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Title: CELLULAR RAFT AS A FOUNDATION SYSTEM FOR ONSHORE WIND TURBINES

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Abstract

Onshore wind turbine foundations withstand significant overturning moments while ensuring structural integrity and cost-effectiveness. Conventional gravity-based foundations reach the resistance by using large volumes of reinforced concrete, leading to high construction costs and considerable embodied carbon emissions. This study examines the feasibility of a cellular raft foundation as an alternate support system for a Vestas V80 2 MW wind turbine within the geotechnical conditions of the Gabal El-Zeit Wind Farm in Egypt. A framework for analytical overturning capacity and three-dimensional finite-element calculations utilizing PLAXIS 3D was developed to assess the structural and geotechnical performance of the proposed foundation in comparison to the conventional gravity-base foundation. Parametric analyses were performed to investigate the impact of foundation diameter, tower weight, and backfill soil characteristics on overturning resistance. The findings indicated that the cellular raft foundation shows substantially greater overturning resistance compared to the conventional foundation of identical diameter, with analytical enhancements surpassing 50% and numerical assessments revealing an approximate 37.5% increase in ultimate overturning capacity. The improved performance is attributed to the stabilizing contribution of the soil infill and the developed structural efficiency of the cellular configuration. The parametric analysis indicated that foundation diameter is the primary factor influencing overturning capacity, whereas tower weight and backfill density demonstrated rather minor impacts. The proposed approach reduced the estimated material-related foundation cost by roughly 21% by significantly lowering excavation volume, concrete usage, and reinforcement needs. The results indicate that cellular raft foundations offer a structurally efficient, economically viable, and potentially more sustainable alternative to traditional gravity-based foundations for onshore wind turbine applications.

Keywords

Onshore Wind Turbine; Cellular Raft; Gravity base footing; Overturning moment; PLAXIS 3D; Foundation cost

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1. Introduction

With increasing electricity demand, renewable energy generation has become increasingly important, with wind energy playing a major role. Countries around the world have significantly invested in developing wind turbines with high capacities owing to the improved sustainability and efficiency associated with generating energy from those sources. There is an expectation of growth of more than twofold in terms of installation of solar PVs and wind installations between 2022 and 2028 [1]. Wind and solar installations are expected to continue reaching record levels, with total capacity projected to exceed 710 GW by 2030. This explains the necessity for foundation systems for larger wind turbines. Advanced wind turbine designs utilize taller towers and larger rotors with higher hub heights, resulting in greater loads on the foundation structure. Unlike other structures, wind turbines are subjected to overturning loads, which are quite significant considering the cyclic nature of loadings coming from wind action, rotation, and vibrations [2]. These loads produce significant overturning moments that must be safely supported and transmitted to the ground during the turbine's operational lifespan, usually exceeding 20 to 25 years [3]. Therefore, foundation design is critical for structural safety, project feasibility, construction costs, and environmental performance.

Several factors govern the selection of a suitable foundation system for wind turbines. These factors mainly include the site conditions, stability requirements, and cost considerations. Each of these considerations influences the overall feasibility of a wind farm and must be considered collectively rather than in isolation. Establishing a suitable balance among foundation performance, construction feasibility, and cost is an essential aspect in the design of onshore wind turbine foundations [4]. Traditional gravity foundations have several advantages; nonetheless, they require significant quantities of concrete and reinforcing steel, particularly for contemporary multi-megawatt turbines, which experience continually growing overturning moments. The construction of foundations may represent roughly 15-20% of the entire capital costs for a wind farm, making it one of the highest civil engineering elements of the project [5]. Moreover, conventional gravity-based foundations require substantial quantities of concrete and reinforcement, contributing to material consumption and environmental impacts. Reducing foundation material demand can therefore contribute to more sustainable wind energy infrastructure. Therefore, even a modest reduction in foundation material demand would create more opportunities for wind energy expansion worldwide, especially in developing regions [6,7].

Various alternative foundation configurations have been investigated for onshore wind turbines to improve foundation performance and reduce material requirements, including rock-anchored, piled, conical, shell, and prefabricated foundation systems [4,8]. However, these alternatives may involve additional construction requirements or may depend on specific site conditions. Rock-anchored foundations can provide an efficient alternative where suitable high-quality rock is available, but their applicability is strongly dependent on the geological conditions of the site [4]. Mohamed and Austrell [9] compared different foundation configurations for onshore wind turbines, including conventional flat, deep flat, and conical raft foundations, and reported improved tilting performance for the conical configuration. The Cone-Shaped Hollow Flexible Reinforced Concrete Foundation (CHFRF), proposed and tested by Li et al. [10], is a foundation designed for onshore wind turbines in China. The CHFRF hollow is filled with excavated soil from the wind farm site. It was found to constrain the rotational movement of the footing under horizontal loading, while model tests indicated reductions in concrete consumption and construction costs compared with a conventional circular gravity-base foundation. Moreover, the model test has shown a reduction in concrete consumption and construction expenses relative to the circular gravity-base foundation [10]. Huat et al. [11] investigated the performance of upright and inverted triangular shell footings using finite-element analysis and field model tests. The results showed that the inverted triangular shell provided higher load-carrying capacity than the upright configuration and conventional flat strip footing. The feasibility of construction poses a difficulty for employing triangle geometry in footings, which may be inappropriate in certain soil conditions. These studies demonstrate the potential benefits of hollow and cellular foundation configurations, which may improve overturning resistance while reducing material consumption.

Previous studies on cellular and hollow foundation systems have demonstrated the potential to reduce foundation material consumption and self-weight while maintaining the required structural performance [9,10,12]. In these systems, portions of the foundation volume are replaced by internal voids or soil-filled cells, reducing the amount of concrete while retaining the external dimensions and the foundation's resistance mechanism against overturning [12]. However, most of the performed studies have been developing concepts or applications outside the wind energy sector. The overall performance of cellular raft foundations under combined vertical loads, horizontal loads, and overturning moments is not widely investigated through existing literature. Among the performed studies, Mohamed et al. [9] introduced a reusable foundation system consisting of a cellular raft integrated with

an active stabilization system. The used stabilization system consists of sensors that monitor the wind direction, move internal wagons within the cellular structure, and generate a counterweight towards the applied loads. The study evaluated the effectiveness of the active stabilization concept, its effect on load-bearing performance, and the environmental impact of the proposed system. The results demonstrate promising structural performance and lower carbon emissions [12].

The present study investigates the suitability of a cellular raft foundation to support the Vestas V80 2MW Wind Turbine class. Unlike the previous studies, the proposed foundation acts as a passive structural system whose performance is derived directly from its geometry and composite action rather than an active stabilizing action. Through numerical analysis, the research studies the soil-structure response to determine whether the cellular raft would provide a comparable stability performance under high overturning moments as the traditional gravity-based foundation.

The foundation system provided is assessed using the Gabal El-Zeit Wind Farm as a case study, although the approach established in this research cannot be restricted to the examined location. The analytical framework and finite-element modelling approach can be modified for various onshore wind turbine projects by integrating site-specific soil characteristics, load circumstances, and foundation configurations. The numerical findings presented in this paper are considered representative of the examined conditions, whereas the suggested evaluation framework establishes a foundation for assessing the suitability of cellular raft foundations in alternative geotechnical and turbine configurations.

Accordingly, the objectives of this research are to: (i) conduct a numerical analysis of the overturning moment capability of the cellular raft and the gravity base footing in an Egyptian wind farm; (ii) compare the load-bearing capacity between two foundation systems; (iii) investigate the influence of diameter on the load capacity of the cellular raft foundation; (iv) investigate the influence of the relative density of the filling soil on the efficiency of the proposed system; (v) estimate the cost associated with both systems and deducing the impact of the proposed system on the overall cost reduction of the wind turbine.

2. Case Study and analytical framework

The research included a combination of analytical computations and three-dimensional finite element models. The methodology follows geotechnical foundation design concepts and soil-structure interaction analysis. The finite element model facilitated the examination of foundation performance under the operational loading conditions, producing comprehensive insights into the stress distribution, deformation patterns, settlement behavior, and overturning resistance. Moreover, the methodology enabled a systematic parametric analysis of the principal variables affecting the efficiency of the suggested foundation system.

2.1. Reference Wind Farm Site and Foundation

The investigation was based on conditions representative of the Gabal El-Zeit Wind Farm, one of Egypt's largest onshore wind energy developments. El-Zeit wind farm is located at Gulf El-Zeit, Egypt, 15 km from the Red Sea coast. The site is approx. 8 km west of the N65 Hurghada-Zafarana main road, 80 km NW from Hurghada, and 300 km SE from Cairo, the southern border is about 4 km north of Wadi Darah village. The wind farm comprises 60 V80/2 MW wind turbines with a hub height of 60 m and a total installed capacity of 120 MW. The project site is in the coastal plain of the Egyptian East Delta, an area with a maximum elevation of about 250 meters, flat to the east and hilly to the west. The subsurface conditions at the wind farm were investigated using 12 boreholes drilled to a depth of 15 m. Based on the subsoil descriptions and analysis, the general soil conditions consisted of medium to coarse sand with some gravel, traces of silt, and calcareous material. The soil properties based on the investigations and lab tests and adopted in the finite element analyses are shown in Table 1. The reference turbine considered in the study allowed the proposed foundation system to be assessed under realistic operating conditions and loading scenarios relevant to an existing Egyptian wind farm.

Table 1 Geotechnical properties of the foundation soil in the finite element analyses

Property	Symbol	Value
SPT value	N	$N > 50$
CPT value, (kPa)	q_c	$q_c > 1000$
Empirical friction angle, (°)	φ	40
Soaked direct shear friction angle, (°)	φ'	31.3
Submerged unit weight, (kN/m^3)	γ_{sub}	8.0
Allowable bearing capacity (kPa)	q_c	150
Modulus of subgrade reaction, (kN/m^3)	k_s	60,000
Active earth pressure coefficient	K_a	0.33
Passive earth pressure coefficient	K_p	3.00

The reference footing was derived from the circular gravity-base footing constructed at the Gabal El-Zeit wind farm. The foundation system consists of a 16 m reinforced concrete gravity base footing with a central pedestal and anchor cage assembly that provides connection with the wind turbine tower. With reference to the construction drawings, the footing is reinforced concrete with a 16 m diameter, central pedestal, and anchor cage for the solid connection with the turbine's tower as shown in Fig.1. The external diameter of the pedestal is around 4.99 m and contains the anchor assembly, cable conduits, and access openings required for turbine operation and maintenance. The embedment depth is 2.64 m below ground level. The footing contains approximately 312 m^3 of concrete and 29 t of reinforcing steel. The foundation geometry, loading conditions, and soil profile utilized in the analyses were obtained from the project's design data, enabling analyses to be conducted under realistic conditions that

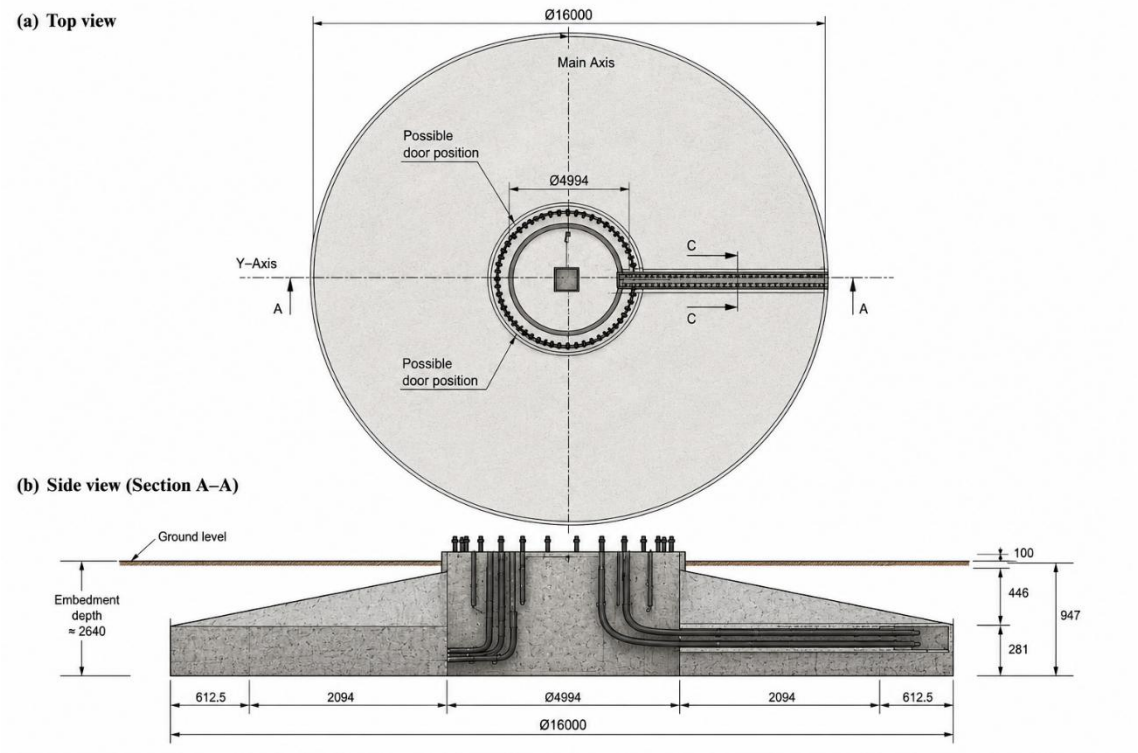


Fig. 1 Geometry of the reference gravity-base foundation at the Gabal El-Zeit Wind Farm: (a) top view and (b) sectional side view.

reflect the operation of an onshore wind turbine, thus offering a reliable base for evaluating the structural, geotechnical, and economic performance of the proposed alternative.

2.2. Proposed Cellular Raft Foundation Geometry

The proposed cellular raft geometry was developed based on the reference footing currently employed in the Egyptian wind farm. It is proposed as an alternative to the conventional design that uses a reduced volume of concrete while maintaining stiffness, stability, and overall performance. To allow direct comparison with the gravity-based foundation, the diameter of the proposed raft is retained at 16 m, and the same pedestal diameter of approximately 4.99 m to maintain a sufficient connection with the turbine's tower. However, the foundation volume is converted to a cellular structural system. The cellular system is described as an upper and lower reinforced concrete slab interconnected by radial concrete ribs that form enclosed soil-filled cells, as shown in Fig. 2.

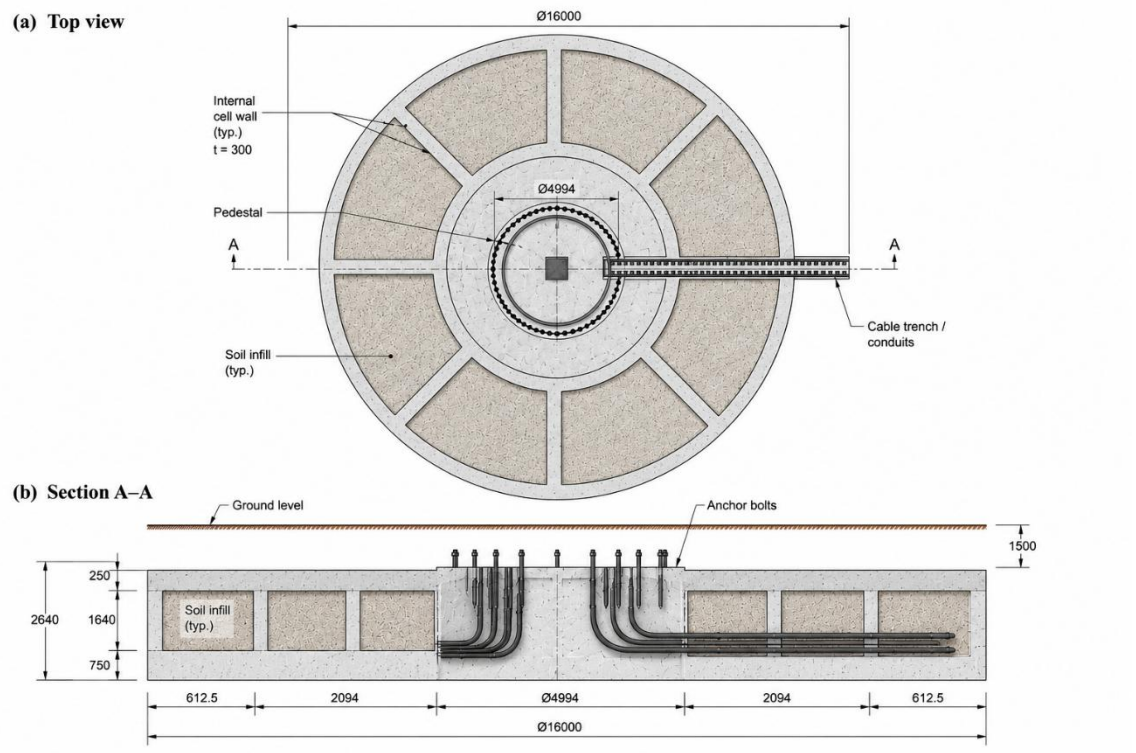


Fig. 2 Geometry of the proposed cellular raft foundation: (a) top view and (b) sectional view along A–A.

The configuration described follows the structural principles of cellular and box-type raft foundations, where the foundation behaves as a stiff box section with significantly enhanced flexural rigidity relative to a solid slab of equivalent material volume [13,14]. The stiff box section system increases the moment of inertia of the foundation section and expands its ability to resist overturning moments while reducing the material consumption. Additionally, the geometry of the proposed system is inspired by the geometric ratios recommended by the literature for hollow or cellular foundation systems. Li et al. [10], in their study of cone-shaped hollow reinforced concrete foundations for wind turbines, suggested a slab thickness equivalent to 20% of the footing height and a wall thickness of approximately 15% of the footing height.

The final geometry consists of a total footing thickness of 2.64 m, including a 0.25 m thick upper slab, a 1.64 m thick cellular area, and a 0.75 m thick lower slab. The radial ribs have a thickness of 0.30 m to connect the upper and lower slabs of the footing and to create a series of enclosed cells distributed around the central pedestal. The selected cross-section dimensions are consistent with the reusable cellular raft proposed by Mohamed et al. [9], who investigated a 16 m diameter cellular raft with an active stabilization system and employed the same thicknesses of upper and lower concrete slabs. Unlike the system that uses movable wagons controlled by sensors, which is investigated by Mohamed et al. [9], this study focuses on investigating a fully integrated cellular raft foundation and its interaction with the supporting soil through numerical modeling.

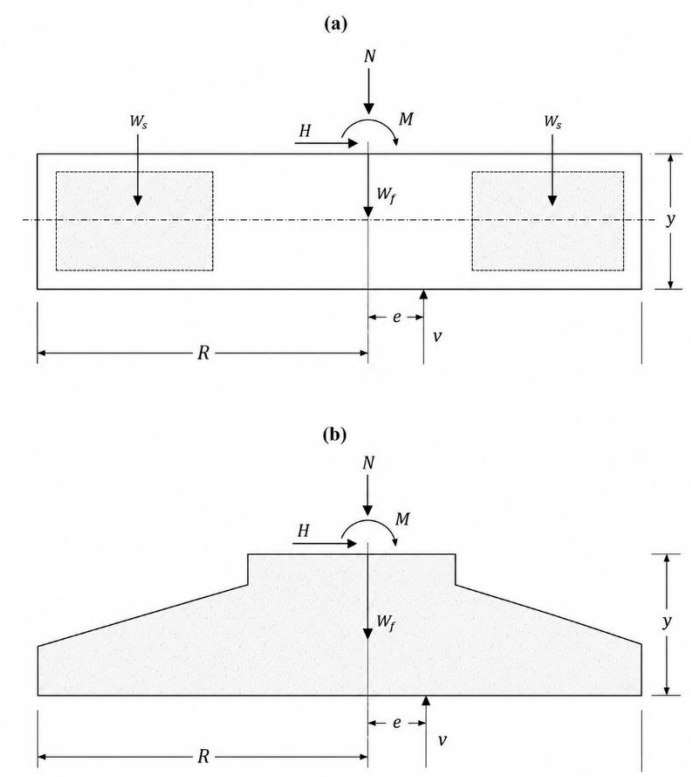


Fig. 3 Loading configuration applied to the analysed foundation systems: (a) cellular raft and (b) conventional gravity-base foundation.

2.3. Design Loads Assessment

The design loads applied to the footing for analysis of the present study are calculated from the wind load assessment performed for the Vestas V80 2MW wind turbine operating at the Red Sea coast of Egypt. The calculations were undertaken to determine the horizontal wind forces and overturning moments transmitted to the foundation base, which are considered the governing loads in the design of the onshore wind turbine foundations. Accurate estimation of the wind loads was conducted in accordance with the Egyptian Code of Practice for Loads and Forces in Structures (ECP 201-2012) [15], specifically the provisions related to cylindrical tower structures. The wind turbine specifications are 80 m rotor diameter, 60 m tower height, and an operational wind speed extending from 4 m/s to 25 m/s. As obtained from the Egyptian wind atlas, the wind velocity was specified at 42 m/s for the wind farm area for design purposes, representing the maximum wind conditions for the project location [16].

In accordance with ECP 201-2012 [15], the resultant wind force acts at a height equal to 0.6 times the tower height. Therefore, in the case of the Vestas V80 wind turbine, the resultant force acts at 36 m above the foundation level. Using the prescribed code equations, the horizontal force and the corresponding overturning moment at the tower base were 688 kN and 24.8 MN·m, respectively. These values were used as the loading parameters in the numerical analyses of both the conventional gravity-based foundation and the proposed cellular raft foundation. The calculated wind actions were applied as equivalent static loads at the foundation level during the finite element analyses. This approach is consistent with the conventional foundation design principles, where the most critical operational loading condition is represented by the combined action of the vertical tower loads, horizontal wind load, and the associated overturning moment.

The vertical load (N) represents the self-weight of the tower, nacelle, rotor assembly, and related turbine components transmitted concentrically through the pedestal. The horizontal wind force (H) was applied as a lateral load at the pedestal center, while the corresponding overturning moment (M) was applied about the foundation centroid to simulate the moment generated by wind action on the turbine tower and rotor, as shown in Fig. 3. This loading arrangement reproduces the actual load transfer mechanism of onshore wind turbines, where the environmental loads are distributed to the supporting soil through the foundation system. Fig. 3(a) shows the

simplified loading arrangement applied to the cellular raft foundation. The foundation is modeled as a circular rigid system subjected to combined vertical, horizontal, and moment loading at the pedestal location. The horizontal load and overturning moment exert eccentric loading conditions that shift the resultant force (V) away from the foundation center by an eccentricity (e). Therefore, the stress distribution beneath the foundation becomes non-uniform, increasing the compression side and decreasing the uplift side. This loading condition is considered the critical design scenario for the wind turbine foundations and forms the basis for the evaluation of the settlement behavior, bearing pressure distribution, and overturning stability.

The same loading configuration was applied to both foundation systems for a direct comparison of the behavior and to allow the influence of the cellular raft geometry on the foundation behavior. As for the conventional gravity-based footing, the resistance against overturning is primarily dependent on the self-weight of the massive concrete foundation (W_f). For the cellular raft foundation, the weight of the compacted soil filling the cells (W_s) was considered part of stabilizing resistance.

2.4. Analytical overturning-capacity framework

An analytical framework was developed to evaluate the overturning resistance of the proposed cellular raft foundation and to provide an independent verification of the numerical modeling results. The developed framework acts as a preliminary tool for examining the influence of the footing geometry on the overturning stability under the wind turbine's loading conditions explained in the previous section. The analytical calculations used the principles of the static equilibrium and foundation stability concepts and were applied to the two foundations of the study.

High eccentric stress distribution beneath the foundation is created due to the combination of the large vertical loads, horizontal wind forces, and overturning moments. These stresses induce uplift on one side of the foundation if insufficient stability resistance is available. The analytical framework assumed that the foundation behaves as a rigid body, as the dimensions and the stiffness of the reinforced concrete foundation are relatively large in accordance with the expected deformations. Previous studies have shown that the overturning resistance of the gravity-base wind turbine foundations is controlled mainly by their self-weight, geometric dimensions, and the stabilizing moment generated by the foundation mass [10,17]. Therefore, rigid body equilibrium provides an appropriate basis for the estimation of overturning stability and load eccentricity. The overturning moment assessment was performed by comparing the overturning moment (M_t) generated by the applied loads with the total stabilizing moment (M_s) developed by the foundation weight about the toe of the foundation. The total stabilizing force included the self-weight of the concrete foundation, the weight of the tower, and, in the case of the cellular raft, the weight of the compacted soil contained within the cells. The corresponding lever arm of each component is evaluated with respect to the assumed rotation point. Morgan et al. [18] suggest defining a safety factor against overturning in relation to the stability moment as one method of preventing overturning. The safety factor against overturning is given as:

$$f_s = \frac{M_s}{M_t} \geq 1.5 \tag{1}$$

where M_t is the total overturning moment which can be calculated,

$$M_t = M + Hy \tag{2}$$

where (M) is the structural overturning moment, (H) is the horizontal wind force, and (y) is the vertical distance between the foundation base level and the point of application of the horizontal force.

The eccentricity of the resultant vertical load is determined to evaluate the location of the resultant force (V) within the foundation base. The evaluation of this parameter is important for the wind turbine foundation as it influences the stress distribution beneath the foundation base. Foundations showing smaller eccentricity are considered to have higher resistance to overturning. The resultant vertical load (V) can be determined from:

$$V = N + W_f + W_s \tag{3}$$

where (W_s) is the weight of the soil filling the cells, in the case of the cellular raft. The compacted soil in the voids of the cellular raft is assumed to act compositely with the surrounding concrete mass and contribute to the stability of the foundation system, since the cellular sections are enclosed by reinforced concrete ribs and slabs, preventing the lateral displacement of the filling material under loading.

Szerző [19] offers a recommendation that concentrates on eccentricity limitations instead. The limits of the eccentricity should be fulfilled according to Equation 4.

$$e = \frac{M_s}{V} \begin{cases} \leq 0.25\,R & \text{, for serviceability limit state} \\ \leq 0.58\,R & \text{, for ultimate limit state} \end{cases} \quad (4)$$

The overturning capacity calculations were estimated using the ultimate limit state (ULS) eccentricity criteria proposed by Szerző [19], which limit the eccentricity to 0.58 times the radius of the footing (R). This study focuses primarily on the assessment of the maximum overturning resistance and ultimate load-bearing capacity of the investigated foundation systems under extreme wind loading. Under such conditions, the performance of the foundation systems is governed by stability requirements associated with overturning, uplift, and bearing capacity failure rather than serviceability considerations. Consequently, the ULS eccentricity limit is selected as the more suitable basis for evaluating the ultimate stability of the foundation systems and comparing the resistance of the conventional gravity-based foundation and the proposed cellular raft foundation.

The objective of the analytical model was to evaluate the available stabilizing moment and the resulting eccentricity of loading rather than to simulate local soil separation or nonlinear contact behavior. Such effects were considered within the finite element analyses, which provide a better representation of the soil-foundation interaction. The resulting analytical computations provide a clear understanding of the mechanism through which the cellular raft resists the overturning loading conditions while reducing the concrete demand.

2.5. Parametric analytical study — diameter and tower weight

A parametric analytical study was performed to investigate the impact of the foundation diameter and tower weight on the overturning capacity of both the conventional gravity-base foundation and the proposed cellular raft foundation. The parametric study is part of the analytical assessment framework developed for the Vestas V80 2MW wind turbine considered in the current research. The approach for the study was analytical and based on the equilibrium overturning capacity equations presented in the previous section. This approach is adopted because it enables direct evaluation of the impact of an individual design parameter on the foundation stability without computational complexity. The investigation focused on two parameters that play a primary role in determining the stability of gravity-based foundation systems: foundation diameter and tower vertical load. The foundation diameter influences the lever arm available to generate the resistance moments. To isolate the influence of these parameters, all other variables were kept constant throughout the analysis.

Four tower vertical loads of 2000, 3000, 4000, and 5000 kN were considered. These values were selected to represent the range of vertical loads transferred from alternative tower configurations and future repowering scenarios involving the Vestas V80 2MW turbine. Veers et al. [20] emphasized that future wind energy development will rely on larger turbines, increased hub heights, and improved structural efficiency to meet growing energy demands. Although the rated power output remains unchanged, an increase in associated modern structural mass can significantly change the load transferred to the foundation, making the tower weight a key parameter in the design and life-extension assessments [21]. Repowering commonly involves replacing the current turbines with new advanced units while maintaining the existing infrastructure, which includes foundations, access roads, and electrical networks. Typically, modern turbines of similar rated capacity are equipped with larger rotors to improve energy production, resulting in increased vertical loads acting on the foundation. The evaluation of the influence of tower weight on overturning capacity provides insight into the ability of the proposed cellular raft to accommodate future turbine upgrades without requiring complete foundation replacement. The vertical tower load (N) was set at 2000 kN for the baseline scenario, whereas the associated horizontal wind load (H) and overturning moment (M), derived from the wind load evaluation, were determined to be 688 kN and 24.8 MN·m, respectively. The diameter was maintained at 16 m, corresponding to the dimensions of the reference foundation currently employed at the site.

The total foundation depth (y) was taken as 2.64 m for both foundation systems. The self-weight of the foundation geometry and the unit weight of concrete are taken as 25 $\mathrm{kN/m^3}$. The self-weight of the cellular raft configuration was calculated as 7,666 kN compared with the 15,481 kN for the conventional gravity-base foundation. The enclosed cells are assumed to be filled with compacted soil having a unit weight of 20 $\mathrm{kN/m^3}$. An additional stabilizing soil weight (W_s) is calculated to be 274 kN, whereas no soil infill contribution was considered for the conventional foundation. The weight of each cell was determined based on the respective cell volume and the unit weight of the compacted infill material. The stabilizing moment contribution of each soil-filled cell was calculated by multiplying the cell weight by the corresponding lever arm, measured from the cell's centroid to the critical

overturning edge of the foundation. The overall stabilizing moment produced by the soil infill was derived by aggregating the moment contributions from each individual cell. This methodology was implemented to reflect the true distribution of the infill material within the foundation, rather than representing the total soil mass as a singular resultant force. The computed stabilizing moment reached 188.30 MN·m for the cellular raft foundation and 139.84 MN·m for the traditional gravity-base foundation. The applied overturning moment was consistently maintained at 24.8 MN·m for both systems, facilitating a direct comparison of the effects of foundation geometry and mass distribution on overturning resistance. Fig. 4 represents the influence of the tower weight on the overturning moment resistance of a 16 m diameter foundation for both the cellular raft and conventional gravity-base systems. As the tower weight increases from 2000 to 5000 kN, the allowable overturning moment of the cellular raft increases from approximately 129 MN·m to 144 MN·m, whereas the conventional gravity-base

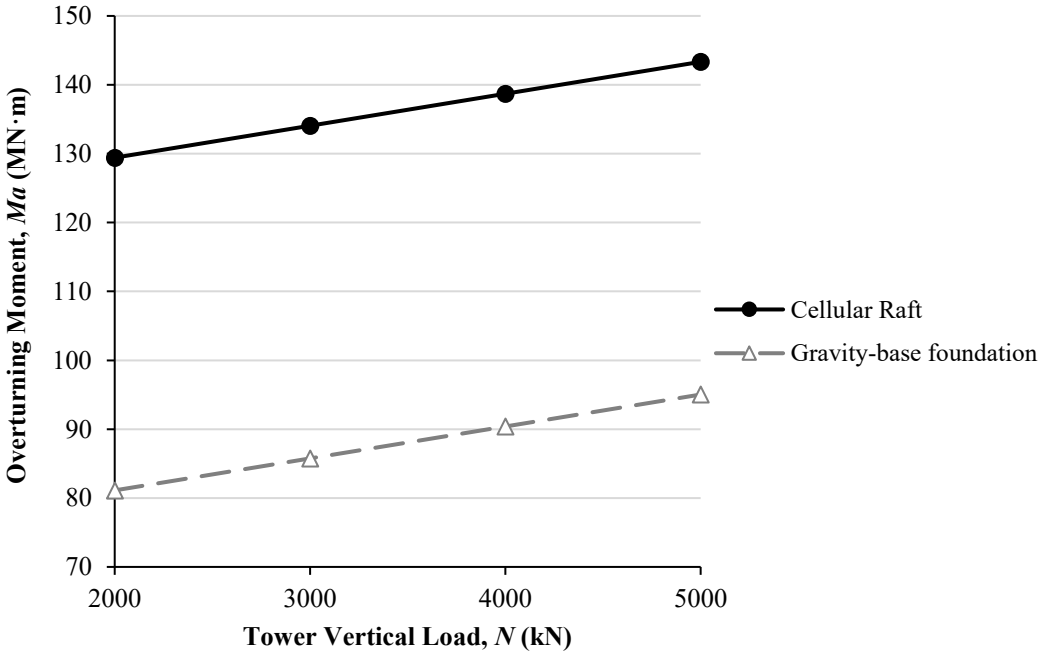


Fig. 4 Effect of tower vertical load on the allowable overturning moment of the cellular raft and conventional gravity-base foundations (D = 16 m).

foundation displays a lower increase from 81 MN·m to 95 MN·m. The difference between the two systems remains relatively constant, with the cellular raft providing approximately 50-60% higher overturning capacity than the corresponding gravity-based foundation. The similar line slopes suggest that both foundation systems respond similarly to the increase in tower weight. This implies that the adoption of the cellular raft configuration provides an improved overturning resistance compared to depending solely on increased structural weight.

Fig. 5 represents the variation of the overturning resistance capacity of the proposed cellular raft and the conventional gravity-based foundation at diameters 12, 14, 16, and 18 m. For both foundation systems, increasing the diameter from 12 m to 18 m results in an increase in overturning capacity. The chart demonstrates an improvement exceeding 45-50% under several loading cases. This finding suggests that the stability requirements may be satisfied using reduced concrete volume and potentially a smaller foundation diameter. This behavior suggests that the reductions in concrete demand in cellular rafts would lower excavation requirements, material consumption, and construction-related carbon emissions, therefore improving the overall sustainability and stability of the wind turbine foundation systems.

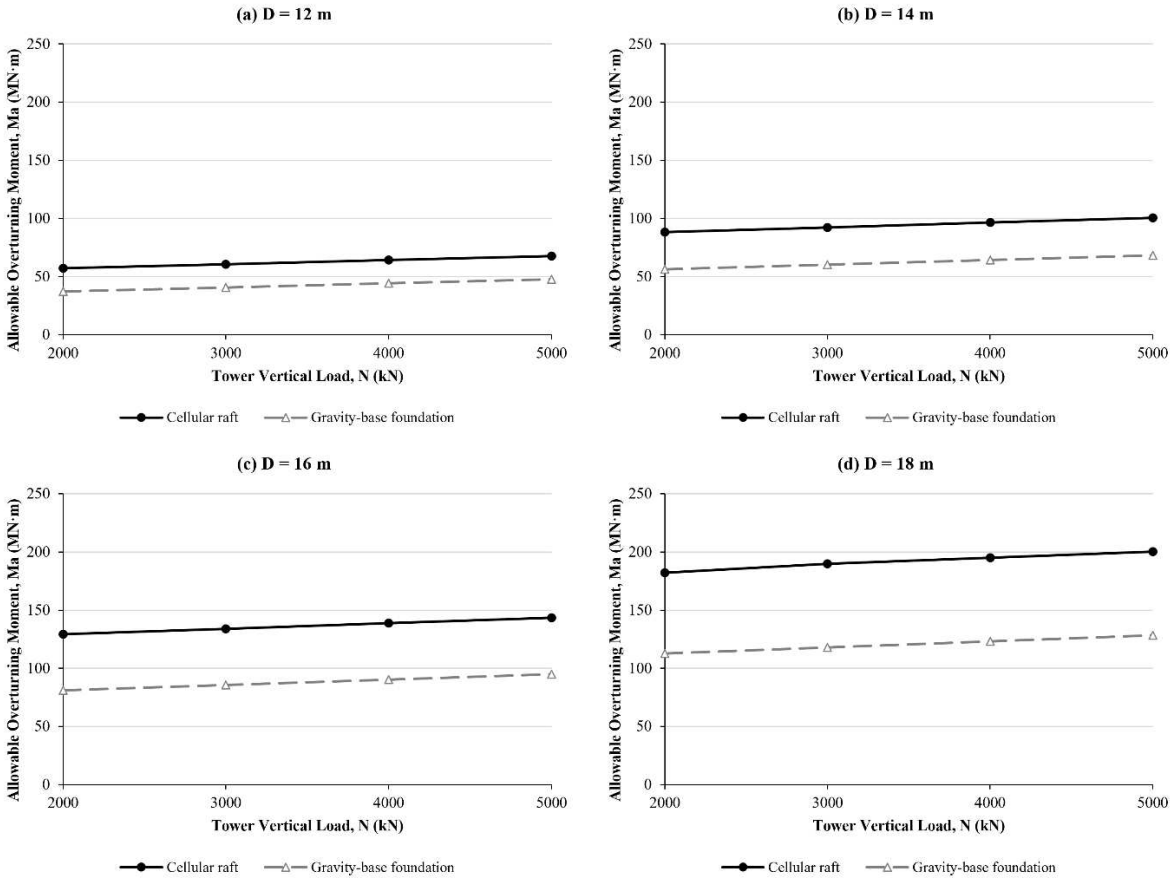


Fig. 5 Effect of tower vertical load and foundation diameter on the allowable overturning moment of the cellular raft and conventional gravity-base foundations: (a) D = 12 m, (b) D = 14 m, (c) D = 16 m, and (d) D = 18 m.

3. Numerical Modelling Framework

3.1. Verification of the Finite Element Model

The verification results illustrated in Fig. 6 indicate a strong correlation between the PLAXIS 3D model created in this work and the Abaqus 6.13 model previously documented by Mohamed et al. [9]. All materials, geometric dimensions, boundary conditions, and analysis procedures adopted in the verification model were reproduced as closely as possible from the Abaqus model to allow direct comparison between the two finite element platforms. The cellular raft has a total depth of 3.0 m and a diameter of 16 m. The soil infill contained within the cellular zone had a unit of weight of 22 kN/m^3, corresponding to the compacted granular material used in the reference study. The soil profile for the verification model was represented using a Young's Modulus of 26 MPa, a total unit weight of 18 kN/m^3, an effective unit weight of 8 kN/m^3, an effective friction angle of 33°, and zero cohesion, representing a cohesionless granular soil profile.

The moment-settlement responses derived from the two numerical platforms demonstrate a consistent overall trend during the loading process, suggesting that the employed modeling assumptions, material constitutive models, boundary conditions, and analytical procedures effectively replicate the behavior of the reference case. As loading advances towards the final state, both curves exhibit a significant decline in load-carrying capability, coupled with a severe increase in settlement, indicative of foundation systems nearing instability under overturning conditions.

The strong alignment between the two numerical predictions encourages confidence in the PLAXIS 3D model's capacity to accurately represent the essential soil-foundation interaction mechanisms that determine the behavior of cellular raft foundations. The agreement noted during the elastic and intermediate loading stages indicates that modeling the concrete foundation as a linear elastic material and employing the Mohr-Coulomb constitutive model for the surrounding soil yields a satisfactory approximation of the behavior documented by Mohamed et al. [9]. The peak overturning moment predicted by PLAXIS differed by 10.9% from the digitized Abaqus results, indicating a reasonable prediction of the ultimate foundation capacity. The calculated correlation coefficient (R =

0.879) and coefficient of determination (R^2 = 0.773) further confirmed the strong relationship between the two datasets and their similar nonlinear response characteristics. The agreement between the two numerical models improves progressively as the loading increases. At large settlements approaching the ultimate response, the difference is relatively small between Abaqus and PLAXIS models, which reaches less than 3% at the settlement 0.228 m and reduces to a negligible value at the maximum settlement considered in the comparison. The reason behind the large discrepancies at relatively small settlements is explained by the fact that the PLAXIS model predicts a stiffer initial response than the Abaqus simulation. This finding aligns with prior research on wind turbine and raft foundations, indicating that Mohr-Coulomb-based numerical models yield satisfactory predictions of global foundation behavior, particularly when the primary objective is to assess overall stability and bearing response rather than involved local soil deformation mechanisms [10,22].

Numerical simulations are affected by various parameters, such as element formulation, stress integration algorithms, contact treatment, mesh discretization methods, convergence tolerances, and the use of constitutive models. Prior verification studies have shown that even with identical geometries and material properties, divergences between commercial finite-element codes are frequently noted, especially during highly nonlinear loading phases where plastic strains localize and contact conditions change [23, 24]. The minor discrepancies noted in Fig. 6 are deemed acceptable and align with the range commonly documented in numerical benchmarking studies [25]

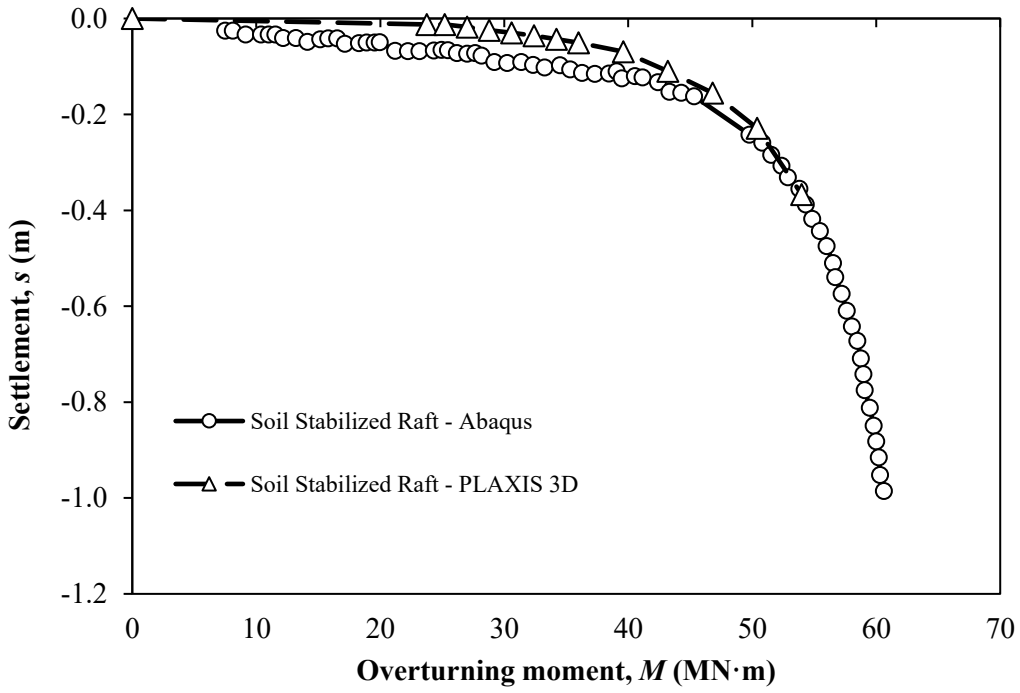


Fig. 6 Verification of the PLAXIS 3D finite-element model based on the moment–settlement response of the cellular raft foundation compared with the Abaqus results reported by Mohamed et al. [9].

The verification results additionally offer implicit validation for the theoretical framework behind the current study. The cellular raft concept is based on the interaction between the solid framework and the stabilizing soil within the interior cells. Mohamed et al. [9] initially showed that utilizing the weight of constrained soil can markedly improve overturning resistance while decreasing concrete usage. The PLAXIS model's capacity to replicate the documented moment-settlement behavior demonstrates that the stabilizing mechanism linked to the cellular arrangement is sufficiently illustrated. This is especially significant as the present study broadens the use of the cellular raft idea to wind turbine foundations, where overturning loads, rather than traditional bearing capacity factors, influence design.

From a practical perspective, successful verification is an essential requirement for the subsequent analyses conducted in this work. The validated numerical model offers a dependable framework for evaluating the performance of the proposed cellular raft foundation under wind turbine loading circumstances and for contrasting its behavior with that of the traditional gravity-based foundation utilized at Gabal El-Zeit Wind Farm. Thus, the

conclusions drawn from the parametric analyses and performance evaluations are validated by a numerical model that has been validated against an independently produced and previously published reference solution.

3.2. Numerical Performance of Cellular and Conventional Foundations

Three-dimensional finite element analyses were conducted using PLAXIS 3D to evaluate and compare the performance of the conventional gravity-based foundation constructed at the Gabal El-Zeit wind farm and the proposed cellular raft foundation. Both foundations were examined under the same loading conditions. Owing to the geometric symmetry of the foundation systems and loading arrangement, only half of the soil foundation domain was modeled to improve computational efficiency while maintaining computational accuracy. The lateral boundaries were extended 50 m from the foundation edge in all horizontal directions, and the lower boundary was extended 15 m below the ground surface. These boundaries were selected to extend beyond the zone of significant stress influence beneath the foundation, consistent with recommendations for shallow-foundation finite-element analyses. The lateral boundaries of the model were restrained against horizontal displacement, while vertical movement was allowed. The bottom boundary was similarly constrained in the horizontal directions while remaining free to move vertically. The mesh was generated automatically using 10-noded elements with 67,759 three-dimensional soil elements produced with local mesh refinement. A fine mesh was adopted around the foundation, with progressively coarser elements were used with increasing distance from the foundation. This approach is recommended in finite element analyses to concentrate the computation accuracy and effort in the regions where stress distribution and deformations are typically pronounced. On the other hand, minimizing unnecessary refinement in areas subject to uniform stress conditions [22,24]. The foundation geometry and dimensions used in the finite-element model correspond to those described in Section 2.2 and shown in Fig. 2. The conventional gravity-base foundation was modelled using its corresponding solid geometry to allow a direct comparison under identical loading conditions.

A mesh sensitivity analysis was conducted prior to the final simulations to confirm that the numerical findings were not significantly affected by the selected mesh density. The comparison was predicated on the maximum settlement under the operational design loading condition, which corresponds to a horizontal load of 650 kN and an overturning moment of 23.76 MN·m. The settlements obtained from the coarse, medium, and fine meshes were 20.90 mm, 12.45 mm, and 12.14 mm, respectively. The difference between the medium and fine meshes was only 2.6%, indicating that the numerical solution had effectively converged and that further mesh refinement would result in only marginal changes to the predicted response. The fine mesh was utilized for the numerical computations in this study, since it ensured adequate precision in representing the soil–foundation interaction while maintaining a reasonable computational workload.

The material properties used in the numerical analyses were derived from the geotechnical investigation conducted at the Gabal El-Zeit wind farm and the design specifications of the reinforced concrete foundation. The complete soil and concrete material properties are summarized in Table 2.

Table 2. Material properties adopted for the finite-element analyses of the Gabal El-Zeit foundation systems.

Material	**Young's Modulus**	**Unit weight**	**Effective unit weight**	**Internal Friction Angle**	**Cohesion**	**Poisson's Ratio**
	(E)	(γ)	(γ')	(φ)	(c')	ν_s
	MPa	kN/m^3	kN/m^3	°	**kPa**	
Gabal El-Zeit Soil Properties	26	20	8	31.3	0	0.35
Concrete	33	24	-	-	-	0.2

The finite-element simulations were performed incrementally by increasing the horizontal wind load while maintaining the specified vertical tower load, with the corresponding overturning moment applied simultaneously. The resulting foundation settlement and overturning response were monitored throughout the loading process. The finite element analyses were performed by maintaining a 16 m diameter foundation and with a full thickness

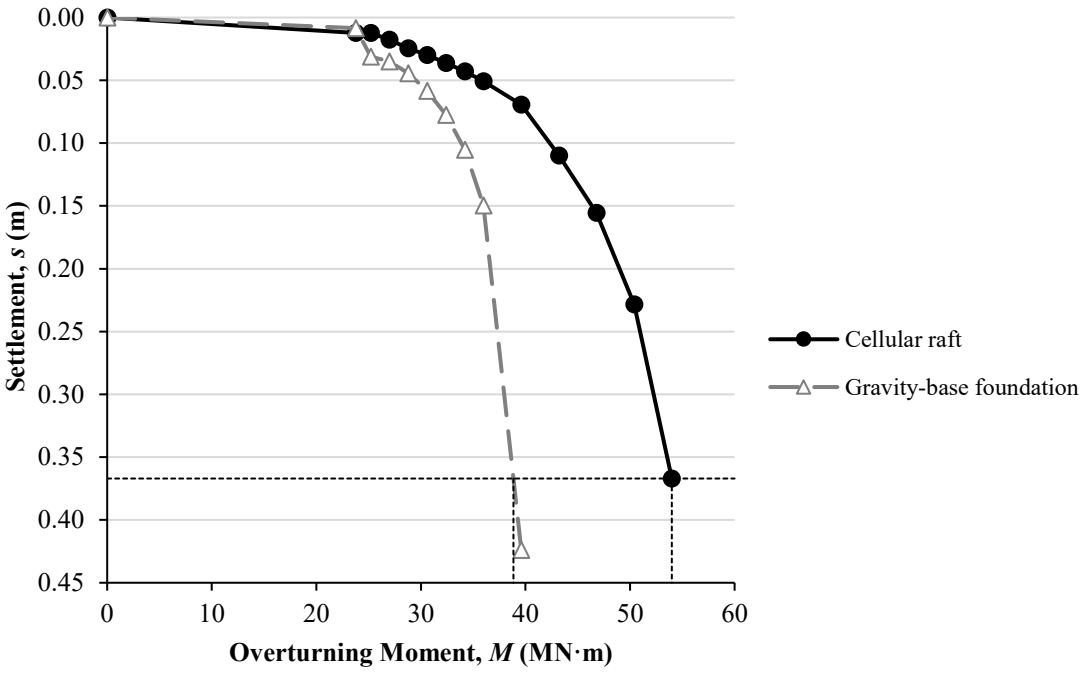


Fig. 7 Moment–settlement response of the conventional gravity-base and cellular raft foundations obtained from the finite-element analyses (D = 16 m).

of 2.64 m, and a vertical tower load of 2000 kN, while progressively increasing the horizontal wind load from 650 kN to 1600 kN, corresponding to the range of the regional wind speeds. The applied overturning moment rises proportionally with the horizontal load, ranging from 23.76 MN·m to 57.60 MN·m. The maximum load was monitored to evaluate the response of the foundation systems under increased overturning demand.

The moment-settlement response presented in Fig. 7 clearly shows the superior overturning resistance of the cellular raft configuration proposed by the study compared with the conventional gravity-base foundation. Both foundations demonstrate a similar response trend, characterized by an initial high stiffness region followed by progressive stiffness degradation while the overturning moment increases. At low moment levels, both footings experience relatively small settlements, indicating that the applied moments are resisted initially through the elastic deformation of the soil-foundation system. When the overturning moment exceeds approximately 25 MN·m, the conventional gravity-based foundation demonstrates a more accelerated increase in settlement, indicative of the progressive concentration of stresses beneath the compressed edge of the footing and the gradual mobilization of soil bearing capacity. On the contrary, the cellular raft exhibits a noticeably stiffer reaction, with settlement escalating at a considerably slower rate for the equivalent level of applied moment.

The settlements presented in Fig. 7 relate to conditions approaching the ultimate overturning capacity of the foundation systems and so do not reflect actual operational serviceability settlements. An additional analysis was conducted to evaluate the foundation performance under typical operating conditions at the maximum operational wind speed of the Vestas V80 turbine (25 m/s). The finite-element study indicated a maximum settlement of approximately 10.7 mm. This value is substantially lower than the settlements observed near failure and indicates a substantially less severe deformation response under the examined service-loading condition. The significant settlements shown in the moment-settlement curves should be considered as ultimate-limit-state behavior indicative of foundation instability, rather than predicted in-service performance.

The distinction between the two systems becomes most apparent at elevated levels of deformation. For a settlement of about 0.42 m, indicative of an ultimate deformation condition, the traditional gravity-based foundation generates an overturning moment of around 40 MN·m. At the same time, the cellular raft endures approximately 55 MN·m. This indicates an increase in overturning resistance of roughly 37.5%. The enhancement is credited to the cellular structure, which allows the compacted soil infill to directly contribute to the stabilizing mass while preserving a substantial effective foundation footprint.

The analytical calculations anticipated a maximum overturning moment capacity of 84.2 MN·m for the cellular raft foundation. In comparison, the finite-element model estimated an ultimate overturning resistance of 57.6 MN·m, yielding a discrepancy of around 32%, as shown in Table 3. This difference is mostly due to the simplifying assumptions included in the analytical computations. The analytical method presumes that the stabilizing forces produced by the foundation's self-weight and the soil infill are entirely activated, and that the foundation functions as a rigid body under idealized force equilibrium conditions. Given these assumptions, the total stabilizing weight efficiently contributes to counteracting overturning through the designated lever arms.

Table 3. Comparison between the ultimate overturning moment predicted by the analytical calculations and the finite element model for the 16m diameter cellular raft foundation under a vertical tower load of 2000 kN

Vertical Load	**Diameter**	**Ultimate Overturning Moment [Analytical Computations]**	**Ultimate Overturning Moment [Finite Element Model]**	**Difference**
kN	m	MN·m	MN·m	%
2000	16	84.2	57.6	32

The finite element model considers actual stress distribution within the soil-foundation system, which involves non-uniform contact pressure development, progressive soil yielding, stress concentration beneath the loaded edge of the foundation, and the reduction of the effective contact area as overturning increases. Therefore, not all segments of the foundation's weight contribute equally to overturning resistance during the loading phase. As the applied moment becomes greater, compression increases near the toe of the foundation, whereas areas on the opposing side exhibit reduced contact stresses, leading to a mobilised stabilising moment that is inferior to that anticipated by the analytical equilibrium model. The ultimate capacity obtained from the numerical model reflects both strength and deformation limitation, whereas the analytical method represents a theoretical upper-bound estimate based on force equilibrium. Although there is an observed discrepancy, both methodologies predict the identical overall behavioural pattern and illustrate the increased overturning resistance provided by the cellular raft principle. The analytical model is beneficial for initial design and parametric evaluation. In contrast, finite-element analysis offers a more accurate depiction of the final response by integrating soil deformation, stress redistribution, and soil-foundation interaction effects.

3.3. Parametric study — backfill relative density

The soil used to fill the internal cells of the cellular raft can be considered backfill. At the Gabal El-Zeit Wind Farm, the natural ground consists predominantly of cohesionless soil, which was considered as the source of the infill material. The excavated soil is assumed to be placed and compacted within the cells before installation of the upper concrete slab. Therefore, the degree of compaction and resulting relative density may influence the stability and performance of the proposed cellular raft system. Mujtaba et al. [26] suggested Equation 5 based on an analysis of a similar soil that resulted in the proposal of a correlation between relative density, overburden stress, and SPT-N value as follows:

$$D_r = 1.96N_{60} - 19.2\left(\frac{P_a}{\sigma_v{}'}\right)^{0.23} + 29.2 \quad (5)$$

Such that,

D_r is the relative density of soil, expressed as a percentage

N_{60} is corrected SPT number of blows

P_a is the atmospheric pressure (kPa)

$\sigma_v{}'$ is the effective overburden pressure (kPa)

According to Mujtaba et al. [26], the friction angle for soil strata ranging from loose to highly dense can be determined using the following linear relation in Equation 6, as shown below. The relationship was further evaluated using an independent dataset.

$$\varphi = 0.276D_r + 18.7 \quad (6)$$

Bowles JE [13] suggests that the soils from a loose to dense state would range between 15 and 65%, and the bulk unit weight ranges between 14.9 and 20.4 kN/m^3. Using Equations 5 and 6, the relative density of the soil beneath the footings in Gabal El Zeit could be predicted. A range of relative densities of $\pm$20 % will be tested, and the soil properties are predicted, tabulated, and used as input for the soil material in PLAXIS 3D models. These conditions represent loose, medium-dense, and dense backfill states, respectively. The three soils are labelled Soil 1, with a relative density of 25%; Soil 5, with a relative density of 45%; and Soil 9, with a relative density of 65%. Therefore, soil 1 represents the loose state, and soil 9 is the very dense state. According to the geotechnical report of the wind farm in Egypt and the borehole log, the internal friction angle ϕ is equal to 31.1°. As a result, the relative density of the in-situ soil is about 45%. The backfilling soils for the parametric study are shown in Table 4.

Table 4. Calculated Soil Properties for Backfilling Soil in relation to Relative Density

	D_r	φ	γ	γ'	γ_{sat}	e
	%	°	kN/m^3	kN/m^3	kN/m^3	
Soil 1	**25**	25.6	16.5	7.8	17.8	0.976
Soil 5	**45**	31.1	16.9	8	19.2	0.673
Soil 9	**65**	36.6	17.5	9.5	19.5	0.610

The results of the effect of changing the properties based on the relative densities of the filling soil are shown in Fig. 8. The graph represents the failure overturning moment of the footing against the relative settlement. At a settlement of approximately 0.39 m, the maximum overturning moment for the cellular raft with D_r = 45% is approximately 53 MN·m, compared with approximately 51 MN·m for D_r = 65%. This corresponds to a difference of approximately 5%, indicating a limited effect of increasing relative density from 45% to 65% on overturning capacity, which is a minor effect on the stability of the wind turbine footing subjected to a high overturning moment. The D_r = 25% condition resulted in substantially lower overturning capacity than the D_r = 45% condition. In contrast, increasing the relative density from 45% to 65% produced only a small change in overturning capacity. Then, it could be concluded that the loose soils with the range of relative density of 35-45% have significantly lower values of overturning capacity, causing similar settlement values. From medium to dense soils, the

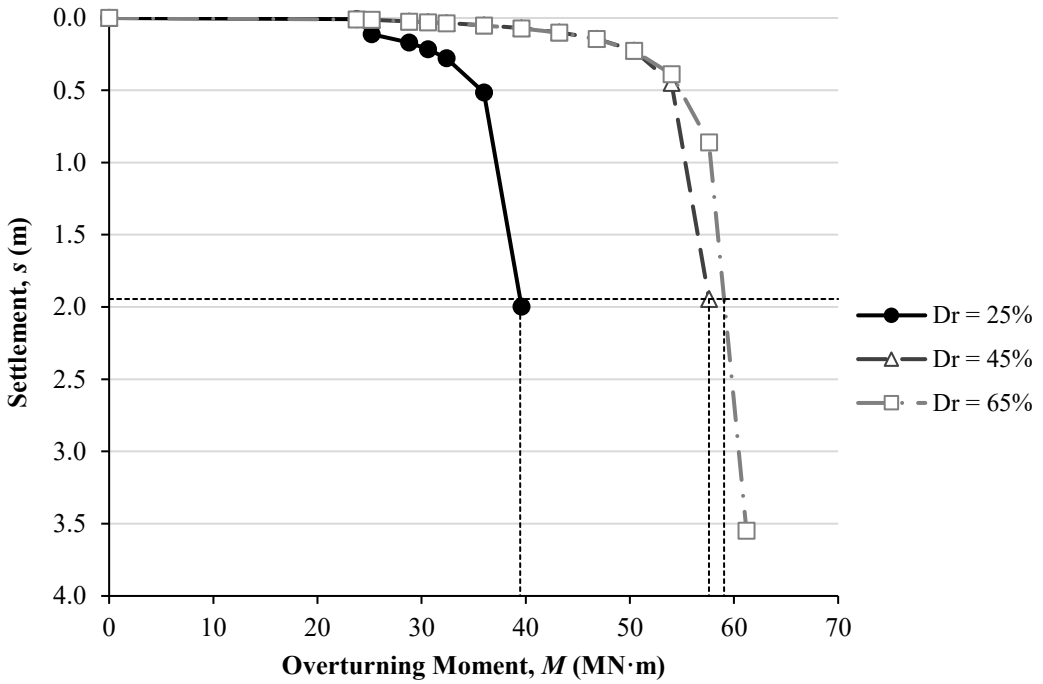


Fig. 8 Effect of soil relative density on the moment–settlement response of the cellular raft foundation obtained using PLAXIS 3D.

difference between the capacities is insignificant; however, the settlement increases by a significant portion due to the increase of the normal weight of the footing because of the higher density of the soil filling the voids.

4. Cost Comparison of the Foundation Systems

A preliminary cost analysis was performed to evaluate the economic efficiency of the gravity-based foundation in relation to the proposed cellular raft foundation. The comparison included the primary construction elements related to each foundation system, including excavation works, blinding concrete, structural concrete, reinforcement steel, and, for the cellular raft, the compacted soil infill within the interior compartments. Unit rates were derived from prevailing prices in the Egyptian construction market and were uniformly applied to both foundation options.

The findings demonstrate a significant decrease in overall construction costs with the implementation of the cellular raft configuration. The projected cost of the traditional gravity-based foundation was roughly EGP 7.13 million per unit, whereas the suggested cellular raft foundation necessitated about EGP 5.61 million. This equates to a total cost reduction of around EGP 1.52 million per foundation, signifying a savings of nearly 21.4%.

It should be noted that the present economic assessment focuses primarily on material-related costs, including excavation, concrete, reinforcement steel, and soil infill. Other cost components, such as labor requirements, equipment utilization, construction duration, transportation, formwork, and site management expenses, were not explicitly considered. Although these factors may influence the overall project cost, the substantial reductions in excavation volume, concrete consumption, and reinforcement demand observed for the cellular raft foundation suggest that additional savings may also be achieved during construction. The principal source of savings is the substantial decrease in concrete usage. The traditional foundation necessitates roughly 312 m³ of structural concrete, but the cellular raft demands merely 84.8 m³, indicating a decrease of approximately 72.8%. This reduction directly lowers expenses associated with materials, transportation, placement, and vibration. The excavation amounts have decreased from around 619 m³ to 168 m³, yielding a nearly 73% reduction in earthworks. Although the cellular structure requires additional compacted soil infill, the reported cost comparison indicates that the reduction in concrete, excavation, and reinforcement costs outweighs the included infill cost. Therefore, the reported 21% reduction should be interpreted as a material-cost saving rather than a total project-cost saving.

Reinforcement steel constitutes the primary cost element for both foundation systems. The conventional foundation necessitates around 433.6 tonnes of reinforcement steel, whereas the cellular raft requires roughly

356.2 tonnes, resulting in a reduction of approximately 17.9%. Given that reinforcement constitutes the most substantial individual building expense, even a modest decrease in steel quantity yields considerable economic advantages for the cellular form.

The cost savings obtained by the cellular raft are especially significant when evaluated in combination with its structural performance. The numerical and analytical evaluations revealed that the cellular raft exhibits greater overturning resistance compared to the conventional foundation, while concurrently minimizing material usage. Thus, the proposed solution offers both structural and economic benefits. Substituting substantial concrete volumes with compacted earth infill allows the foundation to retain stabilizing weight while decreasing the use of expensive and high-carbon construction materials. The cellular raft concept presents significant promise for enhancing the economic feasibility of forthcoming wind energy initiatives while concurrently diminishing the environmental impact linked to concrete manufacturing and construction processes. Since cement production remains one of the largest contributors to embodied carbon in infrastructure projects, reducing concrete consumption in wind turbine foundations can provide significant environmental benefits throughout the project life cycle [27].

5. Conclusions

This study evaluated the structural, geotechnical, and economic efficiency of a cellular raft foundation as an alternative to the conventional reinforced concrete gravity-base foundation developed for onshore wind turbines at the Gabal El-Zeit Wind Farm in Egypt. The objective of the study was to determine whether a cellular foundation design may improve overturning resistance while decreasing material usage and construction expenses. To achieve this objective, analytical calculations and three-dimensional finite-element simulations were performed utilizing uniform loading circumstances based on the Vestas V80-2 MW wind turbine and the site-specific geotechnical conditions at Gabal El-Zeit.

The analytical examination of overturning capacity showed that the cellular foundation generated substantially greater stabilizing moments compared to the conventional gravity-base foundation of identical diameter. Parametric analyses revealed that the cellular raft exhibited enhanced overturning resistance across various tower weights and foundation dimensions, with improvements surpassing 50% in certain conditions. The finite-element calculations validated the superior performance of the cellular design, exhibiting increased overturning capacity and enhanced stiffness retention during the loading history. The numerical findings indicated that the cellular raft effectively mobilized the stabilizing properties of the soil infill, thereby reducing dependence on large quantities of structural concrete. The analytical framework predicted improvements exceeding 50% under several parametric conditions, while the finite-element analyses indicated an increase of approximately 37.5% in ultimate overturning resistance for the studied foundation configuration. This difference reflects the idealized assumptions adopted in the analytical model and the more realistic soil-structure interaction captured by the numerical simulations. The economic evaluation indicated that the cellular raft might decrease overall foundation expenses by roughly 21% by significantly lowering excavation volume, concrete usage, and reinforcement needs.

The findings enhance the existing knowledge on sustainable wind turbine foundation systems by illustrating that foundation efficiency can be enhanced through optimized geometric layout instead of increasing concrete volume. The findings validate the theoretical principles of cellular and box-type foundation systems, wherein the separation of structural components through an internal cellular zone enhances structural efficiency and optimizes the mobilization of stabilizing weight. Consequently, the study demonstrates that various foundation geometries might yield both structural and economic advantages while maintaining stability performance.

The proposed foundation idea presents numerous benefits for wind energy projects. The decrease in concrete consumption directly diminishes building expenses and embodied carbon emissions, thereby supporting the growing emphasis on sustainable infrastructure development [28]. The improved overturning resistance and capacity to support increased tower loads indicate that the cellular raft may offer enhanced adaptability for future wind farm repowering initiatives, enabling existing foundation structures to sustain upgraded turbine systems while reducing the need for demolition and reconstruction.

Despite these encouraging results, several limitations should be recognised. The computational analyses utilized the Mohr-Coulomb constitutive model, which effectively represents overall soil behaviour but fails to account for advanced characteristics such as stress-dependent stiffness, cyclic loading effects, or progressive soil degradation [29]. The economic study concentrated mostly on material costs and did not explicitly incorporate manpower, equipment usage, construction sequencing, transit logistics, or long-term maintenance factors. The finite-element

verification was performed against a published numerical model instead of actual or full-scale field observations, hence constraining the scope of model validation. The limitations do not influence the major trends identified in the study but suggest opportunities for enhancing the analytical approach.

Future research should examine the behaviour of cellular raft foundations utilizing advanced constitutive models and cyclic loading conditions that simulate prolonged wind turbine operation. Experimental investigations and field-scale monitoring programs would offer significant confirmation of the numerical predictions and enhance confidence in the actual implementation of the concept. Further research should assess dynamic performance, fatigue behaviour, life-cycle costs, carbon footprint reduction, and the viability of cellular foundations for larger contemporary wind turbines and repowering scenarios.

Under the investigated geotechnical and loading conditions, the cellular raft foundation demonstrated potential as an alternative to the conventional gravity-base system for onshore wind turbines. The results are specific to the investigated foundation geometry, loading conditions, and geotechnical characteristics of the wind farm site and should not be generalized to other locations without further site-specific assessment. The suggested foundation concept integrates improved overturning resistance with substantial decreases in material usage and construction expenses, providing a viable solution for more cost-effective and sustainable wind energy infrastructure. The findings enhance the present comprehension of cellular foundation behaviour under wind turbine loads and lay the groundwork for future research and the application of resource-efficient foundation solutions in the renewable energy sector.

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