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Scour effects on the dynamic behaviour of monopile-supported offshore wind turbine

Rituraj Singh Sujawat*
Indian Institute of Technology Roorkee, Roorkee, India

Kottala Chandri Naidu
Indian Institute of Technology Roorkee, Roorkee, India

Ritesh Kumar
Indian Institute of Technology Roorkee, Roorkee, India

**rituraj_s@eq.iitr.ac.in (corresponding author)*

ABSTRACT: In recent years, offshore wind turbines have seen increased development worldwide to harness wind energy in coastal regions. The monopile foundation is the most widely used foundation for offshore wind turbines, selected based on met-ocean conditions. This research primarily examines the impact of scour on the natural frequency of offshore wind turbines (OWT) through free vibration analysis. The study investigates the effects of varying scour depths and types on the structural behavior of monopile foundations through a series of finite element simulations. The design of monopile foundations and soil has been considered as per the feasibility studies conducted on the locations that are the potential offshore sites for the upcoming offshore wind farms in India. It aims to determine the influence of different scour types on the natural frequency of offshore wind turbines, considering the reduction in stiffness due to the removal of soil around the monopile foundation.

Keywords: Monopile foundation; Numerical modeling, Free vibration analysis; Natural frequency; Scour formation

1 INTRODUCTION

The combined effects of currents and waves can lead to scour holes forming around fixed supports like monopile foundations. Scour is a critical aspect that must be accounted for during the design, construction, and operational phases of OWT projects (Ma et al., 2018). There have been certain instances of OWTs' foundation failure due to the formation of scour around monopile foundations. Due to the formation of scour around the monopile foundation, two OWT towers need to be decommissioned due to the formation of scour up to a depth of 5.6 m at Robin Rigg Wind Farm (Menendez Vicente et al., 2023). An increment in scour depth from 0.28D to 0.46D is observed at Kentish Flats Wind Farm (Whitehouse et al.,2008). A large mobilisation of suspended sediments has been observed around the OWTs, which are 30-150 m wide at the Thanet wind farm (Offshore Wind Farms Make Wakes, 2015). Qi et al. (2016) has studied the effects of local and general scour on the soil reaction curves of pile foundation for shallowly embedded piles utilizing the centrifuge testing facility and has shown that there is reduction in lateral load capacity of pile foundation due to reduction in soil stiffness. Dingle et al. (2023) has assessed the fatigue lives of offshore wind turbine foundations through calculation of in-service loads on the foundations and by utilizing the advanced soil structure modelling techniques for the evaluation of stiffness. Lin and Jiang (2019) has analyzed the results of pile tension capacity in sands under different scour formations and compared the results of FE analyses with existing methods and analytical solutions that considers the reduction in vertical effective stress. The study has shown that analytical solutions produce results which are in good agreement with FE analyses for case of dense sands, however analytical solutions has shown conservative solutions for case of loose sands. The case mentioned above studies shows the significance of scour consideration during the design process of OWT. Accurately predicting the structural consequences of scour is essential for ensuring OWT's safe and effective design and operation throughout its operational lifespan. These scour holes can directly impact the structure's dynamic characteristics, such as its natural frequency. Considering the design aspects of OWT, the designers usually consider the frequency range, which does not overlap with the forcing frequencies generated by environmental forces such as wind, waves, currents, and 1P and 3P frequencies (Bhattacharya et al., 2014). Recent studies have analysed the shift in the natural frequency of monopile-supported offshore wind turbines (OWTs) under scour conditions. Prendergast and Doherty (2015) examined the impact of scour on natural frequency using a combination of scale model tests and numerical modelling, demonstrating a significant shift in natural frequency due to scour. More recently, Mayall et al. (2025) developed a one-dimensional model aimed at accurately predicting the natural frequency of model wind turbine support structures. This model, tested in the FFF flume, accounts for both scour and scour protection systems. Furthermore, it has shown strong capability in predicting the response of real-world field cases. The soil strata for the upcoming offshore wind farms in India, particularly in the Gulf of Khambhat region, usually consist of sandy material (Patra et al., 2022). Considering the high susceptibility of sandy material towards scour (Whitehouse et al., 2011), these OWTs need to be studied to determine the impact caused by scour formation for the proper risk assessment and mitigation. Hence, in the present study, emphasis has been made on studying the variation of natural frequencies of these OWTs due to the scour formation through consideration of high-fidelity soil structure interaction modelling. A series of finite element analyses have been performed, utilizing the free vibration analysis method to extract the natural frequency of the soil structure model under different scour geometries.

2 NUMERICAL MODELLING

The behavior of monopile-supported OWT is predicted using a finite element platform, PLAXIS-3D. The site under consideration for the present study is the Gulf of Khambat region, one of the suggested sites for the upcoming offshore wind farm in India. Three types of OWTs are considered for the present study, with a rating of 4 MW, 6 MW, and 10 MW. The corresponding geometric dimensions of the support structure and other turbine details have been extracted from the feasibility report details for the site mentioned above (FOWIND, 2018), which have been enlisted in Table 1. The soil properties have been considered per preliminary geotechnical data available (FOWIND, 2018).

2.1 Support Structure Modeling

The component of OWT, which incorporates the structure from the nacelle level of OWT to the bottom of the monopile foundation, is known as a support structure. The support structure usually considers two main components: the tower and foundation components. The geometrical dimensions of the support structure for different ratings of OWT are shown in Table 1. A typical model of the support structure considered in the present study is shown in Figure 1. The whole support structure has been modeled as a uniform cross-section utilizing the 6-noded triangular plate element with six degrees of freedom per node. This is one of the assumptions which has been considered in the present study considering the limitation of numerical platform in modelling non-uniform cross-section. However, considering the scope of the work, where focus has been made to observe the decay in eigenfrequency, this modelling approach can be adopted. The material behaviour of the plate element is considered elastic and isotropic. The elastic modulus of the steel is taken as 210 GPa, while the density is considered as 78.50 kN/m^3. The rotor-nacelle assembly mass has been provided in the model by incorporating the equivalent density to the rigid plate, which is attached to the support structure plate element, as shown in Figure 1. However, in this study no moment of inertia of RNA has been considered which is another assumption to simplify the modelling approach without compromising the scope of study.

2.2 Soil Modelling

The soil has been modeled using the HS small strain constitutive model with ten noded tetrahedral elements. The appropriateness of this soil model for the current study is considered due to its ability to simulate the very small-strain soil stiffness and its non-linear dependency on strain amplitude.

Table 1. Support structure details

OWT Rating	**4 MW**	**6 MW**	**10 MW**
Diameter (m)	4.7	6.2	8.5
Monopile Embedded Length (m)	41	45	52
Height of support structure above mud-line (m)	100.54	117.54	135
RNA Mass (tonnes)	205	365	605

The soil material considered in the present study is sandy soil, and the corresponding strength and stiffness parameters are obtained from the empirical relations demonstrated in past studies (Sujawat and Kumar, 2023). The small strain parameters are calibrated by validating the numerical model to obtain the desired natural frequency. The boundary conditions considered for the present study numerical model incorporate viscous boundary conditions at lateral surfaces, which are expected to affect the direction of loading. These boundary conditions facilitate the absorption of outgoing wave energy. A similar boundary condition has been imposed on the base of the model. The model's top surface is considered free in all directions, and the other two lateral surfaces are normally fixed. The normally fixed boundary conditions consider the vertical model boundaries to be fixed in their normal direction while free in the other two directions.

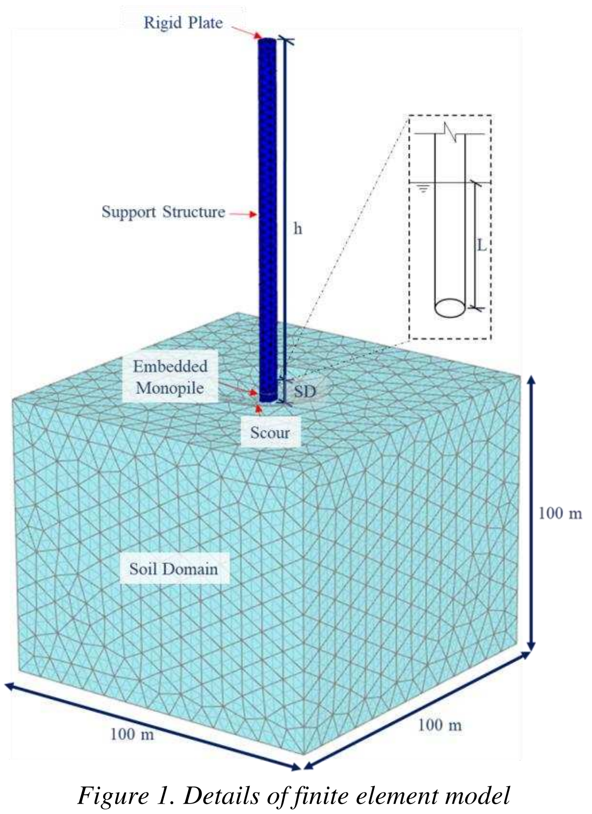

Figure 1. Details of finite element model

2.3 Scour Modeling

To conduct a parametric study on the effect of scour on the offshore wind turbine (OWT), the scour component has been integrated into the model by incorporating the morphologies and dimensions of scour around the monopile foundation. As per the observation of scour formation around the monopile foundation, the shape is generally idealized as global, wide, and narrow. A representative figure for different scour shapes and their associated dimensions has been shown in Figure 2. The global scour is the case where the soil is removed around the monopile foundation for a larger area, and the local scour is the case where the soil has been removed in the form of an inverted conical shape, leading to the formation of the hole (Mostafa, 2012). If the base of local scour is formed at a specific offset from the monopile surface, the scour is identified as wide scour. As shown in Figure 2, the idealized scour under consideration is characterized using scour depth as one of the primary parameters. The other dimension to characterize the scour for narrow and wide scour is the inclined slope of the scour, represented using angle α, and the offset distance of scour base initiation in the case of wide scour, represented by base width (W_b). The top dimension of the wide scour is represented by the top width (W_t). The range of scour depths for the current study is obtained using the metocean conditions mentioned in the feasibility studies (FOWIND, 2018). The scour depths are considered in the range of 0.1 D - 1.6 D, where D is the diameter of the embedded monopile foundation. The inclined angle of the scour (α) is taken as 30º, and the wide scour's base width is considered 0.1 D. The scour has been incorporated into the numerical model by removing some finite element mesh elements. The scour shape in this study is idealized as a shape which resembles to frustum of a cone, for case of both local and global scour scenarios (Figure 2). Specifically, the process involves first generating the elevation view of the scour shape followed by revolving it around the central axis of support structure. This step results in the formation of a solid entity representing the scour volume, which can later be deactivated to simulate the development of scour morphology.

3 METHODOLOGY

Free vibration analysis has been conducted to obtain the natural frequency of monopile-supported OWT. For the assessment, the modeling stages have been divided into four stages. The first stage corresponds to introducing the soil domain, followed by introducing the monopile-supported tower in the next phase. The study does not consider the installation effect on the soil confinement, and the monopile is assumed to be wished in place pile. The following two phases correspond to the evaluation of natural frequency through the free vibration analysis method, which also introduces the scour formation in the model. In this method, the system is disturbed from its initial static position by imparting some displacement, which is released instantaneously.

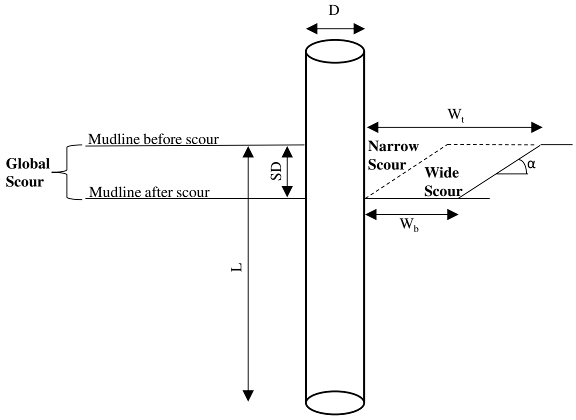

Figure 2. Scour shapes and their associated dimension details (Li et al., 2020))

Due to disturbance, the system undergoes vibratory motion about its static equilibrium position. This vibratory motion depends on the combined stiffness of the support structure and the soil domain. The harmonic motion obtained is then analysed, and the vibration frequency is recorded. This dynamic analysis is performed for a particular duration, and the wave corresponding to the maximum frequency of the system is marked as the natural frequency of OWT. To model this, a point load has been applied to the rigid plate connected at the top of the tower in the third stage, corresponding to the elastoplastic deformation analysis. The following phase corresponds to the dynamic calculation considering the soil's stress waves and vibrations where the point load has been released by deactivating it. Vibrations obtained in the structure are then utilized to analyse the dynamic behaviour of the structure.

4 RESULTS AND DISCUSSIONS

The horizontal vibrations have been obtained for all ratings of wind turbines under consideration, corresponding to the different cases of scours. Some of the findings are presented in this paper. Figure 3 represents the horizontal motion of 4 MW OWT for the scour condition of global scour incorporating the different scour depth scenarios. This time history analysis is performed for 15 seconds, and it is observed how the scour inclusion affects the harmonic motion of the turbine. The results are compared with the case of no scour, and the mean value of all the scour-affected harmonic motions is represented for better comparison. Due to the reduction in soil volume around the monopile foundation, there is a decrease in the stiffness of soil structure assembly.

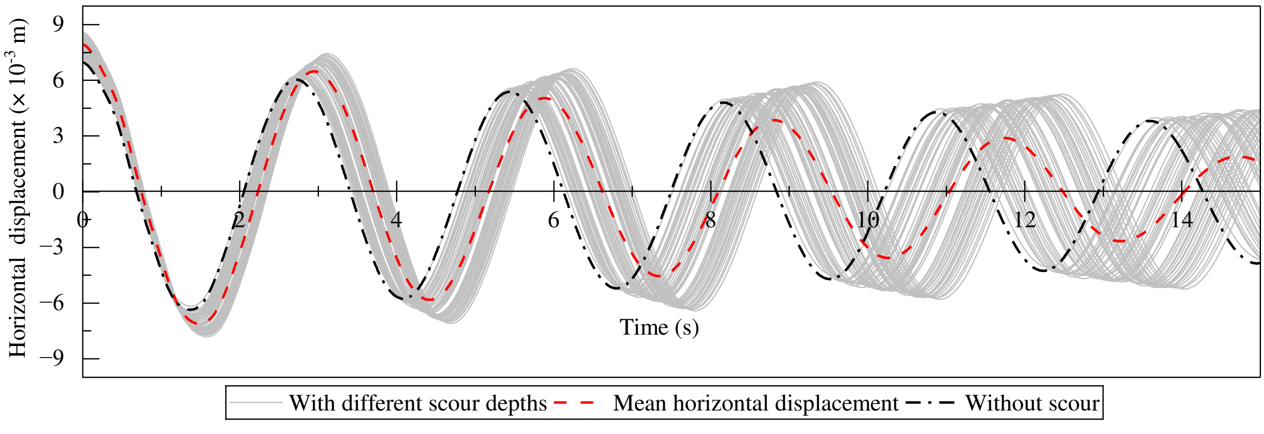

Figure 3 – Horizontal displacement at the nacelle level for 4 MW OWT considering the case of global scour

As the depth of the scour increases, the time period of the structure is observed to increase due to an increase in the flexibility of the structure. Figure 4 comprehensively compares all three types of wind turbines under consideration, highlighting the dynamic motion for different scour scenarios with their mean values. The dynamic response for the case of narrow and wide scour is observed to have a similar response. The response significantly differs from the no-scour case for higher time instants. Figure 5 represents the decay in eigenfrequency evaluated for different scour scenarios by considering different cases of monopile-supported OWT.

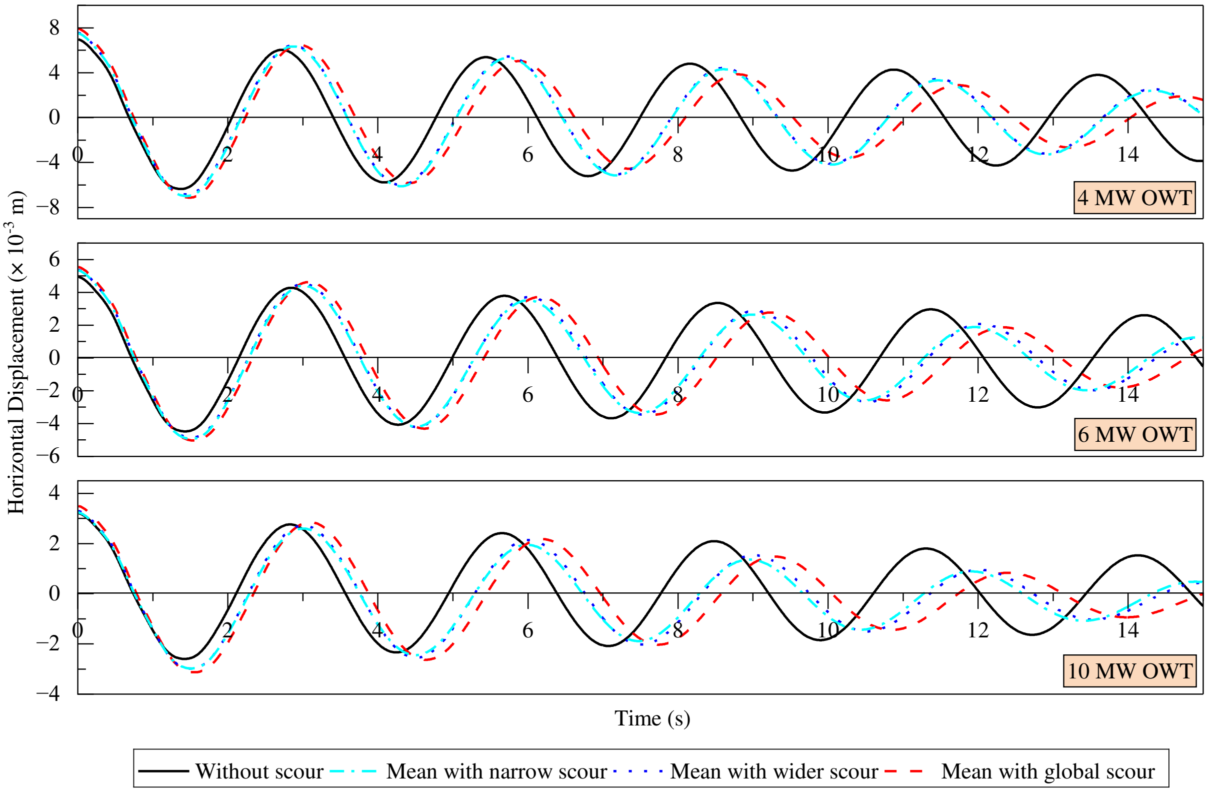

Figure 4 – Horizontal displacement at the nacelle level for all cases of Offshore Wind Turbines with their mean response

Due to the increase in flexibility of monopile-supported offshore wind turbines (OWT), the natural frequency of OWT increases. This reduction in stiffness is observed to be highest in the global scour scenario. For 4 MW OWT, the maximum reduction in eigenfrequency is 14.6 % in global scour, 11.6 % in wide scour case, and 10.8 % in narrow scour case. In the case of 6 MW OWT, the maximum reduction in eigenfrequency is observed to be 15.6 % for the global scour case, 12.7 % for the wide scour case, and 11.8 % for the narrow scour case. For 10 MW OWT, the reduction is 19.5% in the case of global scour, 15.3% in the case of wide scour, and 15.5% in the narrow scour case. However, there are also observations of certain spikes in final results which does not obey the with the expected trend. These anomalies can be attributed to the modeling process used to simulate scour in the finite element model. Specifically, the formation of the scour shape involves the removal of mesh elements corresponding to the scoured region. As a result, the updated mesh may introduce irregularities, leading to slight deviations in the output. Therefore, the observed spikes can be explained by the presence of uneven or non-uniform meshing in the modified scour models. This quantification is believed to be helpful for making better engineering assessments while designing the monopile considering scour cases.

5 CONCLUSIONS

The paper examines the assessment of the damped eigenfrequency of monopile supported offshore wind turbines through free vibration analysis, considering scour conditions and soil-structure interaction. Three types of scour geometries have been considered in the current study, the dimensions of which have been decided based on metocean conditions prevailing at the site under consideration. Hardening soil with a small strain model is utilized to predict the dynamic response of soil structure assembly. Calibration of strength and stiffness parameters are obtained considering the available correlation equations, while the small strain parameters are evaluated by validating the model for the eigenfrequency of the system. The eigenfrequency of the soil structure system is evaluated from the system's dynamic response performed using the free vibration analysis. It was observed that scour can significantly affect the system's eigenfrequency, which cannot be ignored while designing offshore wind turbines. Maximum reduction in eigenfrequency in the case of 4 MW OWT is observed up to 14.6 %, 15.6 % in the case

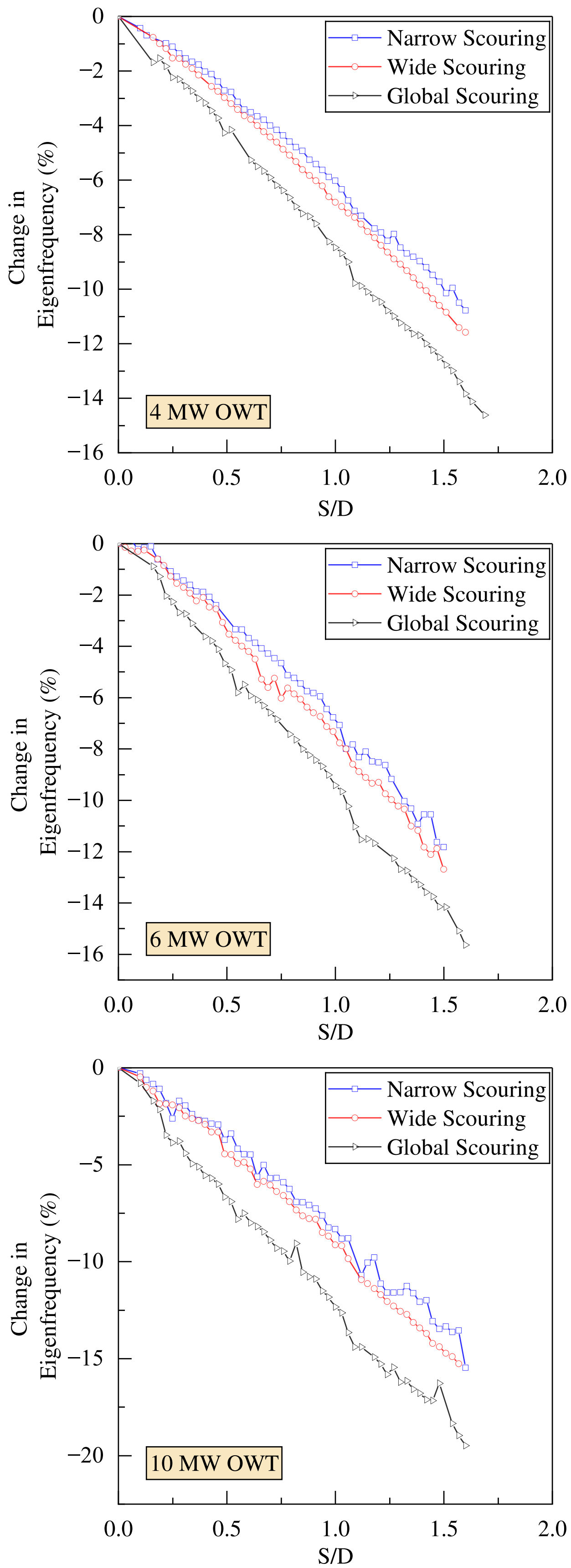

Figure 5 - *Natural frequency evaluated for different cases of scour scenarios*

of 6 MW OWT and 19.5 % in the case of 10 MW OWT. To ensure resilience against continuous dynamic forces, the frequency of the soil structure assembly must be in the soft-stiff range, which demands the proper investigation of the parameters that affect the system's dynamic behavior. The study recommends that designers consider scour and its effects for optimizing structural performance and stability, emphasizing the importance of ongoing monitoring and maintenance of offshore structures. However, the values presented in this study are subjected to the limitations of the modeling, including assumptions related to the representation of the tower components corresponding to designated site study.

AUTHOR CONTRIBUTION STATEMENT

Rituraj S Sujawat: Conceptualisation, Methodology, Investigation, Data collection and analysis, Result interpretation, Writing: original draft; Kottala Chandri Naidu: Investigation, Data collection and analysis, Result interpretation; Ritesh Kumar: Supervision, Conceptualisation, Writing: review and editing.

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