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Design of stiffness sensitive foundations for large telescopes for the Square Kilometre Array project

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ABSTRACT: The Square Kilometre Array (SKA) project is an international collaboration to build the world's largest radio astronomy telescope, giving scientists the ability to map the universe with more sensitivity and speed, and over greater distances. The telescope comprises a collection of telescopes spread over a large area. For each dish to accurately point into space, the dish foundations are required to meet strict stiffness and movement requirements. Compliance of these requirements in design and construction was critical. The foundation performance is driven by stiffness and this paper details the approach undertaken to design these sensitive foundations. A strain-based design approach was applied utilising numerical modelling of the foundation to assess resultant stiffness of the system. The design used a strain-related modulus degradation across the complete ground profile taking advantage of the "activated" strain condition of the ground within the loading zone. The vastness of the site coupled with a large number of dish foundations created additional complexity and risk. Due to the large number of foundations and project timelines, a design assessment of each dish was impractical and unrealistic, this was also coupled with data not being available at each position. This paper also details the use of a digital 3D geological model coupled with the Total Engineering Geological Approach (Fookes et al, 2000, 2008) to derive representative design ground models, decreasing the number of design assessments. The paper also details the verification approach utilised to demonstrate compliance to long-term residual performance criteria.

KEYWORDS: Piling, numerical modelling, strain-based design, telescope foundations, stiffness degradation

1 INTRODUCTION

Upon completion, the Square Kilometre Array (SKA) telescopes – under construction in South Africa and Australia - will be the world's largest radio astronomy telescope arrays, giving scientists the ability to map the universe with more sensitivity and speed, and over greater distances. Cutting-edge technology and innovation are required to make this project a reality, as it tests the limits of engineering and science. The SKA Observatory (SKAO), an intergovernmental organisation which brings together nations from across the world, is one observatory, operating two telescopes, on three sites. The SKAO's mid-frequency telescope, known as SKA-Mid, is being constructed in the Northern Cape of South Africa where the core is located between the towns of Carnarvon, Williston, Brandvlei and Vanwyksvlei with three spiral arms extending over 100 kilometres beyond.

The existing 64 dishes of the MeerKAT radio telescope will be integrated with 133 new radio dishes, which together will form the SKA-Mid array. The project was developed in phases. The MeerKAT Extension project (first phase), a collaboration of SARAO (South African Radio Astronomy Observatory), MPIfR in Germany, and INAF in Italy, comprised the expansion of the existing MeerKAT array adding 24 dishes. The second phase comprised 109 dishes.

The SKA project is unique and the infrastructure different to conventional structures. Due to the unconventional nature of the project and the purpose of the telescope, the client has very strict requirements where compliance is critical. For each dish to accurately point into space, the dish foundations are required to meet very strict stiffness and movement tolerances in the order of mm and be aligned to true north. Compliance was also defined in meeting residual performance requirements. In addition, each dish requires power and fibre connections which serves to relay data over vast distances.

To ensure compliance with the client's strict stiffness and movement requirements, the design of the foundations could not be undertaken based on conventional design methods. This paper details the design approach undertaken to demonstrate compliance of the foundations withthe stringent stiffness criteria, where a strain-based design approach was applied with soil-structure interaction. In addition, the vastness of the site coupled with a large number of dish foundations created additional complexity and risk. Due to the large number of foundations and project timelines, a design assessment of each dish was impractical and unrealistic, this was also coupled with data being unavailable. This paper details the use of a digital 3D geological model coupled with the Total Engineering Geological Approach (Fookes et al, 2000, 2008) to derive representative design ground models, decreasing the number of design assessments. The paper also details the verification approach utilised to demonstrate compliance to long-term residual performance criteria. The interface between geotechnical and structural analyses is shown where this was critical in ensuring a compliant foundation system.

2 DESIGN OF DISH FOUNDATIONS

2.1 *Overview*

The client's requirements for the dish foundations related to the function and performance of the dish and defined vertical, horizontal, tilting and torsional stiffness requirements for operation as well as for survival cases. The requirements also defined long term criteria comprising limits on residual damage and residual movements after survival events occur to ensure operational limits are met. The design methodology was defined to show how compliance to each requirement would be demonstrated. An example of the dish is shown in Figure 1

This was undertaken through the use of advanced numerical modelling, use of digital 3D models and insitu testing. 3D numerical modelling was applied utilising advanced soil-structure interaction analyses. The geotechnical and structural designs were deeply interconnected and the interface between the two 3D models was critical. The first step was to generate a large-scale geological model using LeapFrog (Bentley) and a Total Engineering Geological Approach (Fookes et al, 2000, 2008) to understand the variability of the ground and to help define representative ground models across the site.

The second step involved modelling the foundation, with applied loads at the location of the bolt cage, in a soil structure finite element analysis using Plaxis 3D (Bentley). Representative spring stiffnesses were determined from this geotechnical analysis. The third step applied the calculated spring stiffnesses determined from the geotechnical analysis in the structural 3D model using AutoDesk Robot Structural Analysis to complete the structural design. Alignment between the structural and geotechnical analyses was assessed through resultant movements. These were then assessed per requirement and compliance defined if the stiffness was within limits. The foundation system needed to demonstrate compliance with all requirements.

The foundation performance is driven by movement (stiffness), which in turn is driven by ground modulus. A more advanced determination of representative ground modulus with depth was required to realistically represent the foundation behaviour to achieve the stringent stiffness criteria. The design approach used strain-related modulus degradation across the complete ground profile and took advantage of the “activated” strain condition of the ground within the loading zone. Continuous Surface Wave (CSW) testing was undertakento assist with derivation of representative modulus parameters. Back analysis of full-scale pile and prototype testing was utilised to verify design parameters, induced strain in the ground profile and resultant movements for applied loads.

Two foundation types were applied, namely: A piled foundation comprising 8 No. 750mm diameter piles centred on a 7m diameter pile cap with a 3.2m diameter central pedestal; and an 11m diameter cast insitu raft foundation. The ground conditions drove the foundation design and its compliance to the strict requirements. This was driven by rock depth, rock strength and the nature and consistency of soils overlying rock as shown in Figure 2. An understanding of the ground conditions across the site was paramount to controlling risk and ensuring compliance with requirements.

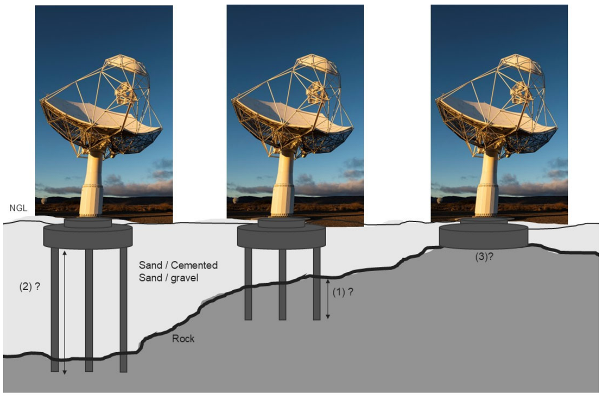

Figure 1. Influence of ground conditions on foundation performance (Photo credit: SKAO/Max Alexander).

2.2 *Derivation of design ground models*

2.2.1 *Total engineering geological approach*

The available data for design was impacted due to the large distances between dish locations as well as access constraints to locations. A geotechnical investigation could not be undertaken at all 133 dish locations to inform the detailed design. This limitation in available data creates risk where changes to the foundation type or size during construction could relate to time delays, increases in material and time-related cost and could impact the foundation not meeting the client’s strict requirements. In addition, due to the large number of dish locations and varying geological profiles across the site, a design for each location was impractical.

The variability of ground conditions needed to be understood and mapped, and representative ground models defined for which design could be undertaken and then assigned to each dish locations. Where in footprint data was not available, this was then verified during construction to ensure the design assigned to the specific dish location complied with requirements. An engineering geological model was created for the full site, based on the Total Engineering Geological approach as proposed by Fookes et al (2000, 2000, 2008). The model was not seen to be rigid, but flexible in that, as new information was received, this was added to the model.

The total engineering geological approach builds the model by combining geology, structural geology, landform evolution and climatic evolution into terrain units of separate assemblages of bedrock geology, overlying soil profiles and landforms with identifiable engineering characteristics. Another important aspect of the approach is the use of Reference Conditions. Reference Conditions consist of groups or units of engineering geological materials with similar engineering characteristics, but possibly from different geological and/or geomorphological origins.

The two most important factors taken as crucial in constructing the model, and hence the engineering geological units, are geology and topography. The model also considered the following: Proximity of dish locations to each other; Dish locations and underlying geology and overall geological setting; Dish locations and associated topography; Test locations and proximity to the dishes; Assessment on the quality of the data; Type of data set e.g. boreholes, Continuous surface wave testing, laboratory tests, test pit data; Comparison of the data sets; Assessment of the variation of the ground data within similar geological facets; Pivotal information from the ground data influencing the foundation design.

Utilising all available data together with the topography and regional geology of the site, a 3D geological model of the site was created using LeapFrog Works software to understand 3D spatial and depth variation of the geology across the site (as shown in Figure 2). This model provided the ability to derive expected ground conditions with better accuracy and map rock level, for instance, across the site. Where no data was available, the geological model coupled with the Total Engineering Geological approach provided a means to make high-level assessments. The value of using a total engineering geological approach coupled with a 3D digital model resulted in a better understanding of the site, better control of ground risk and the development of a 3D geological database of the site.

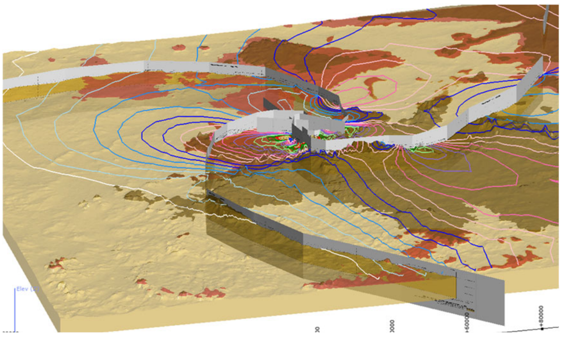

Figure 2. 3D Geological model created with LeapFrog (Bentley) software.

2.3 *Design ground models*

The application of the Total Engineering Geology approach applied for the full site and the geological model created for the site assisted to understand the ground conditions and their variability across the dish locations and map expected conditions to each location. This understanding was then applied to define representative design ground profiles decreasing the number of ground models needed to assess the 133 No. foundations to 5 representative ground models. . The design ground models were derived to represent conditions on site driving design which were defined such as rock levels, overlying soil consistency, rock strength etc.

Design ground model 1 was defined for rock ranging from 4 to 7m below ground level. Design ground model 2 was defined for rock ranging between 3 and 4m below ground level. Design ground model 3 considered a deep soil profile with rock at depth where the deepest rock depth from the available information was observed at approximately 12m below natural ground level. Design ground model 4 considered shallow rock with rock ranging from 1m to 3m below ground level. The overlying material comprises of silty sand / silty gravelly sand / silty sandy gravel (Alluvium). The rock strength varied from very soft rock to medium hard rock siltstone, sandstone and dolerite rock.

Representative design parameters for the design ground models were determined by a detailed assessment of all available data and testing including continuous surface wave (CSW) testing, Dynamic Probing Super Heavy (DPSH) testing, and Uniaxial Compressive Strength with Young's Modulus and Poisson's ratio (UCM) testing conducted on rock samples from the rotary core boreholes. Continuous surface wave (CSW) testing measures the velocity at which Rayleigh waves are propagated along the surface of the ground, from which shear wave velocity and small-strain shear modulus of the ground is determined with depth (Heymann, 2007). CSW testing was used to define the small-strain modulus of each ground horizon. 51 No. CSW tests were undertaken. Small-strain shear modulus (G_0) (in MPa) was plotted with depth for each of the tests and defined into groups representing conditions. These CSW groups were applied with these design ground profiles to determine representative design parameters.

2.4 *Soil-Structure Interaction Analysis*

2.4.1 *Hardening soil model*

Soil-structure finite-element analyses using Plaxis 3D software were conducted on the ground models to assess stiffness and deflection compliance under operational, survival and earthquake load cases. The design approach used strain-related modulus degradation across the complete ground profile and took advantage of the "activated" strain condition of the ground within the loading zone. The soil horizons were modelled with the 'Hardening Soil model with small-strain stiffness' (HS small) constitutive model. This model automatically iterates the soil stiffness based on the induced strains. In addition to employing strain-dependent stiffness, the HS small model also employs stress-dependent stiffness. That is, the stiffness parameters vary based on confining pressure and thus vary with depth.

2.5 *Finite element analysis*

A Plaxis 3D (Connect Edition Version 20.03.00.60) model was created for each ground model and foundation type where piled foundations were applied for the deep rock profiles and a raft foundation applied for founding directly on competent rock. The piled foundation Plaxis 3D model is shown in Figure 3. The piles were modelled as embedded beam elements and as fully fixed to the pile cap (full moment and shear transfer). This was achieved by modelling a 'dummy' plate element at the underside of the pile cap volume element. The pile cap was modeled as a volume element.

Foundation loads were applied at the top of the upstand. Vertical and horizontal loads were applied as a line load on the perimeter of the anchor bolt cage. Moment loading was applied as a point load moment at the centre of the upstand. Torsional loads were applied as a force couple on the perimeter of the anchor bolt cage. A 'dummy' plate was applied at the top of the upstand to allow the correct application of loads (point load moment requires a plate) and to view the resultant tilt of the foundation at upstand level. The overall dimensions of the model were80m × 80m × 40m.

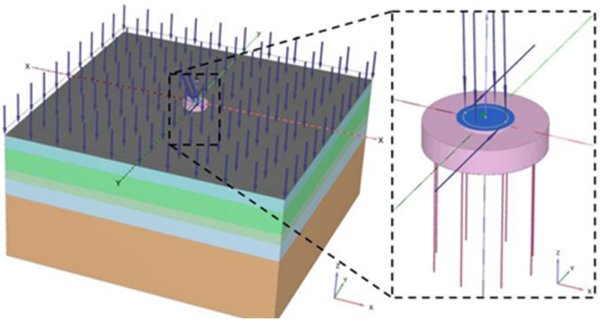

Figure 3. Piled foundation Plaxis 3D model.

Each load was modelled on its own in a model stage to verify movement criteria in accordance with the stiffness requirements. Each resultant deflection and rotation from the model are assessed with a Factor of Compliance (FoC) which is defined as the allowable deflection or rotation divided by the resultant deflection or rotation. A FoC greater than 1 indicates that the foundation design meets the stiffness requirements. The pile length and rock socket depth were changed until the FoC was greater than unity for all four load components and was therefore acceptable. It is noted that these FoC values are from the geotechnical model only and exclude structural displacements such as those of the anchor bolts. Springs were derived and provided as input to the structural model so full compliance could be assessed and the bolt cage design undertaken. An example of the results for Ground Model 3 is summarised in Table 1.

Table 1. Operational stiffness results for Piled Foundation with Ground Model 3

Load Component	Required Foundation stiffness	Allowable deflection / rotation	Pedestal deflection / rotation	Foundation stiffness at pedestal level	FoC
Vertical	3220 MN/m	0.106 mm	0.056 mm	5836 MN/m	1.8
Horizontal	441 MN/m	0.02268 mm	0.0138 mm	723 MN/m	1.6
Moment	9710 MNm/rad	0.05046 mrad	0.0186 mm	2632 MNm/rad	2.7
Torsion	1650 MNm/rad	0.01212 mrad	0.00246 mrad	8129 MNm/rad	4.9 -

A sensitivity analysis was conducted for Ground Model 3 by varying the depth of the pile toes and evaluating the influence of this on the calculated FoC values. The results of this sensitivity analysis are plotted in Figure 4 where it is shown that as the pile toe depth is reduced, the vertical component has the lowest FoC value and thus governed this ground model. The slope of the 'vertical' curve, is steeper than the slope of the 'horizontal' curve, showing that the horizontal stiffness component of the foundation is less affected by the pile length once pile length goes beyond 9m (equivalent to 12 pile diameters).

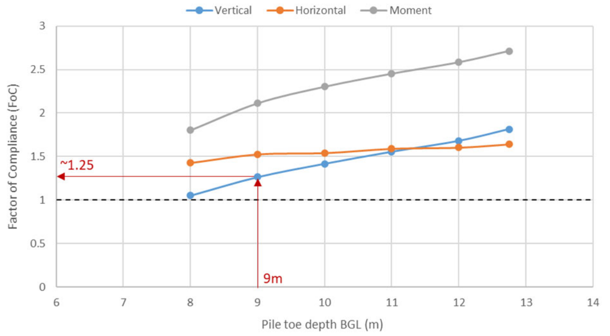

Figure 4. Sensitivity analysis of pile toe depth versus FoC for Ground Model 3.

The Plaxis 3D output was utilised to assess the induced engineering shear strain in the ground profile with depth as shown in Figure 8. These results were plotted on the modulus degradation curve (after Rollins et al, 1998) as detailed in Figure 5 to assess the strain range in which the foundation operates. Figure 6 shows that the strains induced in the ground profile are within a smaller strain range.

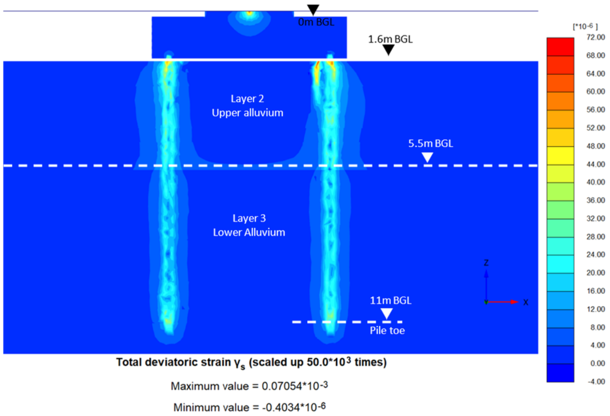

Figure 5. Cross-section through piled foundation with Ground Model 3 showing induced engineering shear strain for operational moment loading.

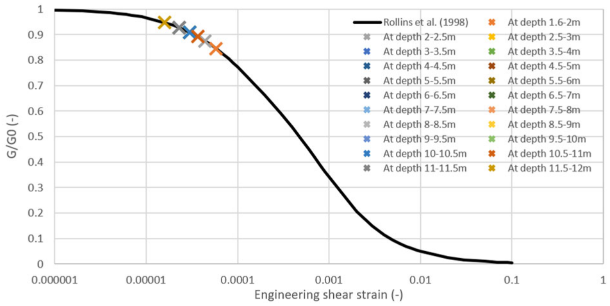

Figure 6. Resultant strain-related modulus with depth plotted onto the Rollins et al. (1998) modulus reduction curve for the piled foundation with operational moment loading.

To achieve the stringent stiffness requirements the piled foundation design was driven by the ground model, applied stiffness parameters and in particularthe depth of rock. The piled foundation required a rock socket to meet the requirements, irrespective of the pile length. The required rock socket for the pile foundation varied dependent on rock strength and the resultant pile length was dependent on the depth of rock level.

The requirements also defined long-term criteria comprising limits on residual damage and residual movements after survival events occur to ensure operational limits are met. Residual performance cannot be effectively modelled, and physical testing is required. This was done by a series of tests including a prototype test and full-scale pile load tests. These were undertaken where load cycles were defined to relate to the design load cases and performance requirements, focusing on stiffness, movement and cycles of loading to test residual performance in specific ground conditions such as deep rock (Du Toit & Wojtowitz, 2025).

3 VERIFICATION

The ground conditions drove compliance and the stiffness of the system where the insitu founding profile was important. A minimum rock socket was required dependent on the rock depth and rock strength, and it was critical that this condition during installation was achieved. Verification of the ground conditions and foundation design for each dish was critical in ensuring the installed foundation met the client's requirements. For the pile foundation, this required verifying the exact rock depth, the strength of the rock, overlying soil material and from this assigning the required rock socket length for the pile. The construction specification document included installation rules guiding decision making of rock socket lengths required for the different ground conditions encountered. The verification process during construction comprised of a geotechnical engineer on site supervising the drilling works. Rock depth levels were recorded, and the rock strength were verified by drilling rates and spoil. This data was then utilised to verify against expected conditions and against the construction rules to define the required rock socket for each dish.

4 CONCLUSIONS

This paper details how a strain-related design approach provides an effective method to design foundations for stiffness sensitive dishes where performance and compliance of the system is defined by strict stiffness tolerances. The paper shows how a Total Engineering Geological approach coupled with a 3D geological model resulted in a better understanding of the site, better control of ground risk and the development of a 3D geological database of the site that was used during construction.

5 ACKNOWLEDGEMENTS

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