Risk, cost and innovation in onshore foundation design

Words: Neil Jacka, CEO and Founder, Total Ground Engineering

As innovations drive down costs in wind turbine components, foundation expenses rise. The National Renewable Energy Laboratory predicts Balance of System costs to soar, posing a challenge. The solution lies in reimagining foundation design. Current methods fall short, risking structural integrity. Advanced modelling offers insight, with micropiles emerging as a cost-effective, efficient alternative, slashing both capital cost and carbon footprint. Redesigning foundations is imperative for the future of wind energy.

While innovation in turbines, blades and towers has resulted in decreasing costs on a per kW basis, the same cannot be said for foundations. Research by the National Renewable Energy Laboratory (NREL)[1] has estimated that Balance of System (BOS) costs will increase to 44% of the overall capital cost of a wind power project by 2030.

This is more than double the cost in 2008 and nearly 50% higher than in 2018. Projecting forward to larger turbines at greater heights, NREL calculates that a 50% reduction in foundation costs will translate to a 5% reduction in the levelized cost of energy (LCOE).

The 50% reduction in cost may be an arbitrary number to demonstrate a meaningful payoff in reduced LCOE but it does serve as a worthy challenge for engineers. NREL's research stopped short of looking into how the cost reductions could be achieved and we are left with the obvious question 'Is it possible to achieve such levels of cost reduction?'. The answer is yes ... but not by using current engineering methods for WTG foundation design.

Rotational stiffness, the critical factor

As turbines, towers and blades all increase in size or length, the rotational stiffness required from WTG foundations has increased dramatically. For the non-engineering readers of this article, rotational stiffness is quite simply the moment loads from the tower divided by the rotation of the foundation.

High load and low rotation translate to high stiffness. The minimum rotational stiffness specified by the turbine OEM is vitally important because the structural analysis of the whole system is predicated on that minimum rotational stiffness. Foundations that do not meet the stiffness requirements will result in loads on the towers exceeding design assumptions and creating potential contributory risk for tower or turbine failure.

A historical perspective: The hidden risk in outdated methods

Over the last couple of decades, the rotational stiffness required from tower foundations has increased nearly four-fold and it is this requirement that should now be driving the design of foundations. Historically, the process of foundation design started with basic calculations of overturning resistance which is generally a function of the mass of the concrete and overburden soils, followed by a check on bearing capacity and rotational stiffness.

The accepted practice for analysing rotational stiffness is to use a single line formula developed in 1943 with some added factors developed predominantly in the 1980s. These formulae are based on a theoretical infinitely stiff disc on a uniformly elastic medium. They are too rudimentary for today's tower requirements and contain several simplifications that result in an opaque assessment of rotational stiffness and therefore uncertainty about performance of the foundation.

While many experienced foundation designers will be aware of the limitations of this current practice and either adopt very conservative input parameters or employ more advanced methods of analysis, international standards for foundation design still reference these rudimentary formulae that the authors believe are no longer fit for design of the foundations of today, nor indeed the future.

Furthermore, the current approach to rotational stiffness could present an unseen risk to the structural integrity of the tower, turbine, and blades above. Finite Element Modelling analysis shows that rotational stiffness can be over-estimated by nearly an order of magnitude using these basic formulae: chart 1.

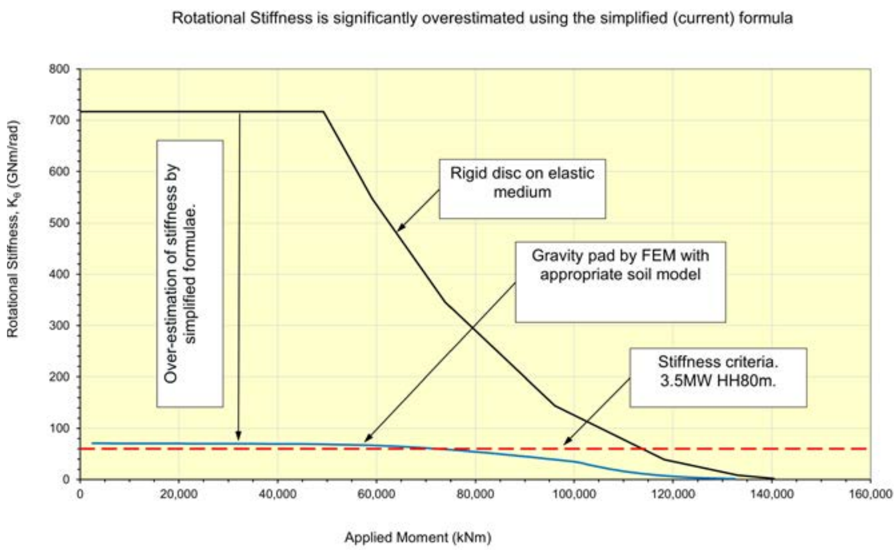


Chart 1

Finding innovation through advanced modelling

The solution to this problem is to elevate the level of geotechnical engineering and focus the analysis on the soil-structure behaviour of the foundations before proceeding with structural analysis and design. Total Ground Engineering (TGE)has deployed three-dimensional finite element modelling (FEM) to WTG foundation designs which has yielded important insights and allowed for innovations that reduce cost and embedded carbon.

For soil-structure interaction problems like WTG foundations, a primary benefit of FEM analysis compared to the current methods are that the 'real' non-linear stress-strain behaviour of the soil can be modelled to accurately predict deformations. This simply cannot be replicated using the currently accepted formulae.

Gravity pad foundations are the most predominant foundation in use today and attempts to 'optimise' these foundations to limit capital cost generally result in reducing pad foundation thickness. The consequent increase in undesirable flexibility, the opposite of stiffness, is unaccounted for by the current analysis methods creating unseen risk to the towers and turbines.

Furthermore, FEM analysis also shows that as the diameter of gravity pads increase there are diminishing returns of increased stiffness: chart 2. This is because the flexibility of the concrete foundation increases rapidly due to the pad foundation cantilevering further from the edge of the tower.

Our analysis shows that on a stiff soil foundation at 20 m in diameter, the flexibility of the concrete pad is contributing nearly 80% of the overall foundation flexibility increasing to 90% at 24 m diameter. Increasing foundation diameter beyond these limits yields virtually no benefit unless the thickness of the foundation is substantially increased with a resulting blow out of costs.

While FEM analysis can highlight risk in the form of significant uncertainty in meeting foundation stiffness using current methods, the flip side is that FEM also reveals where the limitations are and where improvements need to be focussed to deliver innovation.

Using an example of a tower that is 4.5 metres in diameter, modelling reveals that while cantilevering beyond 20 m to 24 m diameter results in diminishing returns, reducing the cantilever beyond the tower diameter can be accomplished in several ways to deliver innovation in the form of more efficient foundations. With efficiency being measured as the required rotational stiffness for the least amount of labour and materials.

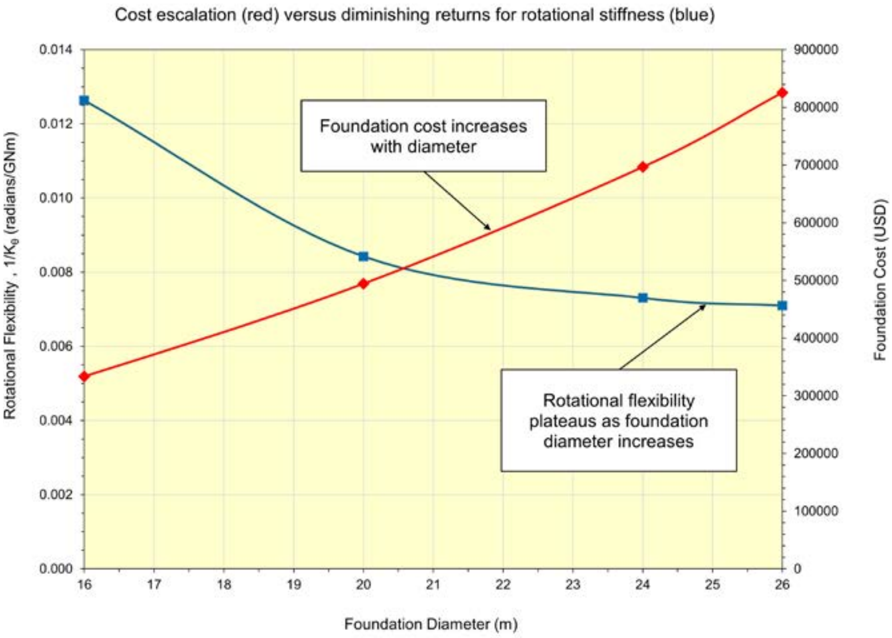


Chart 2

If the cantilever can be reduced by reducing the diameter of the foundations, then this should result in significant reductions in concrete and steel since these quantities are roughly proportional to the square of the diameter.

One way to do this is to drive the loads deeper into the soil layer using a perimeter pattern of piles. The piles drive a portion of the overturning loads deep into the soil profile where the stiffness and strength increases. Mobilising these stiffer soils enhances the stiffness contribution from the soil. Reducing the pad diameter, hence the cantilever, increases the stiffness of the concrete pad. The resulting combination is a more balanced distribution of soil and concrete stiffness, and the overall performance is a much more efficient foundation.

Micropiles are a specialist piling technique that can be suited to wind tower foundations. Micropiles are simply a central bar grouted into a borehole up to 0.3m in diameter. They are efficient to install with relatively compact plant and matching the appropriate drilling methods to the geology can yield high-capacity piles and competitive rates.

The reductions in concrete and steel are offset by the cost of micropiles, but even so, comparing the micropiled-pad with a base case of an actual gravity pad, 24m in diameter, constructed for a 5 MW turbine at a hub-height of 120 m, delivers up to 30% reduction in capital cost and a 47% reduction in embedded carbon for the same rotational stiffness: chart 3.

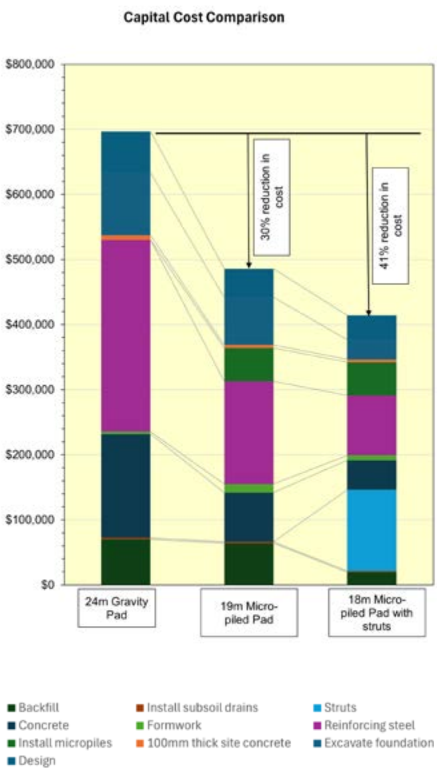
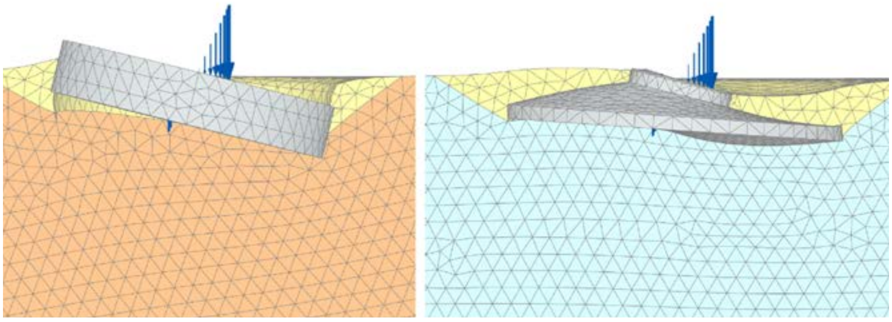


Chart 3



Theoretical foundation disk (left) versus actual concrete foundation (right) showing flexure under load

Using micropiles placed at specified positions to drive the stresses deeper into the ground rather than relying wholly on a broad spread of bearing pressure underneath the pad presents an obvious design iteration. It allows the designer to concentrate the structure of the pad to follow the load path from the tower to the micropiles.

Redundant or lightly loaded zones of reinforced concrete being utilised simply for mass, as ballast, can be replaced by backfilled overburden soil to serve as ballast. This is a much more efficient use of concrete and presents an opportunity to further reduce embedded carbon and cost.

Installing struts to support the ends of the cantilevered pad presents another opportunity to create a more efficient cap/pad. Analysis of one arrangement provisionally patented by TGE yields significant efficiency. The edges of the pile cap become supported by struts rather than in purely cantilevering.

Comparing this foundation to one mentioned above, another incremental reduction in reinforced concrete offset with the introduction of steel struts can achieve an overall reduction in capital cost of 40% from the base-case and a 60% reduction in embedded carbon.

Gravity pads have served their purpose, but more efficient foundations as well as more advanced geotechnical analysis and design methodologies are required to support the turbines of the future and to deliver the meaningful reductions in LCOE as suggested by NREL.

The author will be presenting on this topic on July 11th at Australia Wind Energy 2024 and welcomes discussions with others who are interested in innovation and optimisation of WTG foundation design or current asset risk. A more comprehensive technical paper on this topic is also available.

totalgroundengineering.com

1. Key, A., Roberts, O., & Eberle, A. (2022). Scaling trends for balance-of-system costs at land-based wind power plants: Opportunities for innovations in foundation and erection. Wind Engineering, 46(3), 896-913.

About TGE

Total Ground Engineering (TGE) is a specialist ground engineering company with deep expertise in complex foundation design and the use of advanced geotechnical technologies.

TGE has undertaken significant investment in research and development of innovative WTG foundation designs and are also experts at supporting owners and funders in clarifying risk related to existing foundations.

Neil Jacka

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Neil is a geotechnical engineer (Chartered Professional Member, Engineering NZ) with over thirty years of experience leading projects in the civil construction industry.

He possesses a deep expertise in complex soil-structure problems across a range of environments including hydro, geothermal and wind power, infrastructure, telecommunications, and commercial projects.

Neil leads a team of engineers who are driven to deliver innovation, value, and improved management of risk to the wind power sector.