Fragility Analysis of High-Tension Line Towers Under Wind Loads Considering Soil-Structure Interaction

Kalim Qureshi[1], Vinod Kumar Modi[2]
[1]*M.Tech. Scholar, Kautilya Institute of Technology & Engineering, Jaipur*
[2]*Associate Professor, Kautilya Institute of Technology & Engineering, Jaipur*

***Abstract*—The structural stability of high-tension line towers is essential for maintaining reliable power transmission, particularly in the face of environmental forces like wind. Failures caused by wind forces in these towers can lead to extensive service outages and significant economic losses, highlighting the need to evaluate their performance under various conditions. This study explores the structural behavior of high-tension line towers exposed to wind loads, with a focus on the effects of different soil types (hard, medium, and soft). By integrating soil-structure interaction, the research seeks to provide a detailed understanding of how these towers respond to wind-induced forces.**

The study employs advanced numerical modeling in STAAD Pro to analyze key structural parameters, including base shear, overturning moment, and maximum displacement, under varying wind speeds and soil conditions. The analysis reveals notable differences in structural responses based on soil stiffness. Soft soils show increased base shear and overturning moments due to their lower resistance to lateral and rotational forces, while hard soils exhibit greater stability but slightly higher top-level displacements under similar conditions. Additionally, the findings indicate that in high wind zones, wind load intensity becomes the primary influencing factor, diminishing the relative impact of soil properties on the overall structural response.

The research emphasizes the importance of considering site-specific soil characteristics and wind conditions in the design of high-tension line towers. It highlights the need for customized foundation designs in softer soils to address increased vulnerability, as well as the implementation of wind-resistant design strategies in regions with high wind speeds. These insights offer a valuable framework for improving the resilience, reliability, and safety of high-tension line towers, particularly in areas susceptible to extreme wind events.

***Index Terms*—High tension line tower, Fragility analysis, Wind loads, Soil-structure interaction, STAAD Pro**

I. INTRODUCTION

Overhead transmission lines are indispensable to a dependable electrical power system, playing a key role in sustaining industrial productivity and ensuring the efficient operation of critical sectors of the national economy. Ensuring the safety and reliability of power transmission infrastructure is vital to prevent service disruptions and minimize economic losses. Transmission line towers, which support electrical conductors while maintaining required clearances from the ground and other conductive elements, are a fundamental part of this system. However, from a power transmission standpoint, the tower structure is considered non-productive, with the conductors serving as the primary functional components. Despite this, tower structures account for a substantial share of transmission line costs—approximately 36% of the total—underscoring the need to optimize tower design and construction to balance cost-efficiency with safety and reliability.

Transmission line towers have primarily concentrated on individual structural components, such as the performance of single-angle members and the effectiveness of various bracing systems, including X and K braces. However, comprehensive investigations into the failure mechanisms of full-scale transmission towers are relatively scarce, and experimental data on their behavior under real-world conditions remain limited. This gap in the existing literature underscores the urgent need for in-depth studies to evaluate the performance and failure modes of transmission line towers, especially when exposed to complex loading scenarios like wind forces across diverse soil conditions.

Objectives

- To analyze the structural performance of high-tension line towers under wind loads, with a focus on understanding the effects of soil-structure interaction on tower stability and overall behavior.

- To investigate the influence of varying soil types (hard, medium, and soft soils) on the wind-induced responses of transmission towers, including displacement, base shear, and bending moments.
- To develop fragility curves for high tension line towers, illustrating their vulnerability to wind loads across different soil conditions and wind intensities, and quantifying the probability of structural failure.
- To identify potential failure mechanisms in transmission line towers through a combination of numerical analysis and available experimental data, focusing on buckling, bending, and joint failure due to wind loads.

II. LITERATURE REVIEW

Numerous studies have investigated the structural behavior of tall and flexible structures under environmental loading, with a focus on nonlinear effects and advanced numerical modeling techniques. In this study, Zhao et al. (2023) conducted a comprehensive review of nonlinear wind-induced vibrations in tall buildings, high-rise structures, flexible bridges, and transmission lines. Their work emphasized the importance of accounting for aerodynamic nonlinearity in finite element analysis (FEA) to accurately predict structural responses to wind loads. Li et al. (2023) developed a nonlinear finite element model to study wind-induced vibrations in tension cable-supported transmission structures. The research highlighted the critical role of geometric nonlinearity and provided valuable insights into fatigue damage assessment under wind loading conditions. Flores et al. (2023) used finite element-based computational fluid dynamics (CFD) analysis to evaluate wind loads on structures. Their findings demonstrated the importance of precise wind load calculations to ensure structural safety, particularly in regions with strong wind activity. Pan et al. (2021) employed a three-dimensional finite element model in ABAQUS to examine the seismic fragility of transmission towers. The study underscored the significant impact of soil-structure interaction on dynamic responses but lacked a comprehensive analysis of varying real-world soil types or diverse tower designs. Forcellini et al. (2021) performed nonlinear dynamic analyses using OpenSees PL to explore the combined effects of pile flexibility and soil deformability on the seismic behavior of towers. The research revealed the mutual influence of these factors in seismic-prone areas but was limited to specific pile configurations. Mailyan et al. (2020) utilized computer modeling in ANSYS to demonstrate that incorporating pipe concrete into wind turbine towers could enhance load-bearing capacity by 37%. However, the study did not analytically address nonlinear effects. Ibrahim et al. (2019) developed a validated numerical model that showed longitudinal forces due to downburst loading were not dynamically sensitive. A noted limitation was the absence of turbulence representation in the wind field model**.** Seo et al. (2019) integrated FEM and CFD simulations to evaluate offshore wind turbine responses to combined wind and wave loads. Their approach effectively coupled aerodynamic and structural analyses for accurate predictions of structural behavior.

Hu et al. (2016) presented a comprehensive fatigue analysis framework for composite wind turbine blades, incorporating variable wind loads, aerodynamic analysis, and FEA. The study underscored the necessity of combining aerodynamic and structural analyses for precise fatigue life predictions. Ahmed et al. (2010) developed heuristic models to assess the vulnerability of transmission towers to cyclonic winds, offering valuable insights into structural responses. However, the study provided an incomplete understanding of behavior under extreme wind conditions.

This study aims to bridge the existing gap by investigating the effects of soil-structure interaction (SSI) on cooling towers, with a focus on varying soil types, base conditions, and other influencing factors. Realistic SSI modeling is crucial for the safe and reliable design of cooling towers, especially given their structural significance. By integrating these considerations, the study endeavors to provide a more precise understanding of cooling tower behavior under dynamic loading conditions, thereby contributing to improved safety and efficiency in design practices.

III. METHODOLOGY

The transmission tower is designed with a square base geometry, ensuring a balanced and stable foundation. It stands at a total height of 39.5 meters, providing sufficient elevation to meet operational and clearance requirements for the transmission lines. The tower's base is equipped with fixed supports, spaced 10 meters apart center-to-center, to guarantee structural stability and integrity.

Ground clearance is maintained at 20 meters, a critical safety feature that ensures adequate distance between the lowest conductor and the ground. To account for the natural sag of transmission lines, the sag of the lowermost conductor wires is set at 3 meters. The design also incorporates a vertical spacing of 6 meters between adjacent conductor wires, minimizing electrical interference and maintaining proper separation. Additionally, a vertical distance of 4.5 meters is maintained between the top conductor and the ground wire, ensuring reliable performance under both normal and extreme loading conditions.

The tower's wings extend 10 meters, providing additional support for the conductor wires and further enhancing structural stability. This thoughtful design addresses operational, safety, and structural efficiency requirements, ensuring the tower performs effectively in varied conditions.

Table 1 Sectional parameters

Parameter	Specifications
Geometry of Tower	Square Base
Height of Tower	39.5 m
Centre to Centre distance of Fixed support at base	10 m
Ground Clearance h_1	20 m
Sag of the lowermost conductor wires h_2	3 m
Vertical distance between conductor wires h_3, h_4	6 m
Vertical distance between top conductor and ground wire h_5	4.5 m
Length of wings	10m
Main Vertical Members	ISMB 500
Horizontal & Inclined bracings and cross arms	ISA 150*150*15

STAAD Pro was utilized to model the soil-structure interaction for a high-tension line tower. The soil was represented using elastic and non-linear spring models, while the tower was modeled as a beam-column structure with realistic boundary conditions. The wind load analysis focused on two primary factors: soil type (hard, medium, and soft) and the geographical location of the tower (Delhi and Jaipur). Six conditions, as detailed in Table 3.3, were analyzed to evaluate the tower's structural behavior under varying wind conditions.

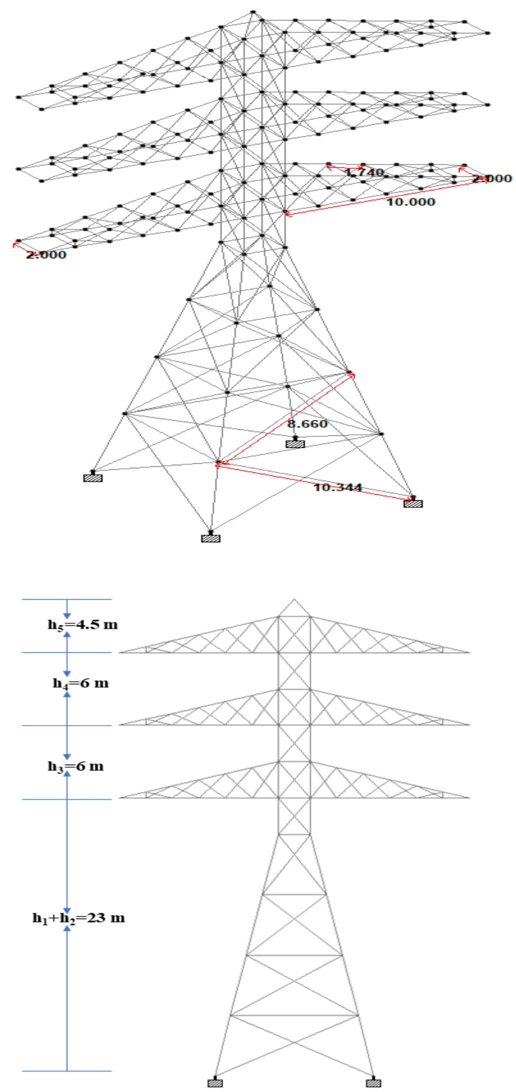

Fig. 1 Detailing of the Tower elements

Wind-induced forces and moments were calculated along the x-axis and z-axis, identifying maximum values for comparison. Displacements at critical nodes along the x, y, and z-axes were examined to evaluate stability. Shear force and bending moment distributions across the tower's height were analyzed to assess the structural response under diverse wind pressures and soil conditions. This comprehensive analysis provided insights into the impacts of wind loads on the tower, contributing to the development of optimized and resilient design strategies.

Table 2 Combination of each condition for seismic analysis

Model	City	Zone	Soil Type
Model 1	Delhi	1	Hard
Model 2	Delhi	1	Medium
Model 3	Delhi	1	Soft
Model 4	Jaipur	2	Hard
Model 5	Jaipur	2	Medium
Model 6	Jaipur	2	Soft

IV. RESULTS AND DISCUSSION

The study evaluates the overturning moment, base shear, and maximum displacement of a high-tension line tower under varying wind loads and soil conditions. Overturning moments are highest in soft soils due to lower stiffness, with values ranging from 20.156 kN-m (hard soil) to 27.883 kN-m (soft soil) in Delhi, and higher values observed in Jaipur due to stronger winds. Base shear also increases with softer soils, ranging from 543.605 kN (hard soil) to 899.03 kN (soft soil) in Delhi. However, in Jaipur, base shear values are nearly uniform (~795 kN), reflecting the dominance of wind forces over soil variability.

Displacement analysis shows reduced top displacements in softer soils in Delhi, attributed to base flexibility, while in Jaipur, maximum displacements (~402.5 mm to 406 mm) remain consistent across soil types, dominated by wind forces. These results emphasize the critical role of soil stiffness and wind conditions in structural stability and foundation design.

Table 3 Maximum outcomes for each condition

Soil Type	Wind Zone	Base Shear (kN)	Maximum Resultant Displacement (mm)	Overturning Moment (kN-m)
Hard	Delhi	543.60	434.277	20.156
Medium	Delhi	848.98	389.373	26.971
Soft	Delhi	899.03	384.539	27.883
Hard	Jaipur	796.18	402.525	24.04
Medium	Jaipur	795.62	406.013	24.81
Soft	Jaipur	795.773	405.893	24.809

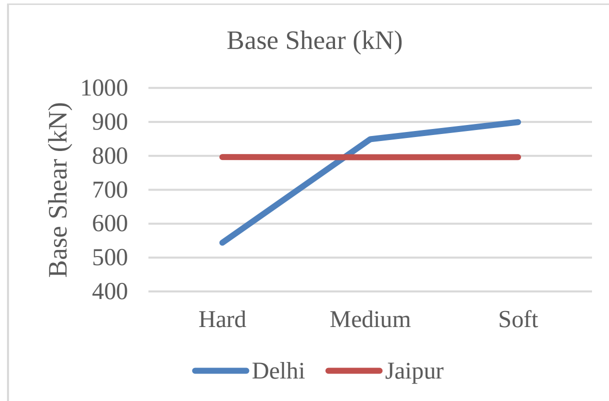

Fig. 2 Base Shear for different soil condition

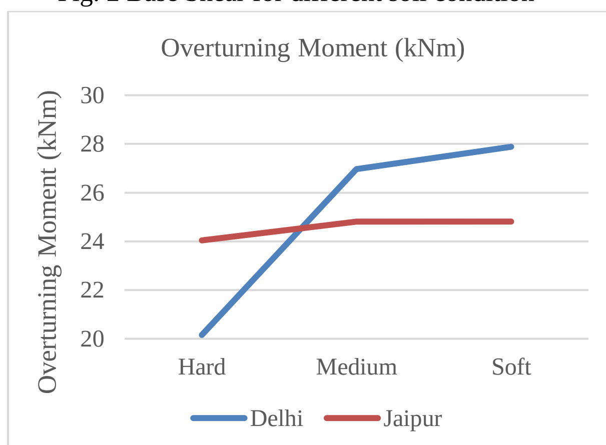

Fig. 3 Overturning Moment for different soil and water level condition

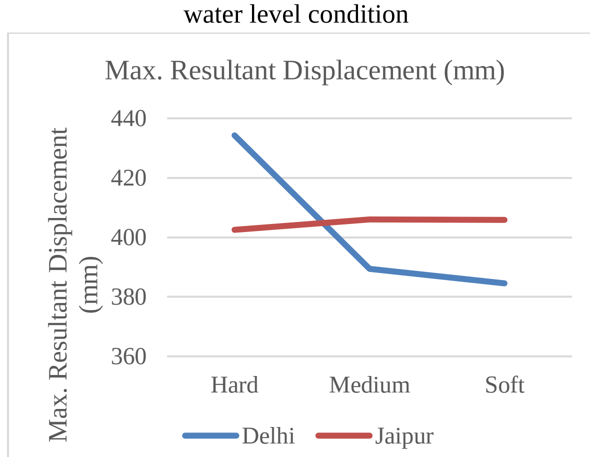

Fig. 4 Top Displacement for different soil and water level condition

V. CONCLUSIONS

Impact of Soil Type on Structural Response:

- In Delhi, softer soils exhibit significantly higher base shear and overturning moments due to their lower stiffness and higher deformation under wind loads. This amplifies the lateral and rotational forces acting on the structure, necessitating careful foundation design for such conditions.
- In Jaipur, the higher wind speeds dominate the structural response, resulting in relatively uniform values of base shear and overturning moments across all soil types. This indicates that wind load intensity, rather than soil compliance, is the governing factor in this region.

Displacement Behavior:

Maximum displacements for all scenarios remained within permissible limits, ensuring the operational safety and serviceability of the tower. In Delhi, softer soils exhibited slightly reduced top-level displacements due to their flexibility, which allows for energy dissipation at the foundation level. In Jaipur, the strong wind forces led to consistent displacement values across all soil types.

Safety and Stability:

The transmission tower's design is robust and capable of withstanding varying wind and soil conditions. However, for softer soils, additional measures, such as deeper foundations or soil improvement techniques, may be required to counteract the amplified effects of base shear and overturning moments.

Wind Load Dominance in High-Speed Zones:

In regions with higher wind intensities, such as Jaipur, wind forces dominate the structural response, reducing the influence of soil properties on performance. This suggests that foundation design in such regions should prioritize wind load resistance.

to standard concrete blocks.

REFERENCES

[1] Zhao, Shuang, et al. (2023). "Nonlinear effects of wind-induced vibrations on tall buildings, high-rise structures, flexible bridges, and transmission lines." Journal of Structural Engineering, 149(3), 04023024.

[2] Li, Jingyang, et al. (2023). "Nonlinear finite element modeling for wind-induced vibrations in tension cable-supported power transmission structures." Engineering Structures, 283, 115992.

[3] Flores, Benjamin D., et al. (2023). "Finite element-based computational fluid dynamics analysis of wind loads on structures in high wind zones." Computers & Structures, 275, 106871.

[4] Pan, Haiyang (2021). "Seismic fragility analysis of transmission towers considering soil-structure interaction using ABAQUS." Soil Dynamics and Earthquake Engineering, 144, 106671.

[5] Forcellini, Davide (2021). "Non-linear dynamic analysis of tower foundations: Effects of pile flexibility and soil deformability." Geotechnical Earthquake Engineering and Soil Dynamics Journal, 10(2), 245–262.

[6] Mailyan, Levon (2020). "Incorporation of pipe concrete in wind turbine tower design to enhance load-bearing capacity." Energy Procedia, 152, 899-906.

[7] Ibrahim, Ibrahim (2019). "Numerical modeling of longitudinal forces due to downburst loading in transmission towers." Journal of Wind Engineering and Industrial Aerodynamics, 186, 234-245.

[8] Seo, Junwon, et al. (2019). "FEM and CFD coupled analysis of offshore wind turbines under combined wind and wave loads." Renewable Energy, 132, 711-723.

[9] Hu, Weifei, et al. (2016). "Fatigue analysis of composite wind turbine blades using aerodynamic and structural finite element analysis." Composite Structures, 150, 49-58.

[10] Ahmed, Ammar (2010). "Heuristic models for transmission tower vulnerability to cyclonic winds." Engineering Structures, 32(8), 2446-2457.

[11] Li, Feng, et al. (2007). "Finite element and experimental investigations of geometric nonlinearity in transmission tower design." Structural Engineering International, 17(3), 205-213.

[12] Jayalekshmi, B. R. (2015). "Soil-structure interaction effects on chimneys with piled raft foundations using 3D finite element techniques." Geotechnical and Geological Engineering, 33(5), 1167-1180.

[13] Wang, Dahai (2011). "Dynamic tension in transmission lines analyzed using continuous cable theory." Journal of Applied Mechanics, 78(5), 051001.

[14] Yang, Jingbo (2010). "Dynamic response of transmission towers under extreme wind events using 3D finite element analysis." Wind and Structures, 13(3), 223-234.Bureau of Indian Standards, “IS 456: 2000; Plain and Reinforced Concrete – Code of Practice.”

[15] Bureau of Indian Standards, “IS 800: 2007; Code of practice for General Construction in Steel — Code of Practice