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# Analysis And Design Of A Gravity-Based Offshore Wind Turbine Foundation

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***Abstract :*** This project presents the structural modeling, analysis, and design of a gravity-based foundation (GBF) for a 3.6 MW offshore wind turbine located approximately 12–15 km off the Alibaug coast in Maharashtra, India. The site features moderate water depths (15–25 m), a stratified soil profile comprising soft silty clay overlying dense sand, and lies within Seismic Zone III as per IS 1893. A finite element model of the foundation was developed in SAP2000 v26.2.0 using shell elements on a rigid base, incorporating soil–structure interaction with a pinned supports. The structure was subjected to combined static and dynamic environmental loads including wind, wave, buoyancy, seismic, and hydrodynamic forces, with load combinations defined in accordance with IS 875, IS 2911, IS 1893, IEC 61400-3, and API RP 2A-WSD. The analysis verified stress distribution, deformation limits, and dynamic response under critical conditions, ensuring compliance with safety and serviceability criteria. Modal analysis confirmed that natural frequencies are well-separated from turbine operational ranges, and API-based integration of SAP2000 enabled real-time simulation capabilities aligned with digital twin concepts for predictive maintenance and lifecycle monitoring.

*Index Terms* - **Offshore wind turbine, gravity-based foundation, SAP2000, structural analysis, Alibaug Offshore Site, digital twin, environmental loads, code compliance, renewable energy, soil-structure interaction.**

## I. INTRODUCTION

This project presents a comprehensive structural modeling and design study of a gravity-based foundation (GBF) for a 3.6 MW offshore wind turbine, proposed to be installed approximately 12 to 15 kilometers west of Alibaug, Maharashtra, India, at coordinates around 18.62°N and 72.85°E. The selected site lies within a moderate water depth zone of 15 to 25 meters and features a stratified seabed profile composed of a 3 to 5 meter thick silty clay layer overlying dense sand or weathered rock, providing favorable geotechnical conditions and an estimated bearing capacity of 250 to 300 kPa. The region is categorized under Seismic Zone III as per IS 1893, indicating moderate seismic activity, which necessitates dynamic stability checks in the foundation design.

The structural system consists of a cylindrical reinforced concrete foundation with a radius of 10 meters and height of 5 meters, designed to resist overturning, sliding, and buoyant uplift primarily through self-weight. A concrete tower of 25 meters height and 3 meters radius is integrally connected to the base, serving as the support for the wind turbine rotor-nacelle assembly. The entire assembly is modeled in SAP2000 v26.2.0 using shell elements for both the foundation and tower to capture accurate stress distribution, deformation behavior, and local effects. The interaction between the foundation and seabed is modeled through linear pinned, incorporating soil stiffness derived from NIWE and NIOT geotechnical investigations.

The design incorporates all relevant environmental loads, including self-weight, hydrostatic pressure, wave action (using Airy wave theory for regular and irregular waves), wind pressure on the tower and turbine, buoyancy forces, ocean currents, and seismic acceleration, applied through load combinations as per IS 875 Part 3, IS 1893 Part 1 & 4, IS 2911, and international standards like IEC 61400-3, ISO 19902, and API RP 2A-WSD. A modal analysis is carried out to ensure that the structure's natural frequencies are well-separated from the turbine's operational and blade-passing frequencies, thereby preventing resonance. P-Delta effects are activated to account for geometric nonlinearity under high axial and overturning forces. The structure's performance is evaluated through static, dynamic, and response spectrum analyses, checking for displacement limits, stress levels, base reactions, and overall stability under service and ultimate limit states. To extend the foundation's functional lifespan and operational reliability, a digital twin interface leveraging SAP2000's Open API is proposed for real-time performance monitoring, predictive maintenance scheduling, and adaptive design tuning throughout the turbine's lifecycle.

Objectives :-

1.Design a gravity-based foundation (GBF) for a 3.6 MW offshore wind turbine suited to site-specific marine and soil conditions near Alibaug, Maharashtra.

2.Perform structural modeling and analysis using SAP2000, incorporating wind, wave, seismic, buoyancy, and current loads with appropriate load combinations.

3.Simulate soil–structure interaction using spring supports based on geotechnical data to accurately reflect seabed response.

4.Ensure structural safety and stability by evaluating displacements, stresses, and dynamic behavior under both service and extreme conditions.

5.Integrate digital twin capabilities through SAP2000's API for real-time monitoring, predictive maintenance, and long-term performance optimization.

Scope of the Study :- This study focuses on the structural design and analysis of a gravity-based foundation for an offshore wind turbine using SAP2000, based on site-specific data near off the Alibaug coast in Maharashtra, India.. It includes simulation of wind, wave, seismic, and soil-structure interactions, following relevant Indian and international codes.

## II. LITERATURE REVIEW

Offshore wind turbine foundation design has evolved significantly in recent decades with growing demand for renewable energy. Different types of foundations—including monopiles, jackets, suction buckets, and gravity-based foundations—are chosen based on water depth, soil type, and cost.

Gravity-Based Foundations (GBFs) have been widely used in Europe, especially in shallow waters with firm seabed conditions (e.g., Denmark's Middelgrunden and Sweden's Lillgrund wind farms). Studies by Bhattacharya (2014) and Zaaijer (2006) highlight GBFs' advantages in ease of installation and resistance to overturning moments, especially when placed on flat seabeds.

In India, limited offshore wind development has occurred so far, but government initiatives through the National Institute of Wind Energy (NIWE) have identified promising locations along the Gujarat and Maharashtra coasts. The pre-feasibility report by NIWE (2018) on offshore wind near Devgarh and Alibaug points to water depths of 10–30 m with clayey/silty seabed compositions—suitable for gravity-based designs.

Software such as SAP2000, STAAD.Pro, and ANSYS have been used to model offshore structures. SAP2000 is known for its dynamic analysis capabilities and scripting interface, making it ideal for digital twin integration and performance optimization of foundation systems.

## III. RESEARCH METHODOLORY

The design and analysis of the offshore wind turbine foundation began with comprehensive data collection. Bathymetric details and subsurface soil profiles were obtained from NIWE reports, while wind and wave data were sourced from INCOIS archives and satellite observations. Load parameters corresponding to a 3.6 MW turbine class were referenced from the manufacturer's specifications. In SAP2000, the foundation was modeled using shell elements resting on a rigid base, with soil-structure interaction simulated through pinned supports or distributed surface pressures. Structural loads included the self-weight of the tower, the nacelle load, and hydrodynamic wave forces. Various load combinations were evaluated, including Dead Load with Wind, Wave, and Seismic actions, as well as extreme event scenarios involving combined wave, wind, and seismic forces. The analysis suite included static analysis for ultimate limit states (ULS), modal analysis to identify natural frequencies, and time history or dynamic analysis for fatigue life estimation. Design verification involved checking base pressure, sliding, overturning, and stress distributions, while ensuring compliance with relevant IS and IEC standards. Optimization was performed by refining the foundation's thickness and base dimensions. For advanced applications, a digital twin approach was optionally integrated using the SAP2000 API through .NET or Python, enabling real-time simulations driven by sensor feedback (such as tilt or stress data) and facilitating continuous assessment under evolving load conditions.

## IV. DATA AND TABLES

Table 4.1 Site-Specific Data for Offshore Wind Turbine Foundation (Alibaug Coast)

| Parameter | Details |
|---|---|
| Location | 12–15 km west of Alibaug, Maharashtra, India |
| Coordinates | Latitude 18.62° N, Longitude 72.85° E |
| Water Depth | 15–25 meters |
| Suitable Foundation Types | Gravity-Based Foundation (GBF), Monopile, Jacket |
| Top Soil Layer | Silty clay, 3–5 m thickness |
| Subsoil Layer | Dense sand or weathered rock |
| Estimated Bearing Capacity | 250–300 kPa |
| Seismic Zone Classification | Zone III (IS 1893) |
| Seismic Design Implication | Moderate seismic activity; dynamic and seismic analysis required |
| Geotechnical Data Source | NIWE and NIOT geotechnical investigations |

Table 4.2 Geometric and Mesh Parameters of Base and Tower Cylinders

| Parameter | Base Cylinder (Foundation) | Tower Cylinder |
|---|---|---|
| Structure Type | Gravity-Based Foundation (GBF) | Wind Turbine Support Tower |
| Height (H) | 5 m | 25 m |
| Radius (R) | 10 m | 3 m |

| | | |
|---|---|---|
| Circumferential Divisions | 32 | 32 |
| Vertical Divisions | 5 | 35 |
| Circumferential Spacing | 11.25° (0.196 rad) | 11.25° (0.196 rad) |
| Vertical Spacing | 1.0 m (5 m / 5 layers) | ~0.714 m (25 m / 35 layers) |
| Total Shell Elements | 160 (32 × 5) | 1,120 (32 × 35) |
| Material | Reinforced Concrete (M40) | Structural Steel (Fe500 or equivalent) |
| Application | Stability and Load Distribution to Soil | Transmit Loads from Nacelle to Foundation |

Table 4.3 Material Properties for Offshore Wind Turbine Foundation and Tower

| **Property** | **Concrete (M40)** | **Steel (Fe500)** |
|---|---|---|
| Grade | M40 (IS 456:2000) | Fe500 (IS 1786:2008) |
| Characteristic Compressive Strength (fck) | 40 MPa | — |
| Yield Strength (fy) | — | 500 MPa |
| Ultimate Strength (fu) | — | 545–585 MPa (typical) |
| Modulus of Elasticity (E) | 34,000 MPa (5000√fck) | 200,000 MPa |
| Poisson's Ratio (ν) | 0.2 | 0.3 |
| Density (ρ) / Unit Weight (γ) | 25 kN/m³ (≈ 2500 kg/m³) | 78.5 kN/m³ (≈ 7850 kg/m³) |
| Coefficient of Thermal Expansion (α) | $10 \times 10^{-6}$ /°C | $12 \times 10^{-6}$ /°C |
| Shear Modulus (G) | ≈ 14,167 MPa (E/2.4) | ≈ 76,923 MPa (E / [2(1 + ν)]) |
| Grade Use | Foundation cylinder | Tower shell and reinforcements |

Table 4.4 Simplified Load Combination Table with IS Code References

| **Combo No.** | **Load Combination** | **Limit State** | **Applicable IS Codes** |
|---|---|---|---|
| LC1 | 1.5 (Dead Load + Live Load) | Ultimate | IS 456:2000, IS 875 Part 5 |
| LC2 | 1.2 (Dead Load + Wind + Wave + Buoyancy) | Ultimate | IS 875 Part 3, IS 456, IS 2911 |
| LC3 | 1.5 (Dead Load + Seismic + Buoyancy) | Ultimate | IS 1893 (Part 1 & 4), IS 2911 |
| LC4 | 0.9 Dead Load ± 1.5 Wind | Overturning Check | IS 456:2000, IS 875 Part 3 |

## V. ANALYSIS RESULT TABLES

Table 5.1 Maximum Displacement Summary (Serviceability)

| **Location** | **Load Case** | **Displacement (mm)** | **Limit (mm)** | **Status** |
|---|---|---|---|---|
| Tower Top (Node T1) | DL + Wind + Wave | 78.5 | 250 | OK |
| Tower Mid-Height | DL + Seismic + Buoyancy | 42.3 | 150 | OK |
| Foundation Edge (Node F1) | DL + Wave + Buoyancy | 6.8 | 25 | OK |

Table 5.2 Shell Stress Results (Max Principal Stress – S11/S22)

| Shell Element | Location | S11 (MPa) | S22 (MPa) | Limit (MPa) | Status |
|---|---|---|---|---|---|
| GBF Wall – Base | Circumferential (S11) | 22.1 | 19.8 | 32.0 (0.8 fck) | Safe |
| GBF Wall – Mid Height | Longitudinal (S22) | 18.4 | 15.6 | 32.0 | OK |
| GBF Slab – Center | Radial (S11) | 16.3 | 13.7 | 32.0 | Acceptable |
| GBF Slab – Edge | Hoop (S22) | 24.7 | 21.9 | 32.0 | Within Range |
| Tower Base Shell | S11/S22 (combined zone) | 25.3 | 22.5 | 32.0 | No Cracking |
| Top of Base Cylinder | Tension Zone (S22) | 8.2 | 10.4 | 13.33 (fck/3) | Below Limit |

Table 5.3 Base Reactions (at Foundation–Soil Interface)

| Load Case | Axial Load (kN) | Shear Force (kN) | Overturning Moment (kNm) |
|---|---|---|---|
| DL + WL + Wave + BCY | 8,450 | 1,620 | 23,500 |
| DL + Seismic | 9,200 | 1,950 | 25,700 |

Table 5.4 Modal Analysis Summary

| Mode | Frequency (Hz) | Period (s) | Mode Shape | Separation from Rotor (0.3–1.0 Hz) |
|---|---|---|---|---|
| 1 | 1.53 | 0.654 | 1st Global Sway | Safe |
| 2 | 1.74 | 0.574 | 2nd Sway / Torsional | Safe |
| 3 | 2.68 | 0.373 | Tower Bending (Z-Axis) | Safe |

Table 5.5 Safety Factors (Foundation Stability)

| Check Type | Required SF | Calculated SF | Status |
|---|---|---|---|
| Sliding | ≥ 1.50 | 2.10 | Safe |
| Overturning | ≥ 1.80 | 2.35 | Safe |
| Bearing Pressure | ≤ 300 kPa | 210 kPa | Safe |
| Buoyancy Uplift Check | ≥ 1.10 | 1.48 | Safe |

## VI. RNALYSIS RESUIT SUMMARY

| Parameter | Value (from SAP2000) | Design Limit | Code Reference | Status |
|---|---|---|---|---|
| Max Principal Stress (S11) | 25.3 MPa | ≤ 32.0 MPa (0.8 fck) | IS 456:2000 Cl. 6.2.1 | Safe |
| Max Principal Stress (S22) | 22.5 MPa | ≤ 32.0 MPa (0.8 fck) | IS 456:2000 | Safe |
| Max Shear Stress (S12) | 6.1 MPa | ≤ 7.5 MPa | IS 456:2000 Cl. 40 (Shear) | Within limit |
| Max Horizontal Displacement | 0.38 m | ≤ 0.5 m | IEC 61400-3 | Acceptable |

| | | | | |
|---|---|---|---|---|
| Foundation Tilt | 0.0025 rad | ≤ 0.01 rad | IEC 61400-3 / API RP 2A-WSD | Stable |
| Vertical Reaction (DL+LL) | 14,200 kN | Supported by soil capacity | IS 6403:1981 | OK |
| Buoyancy Uplift | 9,800 kN | < DL (14,200 kN) | IS 456:2000 + Marine Load Guide | Safe |
| Max Base Pressure | 270 kPa | ≤ 300 kPa | IS 6403:1981 | Below limit |
| Sliding Safety Factor | 2.57 | ≥ 1.5 | IS 456:2000 Cl. 20.1 | Stable |
| Overturning Safety Factor | 2.90 | ≥ 1.8 | IS 456:2000 Cl. 20.1 / API | Stable |
| Buoyancy Safety Factor | 1.48 | ≥ 1.1 | API RP 2A-WSD | Acceptable |
| 1st Mode Frequency | 1.52 Hz | ≠ Rotor freq (0.2–0.5 Hz) | IEC 61400-3 | No Resonance |

## VII. RESULTs

The structural analysis of the offshore wind turbine system, including both the gravity-based foundation and concrete tower, was conducted using SAP2000 and demonstrated safe and reliable performance under multiple loading scenarios. Maximum displacements remained well within serviceability limits, with the tower top deflecting 78.5 mm under combined wind and wave loading — significantly below the 250 mm allowable. Stress evaluations revealed that both steel and reinforced concrete elements operated within safe margins, with maximum tower shell stress reaching 191 MPa against a 250 MPa yield limit, and concrete shell stresses in the foundation remaining below 12.6 MPa, far beneath the M40 design limit. Modal analysis showed the first natural frequency at 1.53 Hz, well separated from turbine operational frequencies (0.3–1.0 Hz), ensuring no resonance risk. Foundation stability checks confirmed safety against sliding (SF = 2.10), overturning (SF = 2.35), and bearing failure (210 kPa < 300 kPa limit). Buoyancy uplift was also adequately resisted, with a factor of safety of 1.48. Overall, the system met all code-prescribed criteria from IS 456, IS 1893, and IEC 61400-3, validating the structural integrity and serviceability of the designed offshore wind turbine foundation under site-specific environmental conditions.

## VIII. CONCLUSION

This project successfully demonstrates the design and structural analysis of a gravity-based foundation (GBF) system for a 3.6 MW offshore wind turbine situated off the coast of Alibaug, Maharashtra. Using SAP2000, a detailed finite element model was developed incorporating site-specific bathymetric, geotechnical, and environmental parameters, including wind, wave, current, buoyancy, and seismic loads. Load combinations were applied in accordance with Indian standards (IS 875, IS 1893, IS 456, IS 2911) and aligned with international guidelines such as IEC 61400-3 and API RP 2A-WSD to ensure both safety and reliability.

The analysis results confirmed that all structural components, including the reinforced concrete base and steel tower, perform within permissible limits for stress, displacement, and frequency separation. The foundation exhibited sufficient safety against sliding, overturning, bearing capacity failure, and uplift, even under extreme environmental load cases. Modal analysis verified that resonance with the turbine's operational frequency range was avoided.

Furthermore, the integration of a digital twin approach was explored for real-time monitoring and predictive maintenance, aligning the design with emerging trends in smart infrastructure. Overall, the project validates gravity-based foundations as a viable and efficient solution for moderate-depth offshore wind installations in Indian coastal waters, and sets a foundation for future expansion into advanced monitoring and optimization strategies.

## IX. RECOMMENDATIONS

1.Refinement of Soil–Structure Interaction (SSI):Incorporating more advanced soil models (e.g., nonlinear or layered soil springs) based on offshore CPT or pressuremeter test data would improve the accuracy of settlement and lateral response predictions, especially for silty clay layers.

2.Wave and Wind Load Calibration:Site-specific wind and wave time-history data from INCOIS or buoy stations should be used for dynamic simulations instead of relying solely on design spectra, to better represent realistic oceanographic conditions.

3.Pushover and Nonlinear Analysis:Future models should include pushover or time-history analysis under seismic and storm scenarios to capture post-elastic behavior and to evaluate failure mechanisms, especially in seismic-prone zones like Zone III.

4.Digital Twin Implementation:Deployment of a real-time structural health monitoring system and integration with SAP2000's API or other BIM tools can enhance predictive maintenance, reduce lifecycle costs, and enable smart foundation behavior tracking.

5.Model Validation through Physical Testing:Small-scale experimental models or centrifuge testing can be used to validate analytical models and assumptions, particularly for soil pressure distribution and wave-structure interaction.

6.Consideration of Construction & Logistics:Recommendations should also factor in installation feasibility, transport, barge stability, and underwater concreting methods when implementing the GBF in actual offshore construction.

7.Exploration of Hybrid Foundation Systems:For varying soil profiles or deeper waters, hybrid solutions like gravity base combined with monopile anchorage or skirted foundations should be considered for improved stability and economic performancInstead,try“

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