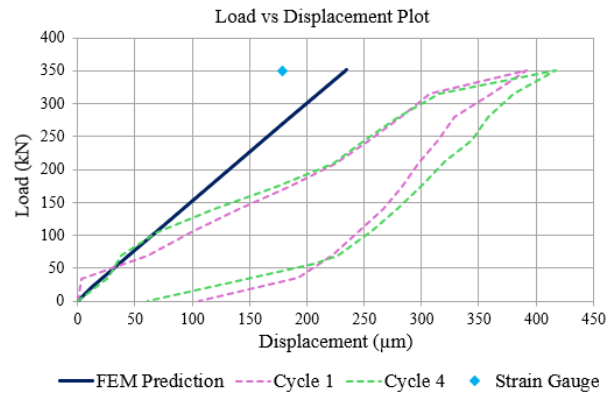


Figure 7. Load-displacement plot for the test pile at operational load using LVDTs.

However, after correction, the true displacements are closer to 0.325 mm and 0.350 mm for Cycles 1 and 4, respectively. Figure 8 shows the better alignment to the prediction by the FEM. The correction shifts the curve left to account for the seating error located between 100 kN and 200 kN, by conservatively extrapolating the slope between 200 kN and 300 kN downwards to 0 kN.

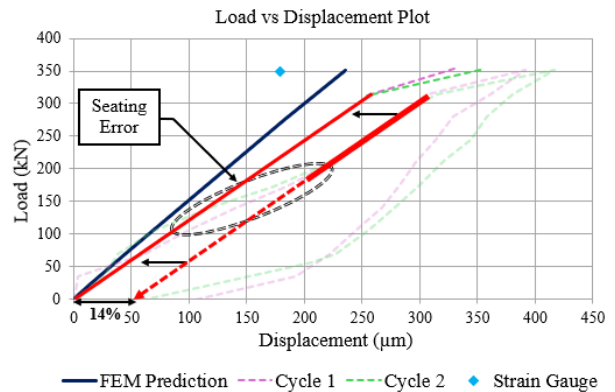


Figure 8. Corrected load-displacement plot.

8.5 Design Criteria Checks

The FoCs of Cycles 1 and 4 were determined by back calculation to be 1.58 and 1.65, respectively, which are greater than 1.25 and therefore meet DC1. The uncorrected permanent plastic deformation for cycle 4 is 14% (shown in Figure 8), indicating that the 20% criterion has been met (DC2).

For the final design check, comparing the stiffness values for Cycle 1 and Cycle 4, the stiffness values are 1 077 kN/mm (350/0.325) for Cycle 1 and 1 000 kN/mm (350/0.350) for Cycle 2. These stiffness values are very similar (within 7% of each other), indicating that there is negligible stiffness breakdown after survival loading, meeting DC3.

In comparison, using the strain gauge data, the displacement was 0.179 mm. This confirms that there were seating errors in the LVDT results, and performing design criteria checks on the LVDT results is considered conservative.

Figure 9 presents the comparison at 800 kN (survival load) of the FEM predicted and measured displacements. The FEM predicted 0.575 mm, and the test measured 0.687 mm in Cycle 2 (uncorrected). Using the same approach used for Cycle 1 to correct the seating errors, the corrected displacement is closer to 0.610 mm.

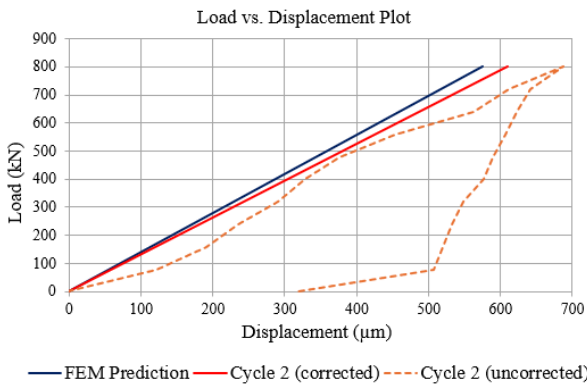


Figure 9. Load-displacement plot for the test pile at survival load using LVDTs.

8.6 Lateral Load Test

The lateral load test was performed to assess pile response to horizontal loading under survival conditions (100 kN). As the test pile was single, the test setup created a free-headed pile condition, where the pile head was not in a pile group but loaded directly via a reaction system. This is more conservative than the fixed-head condition of the actual foundation and results in greater lateral displacements.

To accurately compare the test results with design predictions, the FEM was run as a single, free-headed pile, matching the test configuration. The predicted FEM displacement (0.60 mm) and measured displacements (0.50 mm & 0.47 mm) for the maximum horizontal load of 100 kN are illustrated in Figure 10:

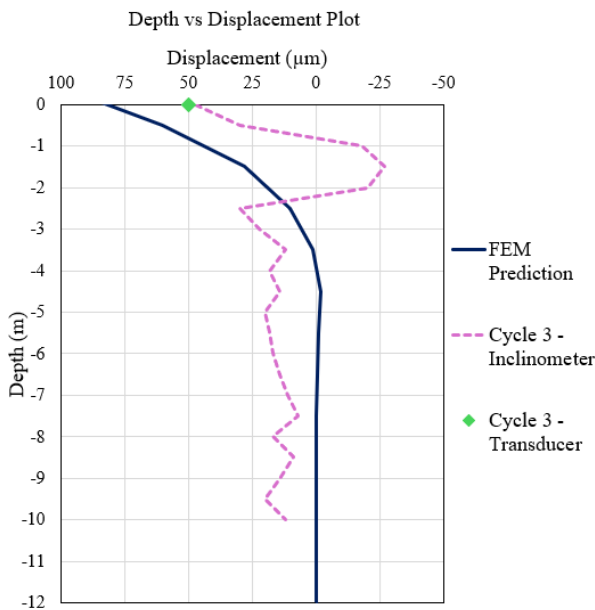


Figure 10. Depth vs displacement plot for the horizontally loaded test pile.

8.7 Pile Load Test Summary

The full-scale vertical pile load tests confirm that measured displacements closely match the FEM predictions. Lateral load tests, modelled as free-headed piles, also showed strong agreement. Data corrections ensured accuracy, and all results demonstrated compliance with the strict design criteria.

9 VARIABLE PILE LENGTH ANALYSIS AND CONSTRUCTION PROCEDURES

9.1 Initial Approach and Further Analysis

During the early stages of construction, pile lengths were determined individually by an HHO on-site geotechnical engineer. This approach involved assessing the rock strength and level encountered during drilling at each pile location and adjusting the socket length accordingly. While this method allowed for tailored solutions per pile, it introduced pile length variability within bases.

To evaluate the impact of varying rock head levels on pile performance, a detailed finite element analysis was conducted. The study considered GM1 and GM3 at rock head differences of 0.5 m, 1.5 m, and 2.5 m across the same base. Two construction scenarios were assessed:

1. Equal Socket-Unequal Length (ES-UL): Piles with consistent socket lengths but varying total lengths due to varying rock head levels. (Figure 11).
2. Unequal Socket-Equal Length (US-EL): Piles with equal total lengths but varying socket depths. (Figure 12)

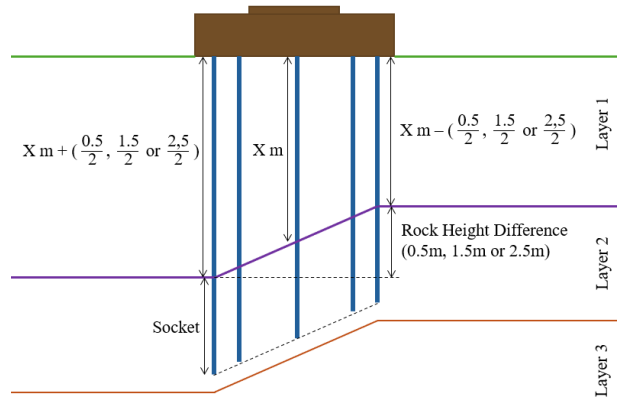


Figure 11. Equal Socket-Unequal Length (ES-UL).

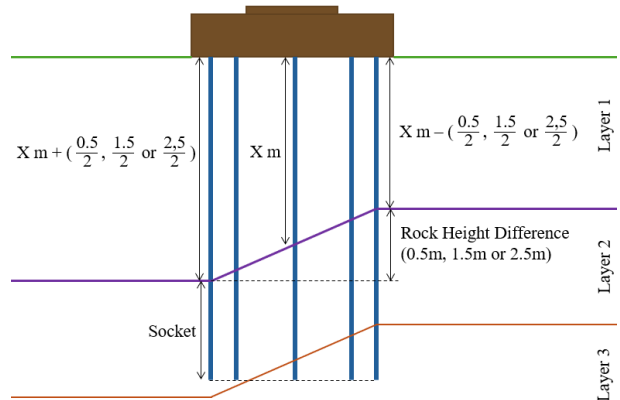


Figure 12. Unequal Socket-Equal Length (US-EL).

The worst load condition, survival non-stow, was used in the FEM as it would provide the most critical results. The moment and lateral load combination were applied to the bases in three different directions to ensure that the worst load direction was modelled. The torsion and axial load remain unchanged. The full loading (axial, lateral, moment and torsion) was applied simultaneously. Figure 13 shows the different directions in which the moment and horizontal loads were applied in relation to the rock head difference. The different load directions are denoted as D1, D2 and D3.

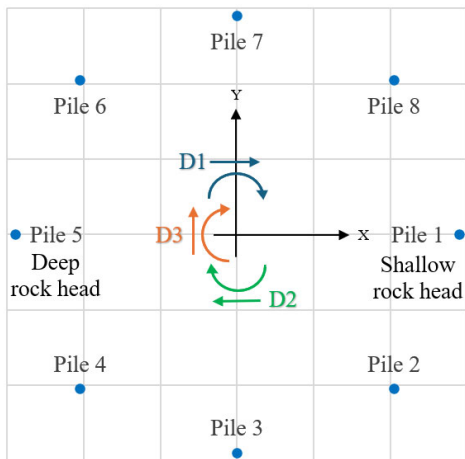


Figure 13. Applied load directions D1, D2 & D3.

If a pile is shorter than another within the same pile cap, it will attract a greater portion of the lateral load. This, in turn, induces larger shear strains in the surrounding soil mass near the shorter pile, as illustrated in Figure 14. Shorter piles loaded to the same axial load compared to deeper piles, with the same socket length, will have smaller elastic compression. These shorter piles could, therefore, attract more axial load.

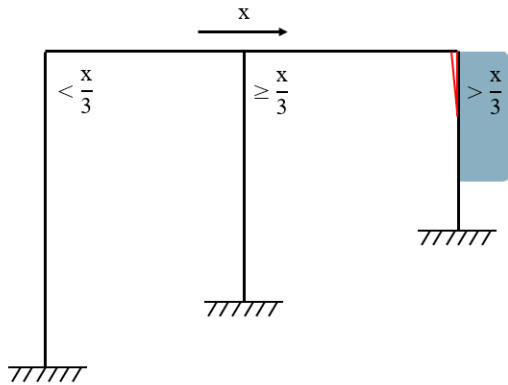


Figure 14. Horizontal load distribution for unequal piles.

The analysis reviewed shear strain in the soil and rock, as well as structural load distribution under survival non-stow conditions, to determine compliance with the design criteria. The following sections present the findings and the resulting recommendations for construction.

9.2 Impact of Rock Head Variation on Pile Performance

The FEM analysis revealed that varying rock head levels across a single base can affect the design. In the ES-UL configurations, shorter piles attracted more load and therefore developed higher shear strains in the adjacent soil and rock, particularly in ground profiles where rock is closer to the pile head. This increased the risk of stiffness degradation and uneven load distribution. In contrast, the US-EL configurations, where all piles were drilled to the same depth, showed slightly better performance, although they still resulted in an overall decrease in performance compared to an idealised case of equal length and equal sockets.

9.3 Structural Capacity and Reinforcement

Structural load plots (M-N diagrams) for both GM1 and GM3 showed that pile reinforcement requirements remained sufficient even under increased axial and lateral loads caused by rock head variation. This can be expected as the piles were loaded to very small shaft stiffnesses.

9.4 Recommendation and Implementation

Although both ES-UL and US-EL approaches were found to be compliant, the analysis recommended adopting the US-EL method for all future bases. This involves drilling at four pile positions at each quadrant of the base and installing all piles to the maximum depth required from the four piles drilled. This approach ensured better consistency in relation to stiffness, simplified design verification, and aligned with the original design philosophy, although it slowed down construction.

10 CONCLUSIONS

This paper presented the design methodology, pile load testing results and construction procedures for the SKA telescope foundations. The design was validated against stringent design criteria for stiffness, displacement, and residual performance under operational and survival load conditions.

Pile load testing confirmed that both vertical and lateral displacements were within acceptable limits and aligned reasonably well with FEM predictions. The expected shape and behaviour of pile load-displacement curves were used to guide interpretation and identify deviations from measured results at these small displacements due to factors such as seating effects.

Further analysis of varying rock head levels, within the same base, demonstrated that while both ES-UL and US-EL approaches met design requirements, the US-EL method offered greater consistency and predictability across bases. The recommendation was to drill all piles to the same length.

This adaptable and validated design supports the long-term stability and precision required for the Square Kilometre Array's scientific mission, ensuring that the foundations will perform reliably under all expected loading conditions.

11 ACKNOWLEDGEMENTS

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