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Seismic Response of Wind Turbine Foundations on Sabkha Soils Improved by Deep Soil Mixing

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Abstract - Wind turbines provide renewable electricity which reduces carbon dioxide emissions and promotes sustainable development globally. Nevertheless, when built on Sabkha soil, their foundations face serious geotechnical challenges. Sabkha soil, with its low shear strength and high compressibility, is highly susceptible to seismic forces. It can cause foundations displacement or overturning. Ground improvement processes are needed to provide a solution to these problems. Among these, deep soil mixing (DSM) has shown capabilities to improve soil stiffness and shear strength thus it can be an option for wind turbine foundations stabilization against seismic forces. The aim of this study is to investigate the seismic response of raft foundations on DSM-treated Sabkha soils using 3D numerical analysis based on site-specific seismic accelerograms. The results indicate that DSM reduces horizontal displacement by over 95%, with maximum displacement decreasing from 0.02321 m to 1.00×10^{-3} m. Additionally, peak acceleration at the top of the wind turbine is reduced by 50%, from 0.16 g to 0.08 g. These findings confirm that DSM significantly enhances foundation stability, mitigating seismic risks and improving dynamic performance. The study provides practical recommendations for optimizing DSM applications, supporting the safe and sustainable development of wind energy infrastructure in Sabkha active regions.

***Keywords*:** Wind turbines, Sabkha soils, Deep soil mixing (DSM), Seismic performance, Plaxis 3D, Foundation stability.

1. Introduction

Wind energy is a renewable source of energy that turns the kinetic energy of the moving air into electricity. It provides a sustainable alternative to fossil fuels and contributes to reducing carbon emissions produced by fossil fuels. Indispensable in the fight against climate change, it enables the transition to low-carbon electricity generation. On the other hand, wind turbines require high financial investment to build. In many cases, wind turbines must be installed in areas with weak or unstable soils which presents significant challenges for foundation design. This problem becomes even more significant in seismic-prone areas. The combination of weak soil and seismic forces increases the risk of excessive settlement, tilting, and structural instability. Hence, appropriate deep foundation designs must be developed to guarantee the structural integrity and safety of wind energy infrastructure in such environments.

Sabkha soil is widely distributed in the Gulf region, especially along its coastal zones like Saudi Arabia, United Arab Emirates, Qatar and Kuwait [1].It forms under arid climate, high rates of evaporation and is characterized by the deposition of soluble salts in its soil [2]. The majority of countries in the Gulf region have expressed intentions to diversify their economies and reduce their reliance on fossil fuels and, as part of this effort, have been focusing more on the construction of wind energy infrastructure. But Sabkha soil is largely widespread, which creates difficulties for the construction of wind turbines. Foundation design for Sabkha soils is difficult because such soils have unusual geotechnical properties. Under arid conditions, their high salt content leads to cementation and thus temporarily enhances soil strength. But upon water entry into the soils, the cementation is destroyed and with it follows reductions in strength and structural instability [1]. The soil is collapsible in nature and are susceptible to large settlements. The complexity of the situation requires detailed geotechnical investigation to examine the most suitable soil improvement and foundation strategy.

Deep soil mixing (DSM) is one of the ground improvement techniques that enhances the properties of soil through the mechanical blending of in-situ soil with cementitious binders. It improves shear strength and soil stiffness and enhances load-bearing capacity while reducing the risk of deformation. DSM is particularly effective for stabilizing soft and problematic soils such as soft clay, peat, and loose sand. In Sabkha soil, DSM has advantages in terms of reducing settlement and enhancing stability. Efficiency of DSM columns depends on various factors including binder type, efficiency of mixing, curing conditions, and composition of the soil [3], [4]. Despite these challenges, DSM is one of the potential solutions for improving foundation performance in weak soils. Research and field testing are essential for optimizing DSM applications for seismically active regions.

Wind turbines are slender and tall structures with a high center of gravity and are thus highly prone to dynamic loads [5]. Ground shaking due to earthquakes induces lateral and vertical loads on wind turbine foundations. These loads can cause excessive settlement, tilting, and structural collapse of the structure, particularly in weak soils. Dynamic response of the wind turbine foundation depends on soil conditions, foundation design, and soil-structure interaction. On the other hand, the abundance of Sabkha soils in the Arabian Gulf region makes it difficult to design wind turbine foundations in such areas. Combining weak soil properties with seismic loads poses challenges for engineers that must be overcome with the help of innovative ground improvement technologies. A detailed investigation of wind turbine foundation behavior under such circumstances is necessary to ensure safe and sustainable exploitation of wind energy in the region.

The study evaluates the performance of DSM in improving the seismic performance of wind turbine foundations in Sabkha soils. Numerical analysis using the assistance of Plaxis 3D software is conducted to study the behavior of the foundation under seismic loading. A baseline model is created to simulate a wind turbine foundation without DSM as the point of reference for comparison. A second model is created with DSM reinforcement using the same site-specific seismic accelerograms for the purpose of comparing the effect of DSM. This technique allows a direct comparison of the performance of the foundation with and without DSM. Acceleration response and lateral displacement of wind turbine under seismic loading are investigated.

2. Numerical Modeling

The numerical model is developed using field data from as-built drawings to model the wind turbine construction process with accuracy. The wind turbine has a length of 38.4 m and a diameter of 2.15 m [6]. It is supported on a circular raft foundation with a diameter of 6 m and a thickness of 1 m at a depth of 2 m. The wind turbine support on a circular pedestal extends 1 m above the ground surface.

A series of numerical models is developed using dynamic analysis in the Plaxis 3D software. The soil profile is adopted from a previously conducted study by Abas et al. (2024) on the suitability of deep soil mixing (DSM) walls for supporting excavations in Sabkha soils [7]. Figure 1 illustrates the adopted soil stratigraphy and wind turbine dimensions. The total depth from the ground surface to bedrock is 30 m.

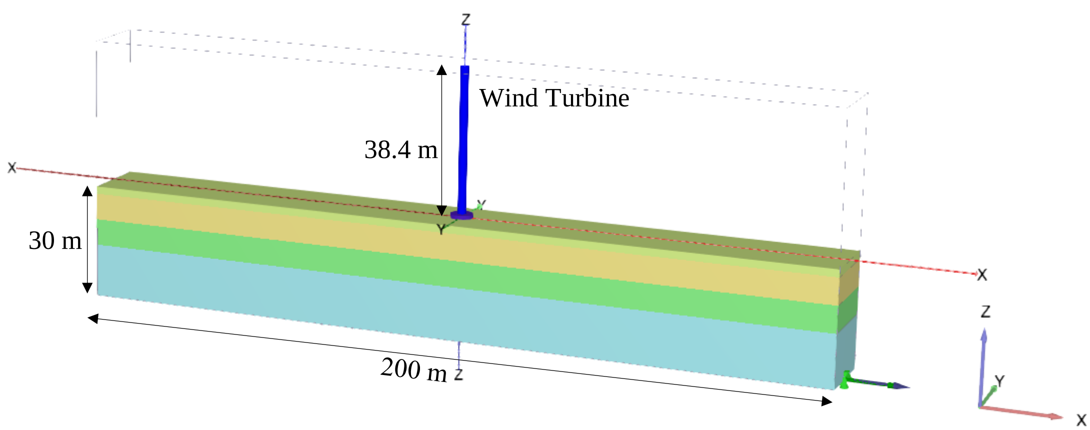

Figure 1: Soil stratigraphy and wind turbine dimensions adopted in the study

To prevent boundary effects, sufficient distance is reserved around the boundaries of the vertical model. Based on Brandt (2014), the most suitable boundary condition for dynamic analysis is selected. A common numerical modeling approach extends the boundaries to three times the soil depth (3H) on each side [8]. In this study, the model is extended 100 m in each of the horizontal directions and has 200 m of total width and 30 m of depth. It is assumed that the groundwater table is 3 m deep beneath the ground surface.

The mesh refinement is optimized for numerical accuracy. A fine mesh is applied for all the soil layers and further refined near the foundation and wind turbine. This is done to ensure that the soil-structure interaction effects are well-captured for reliability of the seismic performance analysis. The Mohr-Coulomb soil model is selected to simulate the mechanical behavior of the soil layers. The corresponding soil properties are listed in Table 1 and the properties of DSM are listed in Table 2. The foundation is modeled as a concrete structure with the material properties listed in Table 3.

Seismic loading is applied using acceleration data of the default earthquake acceleration file of the Plaxis 3D program as depicted in Figure 2. Earthquake load is applied as a dynamic multiplier at the bottom of the model [9]. A rigid bottom boundary is applied to prevent the passage of seismic waves beyond this location. The displacement in the x-direction at the surface of the bottom boundary is prescribed with a uniform value of 0.5 meters to simulate seismic motion. Two scenarios are simulated using a series of dynamic simulations: one without deep soil mixing (DSM) and one with DSM reinforcement.

Table 1: Soil layer properties [7].

Parameter	**Layer 1: Sand (2 m)**	**Layer 2: Sabkha (7 m)**	**Layer 3: Medium Dense Sand with silt (7 m)**	**Layer 4: Dense Sand with silt (14 m)**
Moist Unit Weight, kN/m^3	17.5	16	19	19
Saturated Unit Weight, kN/m^3	19	17	20	20.5
Young's modulus, MN/m^2	7	4	12	30
Poisson's ratio	0.3	0.3	0.3	0.3
Cohesion, kN/m^2	1	10	1	1
Friction angle	30	22	33	36

Table 2: Parameter properties of DSM walls for a linear elastic model [7].

Properties	**DSM Walls**
Unit Weight, kN⁄m3	20
Youngs modulus (MPa)	290
Poisson's ratio	0.15

Table 3:Material Properties of concrete foundation[10].

Parameter	**Unit**	**Value**
Young's modulus, E	KPa	30×10^6
Unit weight	kN/m^3	24
Raleigh Damping, α	-	0.232
Raleigh Damping, β	-	8×10^{-3}

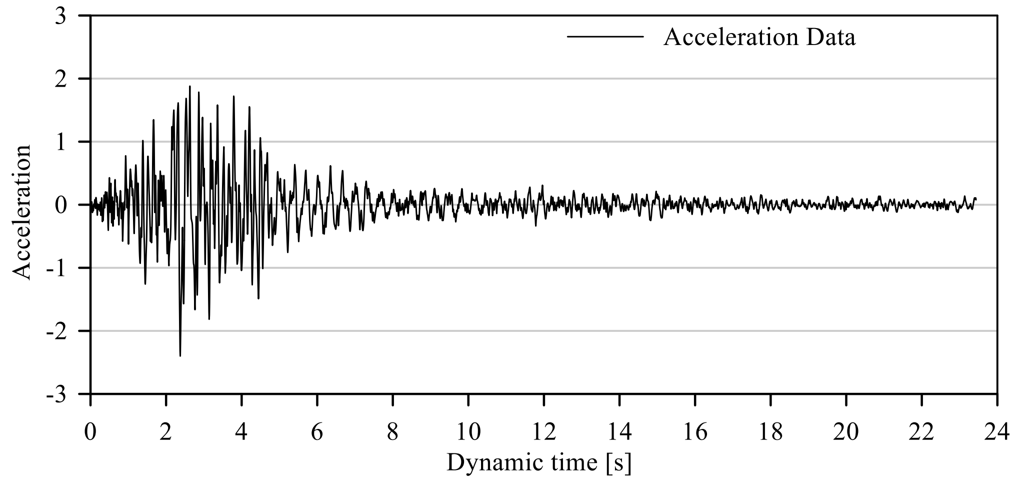

Figure 2: Earthquake acceleration data [9].

4. Results and Discussion

The performance of the wind turbine foundation against the seismic loads is compared through the analysis of the foundation behavior before and after deep soil mixing (DSM) installation. The analysis focuses on horizontal displacement and acceleration, which are key indicators of foundation stability under seismic loading. They are discussed and presented in the subsequent sections.

4.1 Horizontal Displacement

The displacement in the x-direction at t = 20.00 s is illustrated in Figure 3 for the wind turbine foundation without DSM and with DSM under seismic loading. It is evident that displacement values are greater for the foundation without DSM, with a maximum displacement of approximately 0.02321 m at the top of the wind turbine. The irregular displacement pattern illustrates the flexibility of wind turbines due to insufficient support supported by raft foundation, making them more susceptible to seismic loads.

In contrast, the raft foundation with DSM experiences significantly lower displacement, with a maximum recorded value of approximately 1.00×10^{-3} m. The displacement pattern of DSM-treated sabkha soils under the raft foundation is more uniform, indicating increased stiffness and greater lateral resistance. The reduction in displacement confirms that DSM reinforcement stabilizes the foundation, effectively minimizing seismic deformations.

The displacement response at the top of the wind turbine under seismic loading is presented in Figure 4, comparing results before and after DSM installation. The analysis reveals that the wind turbine without DSM exhibits higher peak displacements and greater amplitude oscillations during the seismic event. This reflects increased structural movement and instability due to the weak nature of Sabkha soils. Conversely, the wind turbine with DSM experiences lower displacement amplitudes, confirming the effectiveness of DSM in reducing lateral movement. The DSM-treated foundation dissipates seismic energy more efficiently, leading to reduced vibration intensity and enhanced structural stability. Over time, the oscillations in the DSM-treated foundation subside more quickly than in the untreated case, demonstrating that DSM enhances damping capacity and increases foundation stiffness.

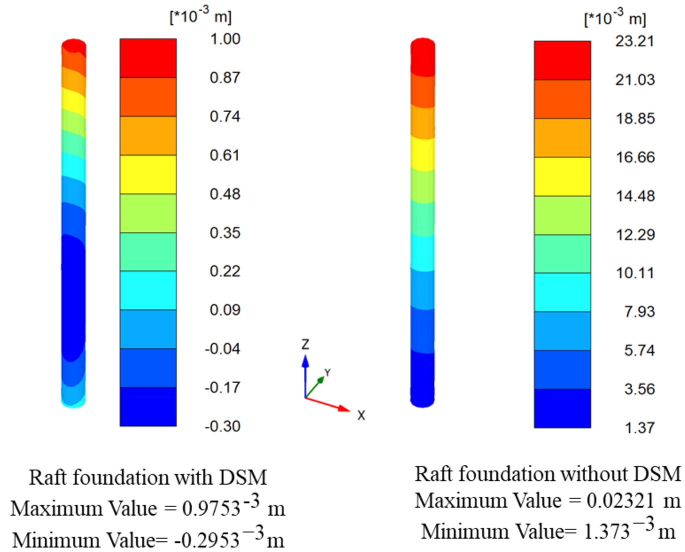

Figure 3: Total displacement wind turbine in the x-direction at time 20.00 s.

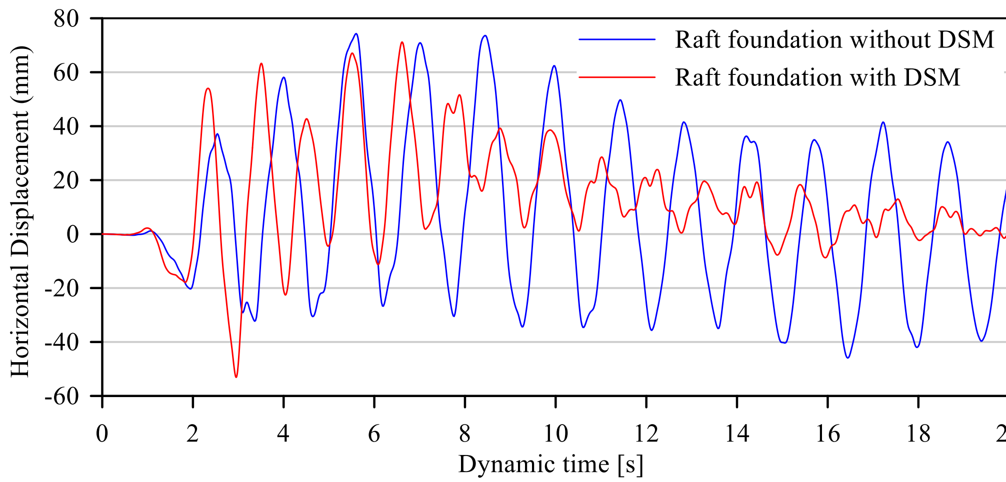

Figure 4: Horizontal displacement at the top of the wind turbine before and after DSM installation.

4.2 Acceleration

The acceleration response at the top wind turbine during seismic loading provides information about the dynamic behaviour of the structure before and after the installation of DSM as shown in Figure 5. Comparison of acceleration amplitudes with dynamic time is carried out in the analysis. It is revealed that the wind turbine without DSM has higher peak acceleration of 0.16 g at dynamic time 3.22 s with higher oscillation intensity throughout the period of seismic activity. These large peaks of acceleration reflect higher structural vibrations, which tend to increase the risk of damage to the wind turbine. In addition, the random fluctuating amplitude also highlights the influence of weak Sabkha soils on the dynamic response of the wind turbine foundation and makes it more vulnerable to seismic loads.

Conversely, the DSM-strengthened wind turbine has lower acceleration values with maximum acceleration of 0.08 g at dynamic time 2.96 s indicating considerably less oscillation magnitude. The DSM-treated foundation has the ability to absorb seismic energy with damp vibrations and greater stability. With time, the oscillations of the DSM-strengthened raft foundation damp more quickly, indicating higher damping capacity and structural stiffness. The remarkable reduction in acceleration response supports the effectiveness of DSM in enhancing foundation stability, reducing the impact of earthquakes, and enhancing dynamic performance for wind turbine structures under weak soil conditions.

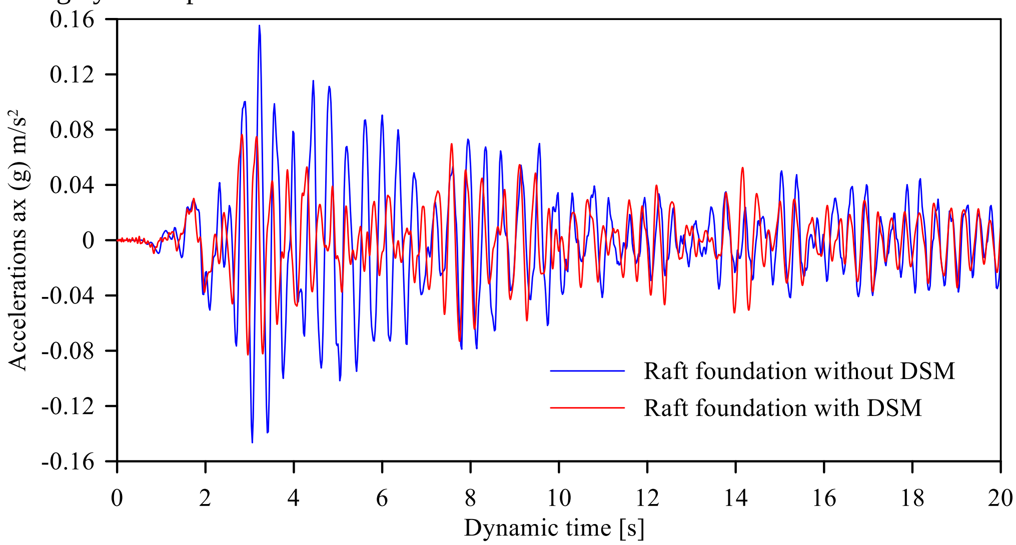

Figure 5 : Acceleration versus dynamic time at top of wind turbine, (a) without DSM and (b) after Installation of DSM.

6. Conclusion

The study proves that deep soil mixing (DSM) is effective as a ground improvement technique for enhancing the seismic performance of wind turbine foundations in problematic Sabkha soils. Numerically, it is demonstrated that DSM significantly reduces horizontal displacement and acceleration in curbing structural instability due to seismic loading. Without DSM, the displacement of the wind turbine raft foundation is maximum at 0.02321 m, while the DSM-treated foundation has minimal displacement of 1.00×10^{-3} m, indicating greater than 95% improvement in lateral stability.

Also, DSM reduces significantly acceleration due to seismic, one of the most critical structural stability parameters. With the maximum acceleration at the top of the wind turbine being 0.16 g at 3.22 s without DSM, the raft foundation with DSM has less maximum acceleration of 0.08 g at 2.96 s with 50% less effect of earthquake. This remarkable decline in acceleration establishes the damping effectiveness of DSM that enhances raft foundation stiffness.

Future studies should explore the effect of DSM column configurations like spacing and depth to find the most efficient design for reducing seismic risk in weak soils. Research into the influence of different earthquake magnitudes, ground motion parameters, and soil conditions will expand the general applicability of DSM solutions for wind turbine foundations across different seismic conditions.

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