Climate change challenges for the geotechnical design of solar farm foundations

David Zhang
Aurecon Australasia Pty Ltd, Sydney, Australia David.Zhang@aurecongroup.com

Hugo Acosta-Martinez
BG&E Resources Pty Ltd, Perth, Australia

ABSTRACT: Solar power provides a clean and cost-effective energy source and construction of solar farms in Australia has increased significantly. Extreme weather conditions such as drought and flooding and other climate-change related events need to be considered in the design of solar farm infrastructure. Novel risk identification approaches that provide sustainable engineering solutions are required. Typically, geotechnical investigation for solar farms comprises borehole drilling, test pitting and geophysics and is carried out to characterise the ground profile over large areas and ultimately to rule out major geotechnical risks, estimate foundation requirements and assess construction cost. Traditional investigation methods are usually constrained by time and budget. Some new techniques have been implemented to reduce the gaps of limited information obtained from conventional investigations. Innovative in-situ testing tools have also been used to assess ground remediation effects and are presented in the paper. Foundation geotechnical design for solar trackers generally involves large areas and thousands of piles. The current design method generally focuses on a simple approach based on saturated soil mechanics or with minor modifications. The presence of reactive soils around Australia solar farm sites introduces complexity to the design due to seasonal moisture variations, resulting in shrink-swell ground movements combined with light vertical loads and high lateral actions from wind loading. Shrink-swell effects are expected to worsen in future due to increased effects from climate change. Recommendations to accommodate these factors in the geotechnical design of piles for solar trackers are presented.

KEYWORDS: solar farm; climate change; expansive soil; pile load test; pre-drilling

1 INTRODUCTION

The Clean Energy Council's Clean Energy Australia Report (2022) states that 32.5% of Australia's electricity came from clean energy sources (solar, wind, bioenergy and hydrogen etc.). Australia committed to a target of net-zero emissions by 2050. The rise in solar photovoltaic (PV) is driven by governments, and businesses chasing targets for low carbon energy. Since 2001, the number of extreme heat records in Australia has outnumbered extreme cool records by almost 3 to 1 for daytime maximum temperatures, and almost 5 to 1 for night-time minimum temperatures (Climate Change Australia, 2022). Consistent with global studies, an increase in the proportion of heavy rainfall has been recorded over Australia. The fraction of Australia receiving a high proportion (greater than the 90th percentile) of annual rainfall from extreme rain days (greater than the 90th percentile for 24-hour rainfall) has been increasing since the 1970s (Climate Change Australia, 2022).

Climate change may impact ground subsurface system in three different ways as shown in Figure 1 (El-Zein, 2014). Pathway 1 refers to the direct impact of a single extreme weather event, for example a flash flood can alter the soil hydro-mechanical properties, decrease suction and shear strength, and temporarily raise the groundwater table. Under pathways 2 and 3, on the other hand, long-term changes in climate variables and repeated occurrences of extreme weather events, respectively, may lead to changes in key soil characteristics and consequently failures of engineered systems. Examples of pathway 2 are the reduction in average precipitation and infiltration and increase in average temperatures and rates of evaporation which may result in a gradual, long-term decline in groundwater table levels and soil water contents, and therefore soil deformation around solar tracker piles. Pathway 3 is a repetitive occurrence of storm surges over several years, eroding and weakening foundations of solar trackers. Another example is repeated flash flood events and pore water pressure oscillations which may lead to softening of clays, with corresponding of loss of shear strength and progressive failure mechanisms.

In many instances, the three pathways may be active simultaneously. The recent Australian eastern coast drought and flooding extreme climate patterns have put many of the built or planned solar farms in uncertainty. There has been reported pile failures such as pile subsidence making torque tube unable to operate which result in damages of solar trackers, and ultimate loss of revenue.

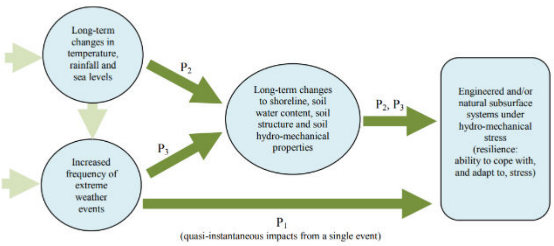

Figure 1. Three pathways (P1, P2, and P3) of impacts of climate change on subsurface systems (El-Zein, 2014)

The unprecedently growth scale of utility solar projects across Australia and the globe comes without specific solar design standards, or guidance have come with growing pains, due to the demands to meet construction milestones and variation in the design, construction, and quality control across the industry. This inevitably brings risks to the developers, asset owners, designers, and constructors. In addition, the design life span of solar farms is typically 25-30 years, and some extension may be required, and as such solar farms, both already built and planned in future, need to withstand extreme weather events such as drought and flooding and other climate change within the given design life span. It is not uncommon that designers ignore the impact of climate change during the life span of solar farms due to the uncountable and unpredictable nature of extreme weather events. Foundation piles for solar trackers may fail due to various causes, including loss of bearing capacity, differential settlement due to seasonable change in groundwater levels and/or erosion of surface soil, slope failure, uplift actions due to wind-induced forces, and soil failure under cyclic/dynamic conditions.

Typically, a geotechnical investigation is the first step to characterise the ground profile over a large area of a solar farm, usually in tens to hundreds of hectares. However, conventional investigation methods such as boreholes, test pit and geophysical methods are usually conducted at a given time slot and are constrained by time and budget. Investigation results obtained at the period when site investigations are undertaken may not reflect the whole range of ground conditions after the solar tracker pile foundations are installed. This is particularly important since most of the built and proposed solar farms are built in temperate to semi-arid areas around Australia. Also, ground spatial variability adds uncertainties in characterisation of ground profiles. The results of geotechnical investigations are utilised to rule out geotechnical risks and estimate foundation requirements and associated cost. There are gaps in between the geotechnical investigations and inevitable risks to the designers and ultimate risks to the developers/asset owners. Application of some novel investigation methods are presented in this paper, and their implications in project outcome are discussed. Reactive soils account for 30% of Australia land, and the design of piles in reactive soils usually follow traditional methods based on saturated soil mechanics. However, due to shrink-swell movement soil around the pile, how to accommodate the pile jacking in reactive soils is rarely considered. A design diagram will be presented, and the implications will be addressed to accommodate these factors. Normally hundreds of thousands to millions of piles are installed on solar farms and pile refusals inevitably occur on site. When the later occurs, pile remediation methods are required. To cover aspects around the QA/QC control of the pile construction, pile load tests are usually adopted to verify the capacity of the remediated piles and confirm compliance with the design intent.

2 SITE INVESTIGATIONS

Site investigations plays a key role in the characterisation of ground profile and design parameters, as well as in determination of geotechnical strength reduction factor, ϕ_g (Kristinof et al. 2019). Preliminary trial pile driveability is included in some early-stage site investigation programs for some projects as a drive from the clients to reduce geotechnical uncertainty. AS1726-2017 is the commonly referred standard for geotechnical site investigations for solar farms in Australia.

The extent and quality of site investigation would provide a determinative approach to the selection of geotechnical strength reduction factors that could be applied to these unique structures. Special attention should be offered to soil dispersity in sloping terrain or obvious erosion-prone features. This can be important especially when pile refusal is expected or recorded during the investigations.

Geotechnical investigations are usually carried out by geotechnical consultants who in many cases are not the geotechnical designers of the solar tracker piles due to accepted planning and procurement processes. Soil parameters such as shrink-swell characteristics are estimated based on empirical correlations, and spatial variability are often not well addressed by generic correlations. Dispersivity testing (Emerson class or sodicity) should be undertaken in geotechnical investigations to capture the scour and disperse potential of soils, particularly to areas prone to large groundwater flows and surface drainage effects, i.e., heavy rainfall events.

In addition, pile pre-drilling rate is always a key economic driver after by the developer/owner at early development stage of a solar farm. The pre-drilling rate is usually based on in-situ SPT N values, however, due to soil spatial variability, the typical method adopted is not accurate and further validation might be required. The discrepancies from actual construction pre-drilling rate are in the order of ±20% but larger variations have been recorded.

2.1 *Novel investigation method*

Geotechnical investigation is usually constrained by restricted budget and very broad brief requirements given by the developer/owner. In addition, good appreciation of local geology and geomorphology is important for the development of a site investigation plan. Poor site investigation plan leads to inappropriate design assumptions and may not provide sufficient information for adequate construction methodologies, which results in project delay and significant additional costs.

With conventional geotechnical investigation methods, it is not practical to carry out one borehole or test pit at each proposed tracker location. A broad range of investigation plan is usually undertaken on site and interpolation of geotechnical units from adjacent boreholes/test pits could lead to either conservative or overenthusiastic prediction of pile pre-drilling rate and design pile embedment lengths, which sometimes causes project delays or even go to dispute during project development stage among developers and designers. Some novel investigation methods are utilised currently for solar farm site investigation. The Investigative Drilling (ID) method, using Measure While Drilling (MWD) data acquisition, offers an alternative approach to conventional geotechnical investigation. The ID method allows a substantial increase in the number of boreholes that can be drilled for a given budget for a widespread footprint of solar farms. The MWD system, on which the ID method is based, consists of measuring the mechanical responses of a drill rig during the process of advancing a drillhole through soil and/or rock layers. MWD was originally developed for application to the oil industry and gradually applied in energy industry in recent years due to the scale of solar farm development demands. The main advantage of ID method over conventional approach is that the density of investigation could be improved in order to ultimately minimise investigation time and cost. However, the conventional investigation method is typically ten investigations out of 1 ha area due to program and cost constraints. This could provide more certainty on ground characterisation and subsequent pile analysis and design, allowing for robust designs to withstand extreme conditions from climate change effects. More details of the ID method can be found in Gui et al. (2012).

2.2 *Alternative compaction assessment method*

Generally there is limited focus on pile drivability during preliminary site investigation, but solar farm usually occupies large footprint up to hundreds of hectares. The current site investigation practices often involve with test pits up to 3 m or early refusal. Hand DCPs (dynamic cone penetrometer) were utilised but its limited depth reach is not efficient for pile design. Preliminary trial pile load testing like Pull-Out Testing (POT) joins forces with early-stage site investigation.

The Panda DCP shown in Figure 2 is a novel tool used to characterise ground compaction effect for pre-drilled piles due to ground refusal. The PANDA® Instrumented DCP measures and displays a material's in-situ resistance to penetration through the depth profile of the material. The PANDA® is used to monitoring layer thickness, and to assess compaction homogeneity. It is also used for layer identification. This can be used to assess the ground compaction effort and ascertain the construction quality. This set tool can be especially useful due to space constraint particularly for built up solar farms with setup solar tracker panels. It has been adopted in a recent solar farm piles remediation project in western New South Wales, due to effects of major flooding events. It was concluded that inadequate compaction of the backfill induced settlement by additional downdrag forces on the piles. Figure 2 shows the comparison of the DCP results conducted at a post before and after pile remediation at a selected pile. It can be found that the cone resistances have increased significantly after pile remediation, particularly in the North and South edges. The cone resistance profiles become more uniform (less variability) after pile remediation. This indicates that ground conditions around the pile shaft become more homogeneous with improved density and stiffness after pile remediation, improving the pile bearing capacity and reinforcing the soil structure around the pile toe.

Figure 2. PANDA DCP (dynamic cone penetrometer)

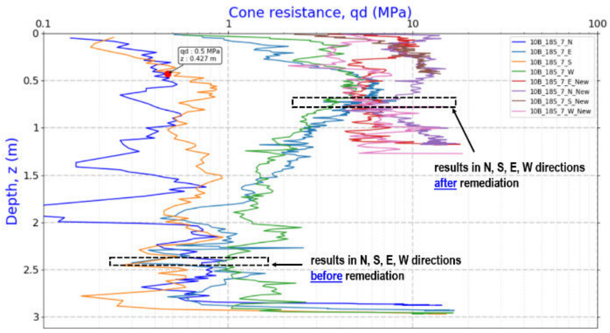

Figure 3. Comparison of DCP results before and after ground remediation at a pile post using PANDA DCP

3 DESIGN OF PILE FOUNDATIONS

Piles for solar trackers are usually short piles, 4 to 6 m long with 1.5 m to 3 m embedment depth below ground level. AS2159 – 2009 is the main standard referred to for pile design in Australia. However, the piling design and installation standard AS2159 is more specifically applicable for buildings and transport and industrial infrastructure. Generally, the piles adopted in solar farm projects are subject to less significant loads compared to large and heavy piles used for major infrastructure projects. AS2159 incorporates a wide range of risk factors such as geological, ground investigation, design experience and construction and monitoring etc., which includes geological complexity, extent of ground investigations and amount/quality of geotechnical data. These factors directly impact the recommended geotechnical reduction factor, ϕ_g. Geotechnical engineers need to cater the demands from client to produce a cost-effective pile foundation design based on limited geotechnical information and extent of solar piles. The desire from the asset owner/developer to reduce capital expenditure costs has incentivised the pile designers to produce economic pile design options, while at the same time commercial model may consider for an extension of design life span up to 40 years.

Design for pile foundations for other renewable assets such as onshore and offshore wind have matured with the industry, however, there is limited awareness design of these lightly loaded structures as most current Australian and international standards and codes for such lightly loaded solar tracker are still in the formulation stage. The recent released ASCE 7-22 (2021) includes some provisions for ground mounted solar panel arrays, but these are largely focused on wind loading. The gaps between the design and construction methods for solar pile foundations lack a completeness of design and installation methods.

In addition, most EPC contractors are not fully aware of the risks posed by reactive soils and extreme climates including flooding and winds of recent years. Most of the solar farms are built in temperate, dry to semi-arid areas of Australia due to the favour of prolonged direct sunshine. For NSW, the current trend is that solar farms are more concentrated in the Southwestern area of NSW with alluvial flood plains containing reactive soils for example, which is in close proximity of the transmission grid and Interconnector fed into the network. Understanding the action of reactive soils and related development on these lightly loaded piles is extremely important for solar pile design. Many solar farms have experienced swelling uplift of foundation piles either during the construction phase or its operational lifespan. Since soil swelling induced post heave is mainly a serviceability limit state related issue, unfactored swelling uplift frictions without any factor of safety is usually preferred by EPC contractors. The swelling induced uplift forces also vary with the pile size, noting that pile sizes adopted in most solar farms are usually 0.3 m to 0.8 m in diameter.

3.1 *Design philosophy*

The limit state method is typically adopted for pile design of solar farms. The two limit states considered are ultimate limit state (ULS) and serviceability limit state (SLS). Although ultimate limit state is typically considered the key design case for foundations, it is often the serviceability limit state that governs pile design for the performance of the solar trackers. The design must satisfy the total settlement of piles and the differential settlement between piles as per tracker manufacturers' requirements.

Usually, a horizontal elastic modulus is more relevant to solar pile design since the driving element of the design is from lateral resistance of piles to wind loads effects. A preferred method to derive horizontal elastic moduli of is from pile load testing. This is seldom performed prior to pile design and only when the project goes to tender. Due to the limited geotechnical investigation data available, owners are more willing to perform pile load testing prior to tender given the pile load test provides optimum pile design which ultimately reflects in the cost for the projects.

Geotechnical properties of the ground can evolve throughout the design life of solar farms due to actions imposed during installation, the operational life or late and end of life management of solar farms. Whole life geotechnical design (Gourvenec 2020) should be adopted to predict soil-structure responses across the design life. In contrast, traditional geotechnical design only considers the 'worst case' single value of minimum resistance or stiffness coupled with the 'worst case' single value of maximum action over the design life. The solar piles are near-ground-surface engineered structures that require the input of likely weather conditions as part of the design process (Fredlund et al. 2012), which little has been considered for the design process of solar piles as observed so far.

3.2 *Design methodology*

Solar pile design in Australia is typically undertaken following AS2159-2009. ULS designs assess pile bearing capacity and minimum embedment against structural compression load under ULS conditions, while SLS design evaluation is carried out to check that vertical settlement and shrink-swell movements are within the tracker suppliers' allowable performance criteria.

As outlined in clause 4.4.6 of AS2159-2009, it is assumed that the ultimate geotechnical strength of a pile in compression and tension is not affected by swelling of the soil around the pile. Shrink swell of soil is an SLS issue rather than ULS issue. However, additional forces induced in the pile due to soil swelling should be factored and considered in structural design.

The additional axial forces on the pile due to movements in the more reactive soils have been assessed from the uplift force analysis for the calculated the upper bound characteristic surface movement. Methods to estimate uplift forces will be discussed in the next section. The design parameters adopted for design soil suction change (H_s), characteristic surface movement (y_s), crack depth, skin friction and soil stiffness. The pile-soil interaction model is analysed as free field (vertical).

Usually, solar trackers are long structures of 90 m to 100 m with rotation of up to 120 deg. Thus, the tracker is extremely sensitive to wind load and wind dynamic effects. Standardised pile design is often adopted to minimise construction complexity for solar tracker classification.

3.3 *Reactive soil*

Reactive or expansive soil refers to clay soils that undergo significant volume change in response to change in soil suction (Fredlund et al. 2012). The volume change occurs as swelling upon wetting, and shrinkage upon drying. Reactive soils go through significant volume changes due to seasonal moisture variations resulting in ground movements. The ground movement related problems are likely to worsen in the future due to climate change, which could lead to pile subsidence or settlement causing solar toque tube unable to operate normally.

Shrink swell index test is commonly adopted to assess the soil reactivity. The pile embedment depth is dependent on the potential shrink swell of reactive soils and the loss of contact between pile and soil due to soil shrinkage induced crack.

AS2870 is often used by designers for solar piles, but it was originally developed for residential slabs and footings, and it is not strictly relevant for solar piles (Dissanayake et al. 2020). Residential construction often involves moisture flow traps under a building and results in heave as reactive soils increase in moisture. Solar farm typically involves little slab on-grade floors or footings. Solar trackers are typically supported on columns elevated above the ground and the footprint is less significant compared to that of residential buildings. The design depth of soil suction change (H_s) for different climatic zones considers the effect of extreme soil moisture and suction profiles which is related to extended period of drought or extreme flooding events. The depth of suction change on a site is also dependent on the type of development. For solar trackers, the depth of suction change should be much less since the elevated structure can't trap moisture under it and within the soil. Hence the crack depth due to soil shrinkage is expected to be proportionally less as well.

Calculated characteristic movement values based on AS 2870 are consistent with the extreme suction profiles which are related to extended periods of drought or extreme rain or flooding events.

Solar piles are typically slender columns that penetrate through expansive soil layers to reach bedrock or stiff to hard soil strata that is not affected by the variation of moisture content. The bedrock or the soil layer that is not sensitive to water content changes supports the tracker loads alleviating pile settlement problems.

For solar piles embedded in expansive soils, special attention is required with respect to the uplift friction generated along the pile shaft in the active zone due to increasing normal stress on the pile shaft. Prior to water infiltration in the embedded section of the pile, positive skin friction is developed along the whole length of the pile. The pile load action is carried by the pile skin friction along the pile shaft and the end bearing of the pile base. However, when water infiltrates into the active zone, expansive soil swells. The ground heave occurs resulting in an increase in the natural surface in the vertical direction. In addition, expansive soil moves in the upward direction relative to the pile. The positive skin friction may increase in the active zone due to an increase in the relative movement between the pile and soil. Typically, the solar pile under the light load may be uplifted due to an increase in the positive friction under constant vertical load applied on top of the pile. The bedrock or soil layer (stable zone) that is not affected by variation in moisture content will not swell when water flows into bedrock or the soil layer because it is not sensitive to water content change. The pile moves upward relative to stable zone that is not affected by variation in water content due to uplift of the pile because of water infiltration. Due to the relative displacement, negative skin friction mobilises along the stable zone close to the pile base. In addition, the end bearing may decrease associated with the influence of water infiltration. When the positive skin friction exceeds the sum of negative skin friction, and solar tracker vertical load, the pile starts to move upwards, which pile uplift occurs.

Currently, piles installed in expansive soils are designed with minor modifications in the conventional design procedure based on the principles of saturated soil mechanics. However, the behaviour of piles in unsaturated expansive soils is significantly different from that in saturated soils.

Figure 4 illustrates the behaviour of a pile subject to water infiltration in expansive soils. Prior to water infiltration associated with rainfall or flood, positive shaft friction is developed along the entire length of the pile. The applied load is typically carried by shaft friction and end bearing from pile base. However, as water infiltrates into the active zone, expansive soil swells. Positive shaft friction increases in the active zone while negative skin friction arises in the stable zone. The net contribution that arises from the negative shaft friction, end bearing, and pile head load combine to balance the increased uplift friction. When positive shaft friction exceeds the resisting force, the pile tends to move upward. The positive shaft friction acting along the active zone upon water infiltration is referred to uplift friction.

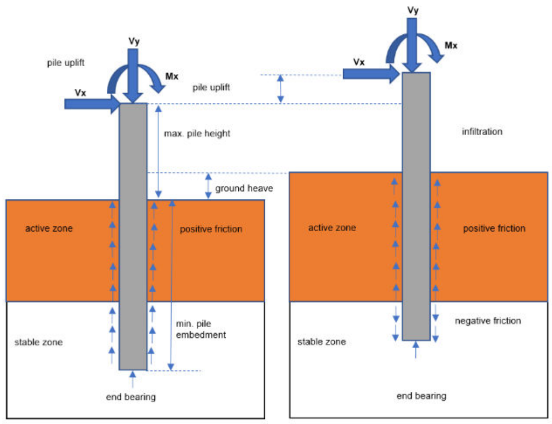

Figure 4. Mechanical behaviour of solar pile in expansive soils before and after infiltration

Swelling induced loads are not the governing loads for building structures hence they are not factored in the design loads standards. However, swelling loads are generally the governing loads for lightly loaded panel supported solar tracker piles.

There are several approaches to estimate the uplift force generated on a pile due to soil swelling. These can be grouped into total stress, effective stress, and elasticity methods (Nelson et al., 2015). Total stress methods use the undrained shear strength to directly estimate the shaft friction. The uplift force is calculated using the average pile-soil adhesion over the surface area of the pile. Effective stress methods estimate the uplift forces considering the shaft friction generated by movement of the soil against the shaft. Poulos and Davis (1980) described an approach to solve for the tension developed in a pile in a swelling clay using an elastic method which calculates the tension in the pile by applying a specified movement of the soil as induced by soil heaving. A numerical analysis or the use of developed program (Poulos, 1989) is required to solve for the tension in the pile. The program computes the axial movements developed in an expansive soil due to moisture changes. This method provides a closed-form solution and can provide a simple prediction with a direct relation to the in-situ soil properties and profile of the expansive soils and the ability to provide a correlation between the amount of swell and the uplift force in the pile. This avoids unnecessary complicated numerical process and is favoured by practicing engineers. One drawback of this method could be that the pile displacement was not considered and only the pile stresses are obtained.

The total stress methods provide a conservative estimate of the uplift force, whereas the elasticity method allows a maximum mobilised shaft friction and thus incorporate pile-soil slip effect (Poulos and Davies, 1980). The benefit of being able to accurately predict the uplift force on piles in expansive soils is twofold: (1) to design the appropriate required structural capacity of the pile, especially for lightly loaded structures where the pile would be loaded in tension, and (2) to allow an estimate of pile head movement and design the required length of pile in the stable soil zone to resist the upward movement with an adequate factor of safety.

Finite element methods (FEM) provide a versatile and robust analysis tool that addresses the limitations of the existing total stress, effective stress and elastic methods. The FEM method allows for pile analysis within complex soil profiles, where soil properties and water content vary with depth or piers with complex construction details, such as screw piles (Kristinof.et al., 2019).

The loads for stopping the upward pile movements are usually around 2.5 times the maximum tensile stress of a free pile under swelling pressure in an expansive soil foundation (Nelson et al. 2015).

4 CONSTRUCTION AND PILE LOAD TESTS

Piles constructed in expansive soils have a high probability to experience failure during their life span, if design is not based on rational design methods. In addition, given current extreme climate change, piles for solar trackers are typically installed in inland arid areas with high potential to experience unexpected rainfall or flooding events. In many scenarios, solar pile failures in expansive soils can be attributed to the upward movement induced by swelling of soils accelerated by flooding of the soil surface.

A large variation in the processes and documentation produced for quality control and quality assurance (QC/QA) of piling activities from solar farms developed and executed by different owners and subcontractors has been observed. Some EPC contractors only require 5% - 10% inspections of piles, whereas some other EPC contractors may require 100%. Due to the increasing number of piles installed on solar farms, the inspection frequency may be scaled proportional to the number of defects observed. Documentation of pile installation records, pile load test results and pile remediation is not standardised. This is especially important when pile defects are noticed on site and hard to correlate to installation methods and pile load test results. Establishing a robust QA/QC system is essential to a successful for project program. Rework to fix remediated piles could be costly and present a risk to overall operation of the whole solar farm.

4.1 *Pile drivability and pre-drilling*

Millions of solar piles are supposed to be driven into ground in a couple of months' duration, usually 3-6 months for a typical size solar farm. The partially embedded solar piles may be fully driven into soil or installed in pre-drilled holes in hard soils and/or areas with boulders/cobbles and rock. When a pile is driven into clay, horizontal and vertical movements are developed in the soil surrounding the pile. These movements tend to develop axial forces and bending moments in adjacent piles that have already been installed.

The installation of piles is usually by vibration methods such as impact driving and vibratory driving. Driveability is firstly assessed by the resonance of the vibrator-pile-soil system (system resonance). Ground vibrations on and below the ground surface show that strong oscillating horizontal stresses are generated. These stresses can temporarily reduce the shaft resistance during driving, which is more efficient in dense granular soils. Noises generated by impact driving can be a severe environmental issue. In addition, vibratory driving is proved to be more efficient in granular soil deposits. No current reliable scientific tools are available for selecting vibratory driving equipment and assessing the bearing capacity of piles after installation. Nevertheless, vibratory driven piles have increasingly been driven using powerful equipment, and it proves to be faster and more cost-effective than impact driving for example. Hammer is clamped to the pile in a steady-state motion.

An important part of project design is the selection of the optimal vibrator capacity (eccentric moment and centrifugal force) for driven piles. Equally important is to optimise the driving process (eccentric moment and vibration frequency). Empirical methods developed by vibrator manufacturers can be utilised to select of suitable vibrators. Unfortunately, limited factual evidence has been published regarding the scientific basis and limitations of these empirical correlations. Vibratory driving of piles can be envisaged as a full-scale dynamic penetration test, proved that the driving parameters (frequency, eccentric moment) are known and kept constant. A key parameter is the measurement of the pile penetration speed at a constant vibration frequency. Sometimes the pile driveability is measured by the incremental driving time per 300 mm or similar and cumulative driving time for each pile are recorded and used to predict pile driveability. Figure 5 shows a damaged pile during a trial pile installation exercise of a solar farm. Pile size and driving/vibration capacity are generally not determined until the first round of pile installation.

Figure 5. Pile damaged during trial installation

Pre-drilling is typically adopted when hard ground conditions, cobbles, or boulders are present underneath the surface and result in pile early refusals. High-production utility scale solar pile pre-drilling can be done for up to 0.4 m pile diameters. Test drilling pilot-holes with Smart Drill "Measure While Drilling" (European Standard, 2016) capability is trending recently for a quick project turnaround. Usually, an auger hole of pile diameter size will be drilled and then backfilled with fill materials such as crusher dust or stabilised sands. Pile remediation methods are usually proposed by the piling subcontractors with expected proper construction quality control. Pile load testing is usually required to verify the suitability of the pre-drilling and pile installation methodology and pile performance. However, this doesn't always happen due to various reasons. Pre-production pile load test in pre-drilled hole should also be conducted in the investigation stage to better represent the range of subsurface and installed pile conditions. The water infiltration into the backfill materials because of flooding event leads to question about the compaction quality of backfill material. Poor compaction of backfill material may lead solar tracker pile settlement or subsidence and disfunction of tracker panels. With more solar farms being installed, asset management is increasingly important and challenging because of challenging environmental factors such as climate change etc. A properly installed pre-drilled pile is shown in Figure 6.

Figure 6. Piles installed after pre-drilling

4.2 *Pile load testing*

AS2159 is typically adopted for pile load testing in solar farm projects. AS2159 specifies minimum pile testing requirements for serviceability and pile shaft integrity where the basic geotechnical strength reduction factor is greater than 0.4. This is simply followed by solar farm designers. However, the quantities and testing regimes differ from one to another, and there is no consensus standard to guide pile testing quantities and requirements. In addition, this is also constrained by budget and timing in the early-stage works. Piling testing procedure developed shall consider all the requirements from different tracker suppliers prior to the procurement stage.

The pile load test follows AS2159 – 2009 with modified changes to fit in solar pile operating environment. Internationally, ASTM Standards (ASTM D1143 – Static axial compressive load, ASTM D3689 – Static axial tensile load, and ASTM D3966 – Static lateral load) are also quoted by many designs conducted by overseas geotechnical consultants.

Pile load test allows a direct derivation of horizontal elastic modulus, which can be used for detailed pile design. Pile designers have benefited from preliminary pile load tests to develop geotechnical design parameters during the pile design stage. Recently this has been more widely accepted by the asset owners/developer prior to tender stage. Some soaked ground pile load tests are also observed in the industry which is intended to simulate flooding scenarios.

5 CONCLUSIONS

Geotechnical design of solar farm faces extreme challenges due to the unprecedent climate change effects. The solar industry has seen rapid growth and maturing into a meaningful contributor to the energy mix. However, the industry needs standardisation and consensus on requirement for pile load testing, yet the requirements need to be site specific conditions and installation methods. A set of organised and accurate records of pile installation, pile load tests could be useful to identify and analysis the root cause for pile failures if encountered on site. Proper pile remediation methods and innovative testing tool can be used to mitigate pile failures such as those from subsidence for example.

Site investigation shall allow sufficient buffer to accommodate the design requirements for increasing developer/owner's demands. Novel investigation methods such as the ID method are introduced with quick turn around and sufficient information to develop ground models and predict pile pre-drill rate. The lightweight PANDA DCP tool kit can be useful especially for space constrained working environments. Design of solar piles in reactive soils has been outlined to address the issues induced because of soil heaving problems. Pile-soil load transfer mechanism under wetting process was schematically elaborated and the methods to estimate uplift forces in the pile were outlined. FEM method can provide a versatile and robust approach to address the limitations by existing total stress, effective stress, and elastic methods. Pile construction issues such as driving hammer selection, pre-drilling, and pile load tests are also discussed. An established robust QA/QC system is essential to a successful for piling program especially with site with pile refusal problems, otherwise rework to fix remediated piles could be costly and present a risk to overall operation of the whole solar farm. Pile load testing have been proved to be beneficial to calibrate geotechnical models and parameters obtained from conventional geotechnical investigation. Modification to prevailing standard has been adopted with considerations of different tracker suppliers prior to procurement stage.

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