Multi-Modal Natural Frequency Response of Utility Transmission Tapered Wood Poles Under Various Soil Foundation Conditions

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***Abstract* — Studied herein is the multi-modal natural frequency response of utility transmission tapered wood poles under various soil foundation conditions. Strong winds and hurricanes in various parts of the world have resulted in collapse of such utility poles and have resulted in the disruption of electrical distribution systems in addition to creating hazardous conditions for the public. To avoid the development of resonance under such dynamic loading, the multi-modal natural vibration of the utility poles first needs to be understood in the presence of practical soil foundation conditions. To capture the soil-structure interaction effects on the multi-modal frequencies, a SAP2000 dynamic finite element model is created in which the foundation soil stiffness is characterized by means of a series of 'soil springs' below the ground level. The properties of the soil springs vary with types of foundation soils and depths. Three types of foundation soils are considered, namely sandy, clayey soils and Granite (Rock). The results are compared to a standard fixed base model. It is found that the fundamental natural frequencies decreased by 52%, 37%, and 3% for sandy, clayey soils and granite, respectively, when compared to fixed base model. It was observed that there was an increase in the frequencies of the embedded utility poles in clay and granite, when compared to those with the fixed based after the 1st mode whereas, poles embedded in sandy soils showed increase in modal frequencies after the 3rd mode. The 10th mode appears to be a starting point of modal frequency convergence, while an apparent convergence occurs after the 20th mode. The convergent modal frequency was about 740 Hz for the Class H1 utility pole. However, there was a significant increase in the higher modal frequencies such as nearly 55% at the 20th mode, in all soil types when compared to the fixed base model.**

***Index Terms* — multi-modal frequency response, soil foundation effects, soil-structure interaction, utility tapered wood poles.**

I. Introduction

In recent years, the dynamic response of transmission poles has become an important aspect of design, including similar structures such as bridge poles, highway sign support structures and telecommunication towers due to failures observed during hurricane-force winds. Keshavarzian and Priebe [1] studied the wind performance of short utility pole structures. Kulhaway, Hirany [2] outlined the design procedure of transmission line foundations. Gajan, McNames [3] proposed a more refined design of foundation for transmission line structures. Lovelace [4] outlined the design considerations for transmission line poles. Shafieezadeh, Onyewuchi, Begovic and DesRoches, [5] studied the fragility assessment procedures for wood poles. However, the current design of transmission poles and similar structures does not consider the dynamic effects or resonance conditions in the design and performance assessment of the wood poles. Consequently, there is a need to understand the dynamic characteristics of such structures to prevent resonance conditions leading to failures. In general, these structures are currently being analyzed and designed assuming that wind is a static force applied at 2ft from the tip of the pole thus ignoring potentially disastrous inertial effects. In this paper, the effect of three types of soil, namely, granite (rock), sandy soil and clayey soils are investigated to quantify and characterize the multi-modal natural frequency response of the utility wood poles of the type used worldwide.

II. Investigation Schemes

A tapered Class H1 wood pole is shown in Figure 1 with z as its longitudinal (vertical) axis, and x (and y axis) as the horizontal axis and fixed at the ground level. This pole will be used as the base model for the subsequent analysis, and comparison with the poles embedded in various types of soils. Wood Pole classifications are given in ANSI 05.1 [6]. The Class H1 wood pole studied in this paper has a length of 24.5 ft (above the ground level), and the diameters at the base and top ends are 12.8 in., and 8.7 in., respectively [4], [6]. The finite element model consists of 28 nodes and 27 equally spaced elements at approximately 10.89 inches.

Figure 2 shows H1 class pole embedded 5 ft 6 inches in soil. The diameter of the pole at the base is 14in. The embedment depth of the pole is based on industry practice of 10% of the height above the ground level plus 2 ft. Figure 2 also shows the analysis model with equivalent soil springs at the selected nodes. The soil is assumed to deform elastically together with the pole element. The nodal displacements and the rate of displacements in the soil and pole are assumed to be the same. Hence the interaction of the soil with the pole can be approximated by treating the soil as nodal springs with the appropriate load displacement characteristics. The soil skin friction on the face of the pole is similarly assumed to behave linearly as a vertical spring at each node. The soil end bearing pressure may have a significant effect on the response of the structure. Hence, an additional spring is included at the bottom of the pole to account for the end bearing capacities of the soils. Lateral (X- and Y-axis) and vertical springs (Z-

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axis) are assigned to each node which represents the soil stiffnesses at the nodes. The magnitude of the soil spring stiffness depends on the characteristics of the soil under consideration and are summarized in tables 1 through 3. In these tables, γ_{soil} is the density of the soil, $A_{E,z}$ is the increase in Soil Young's Modulus per unit length, $E_{S,Z}$ is Young's Modulus at the node, k_x, k_y, and k_z are the lateral and vertical equivalent soil springs constants. Also listed in the tables are the analytical node number and the corresponding depth of foundation soil. The values of $A_{E,z}$ is based on procedures as prescribed in Reference [7].

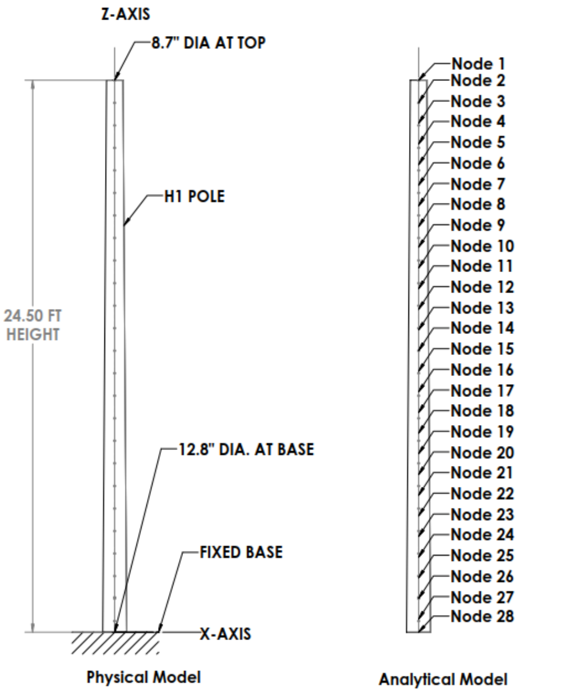

Fig. 1. Fixed base model for a Class H1 utility tapered wood pole and corresponding analytical model.

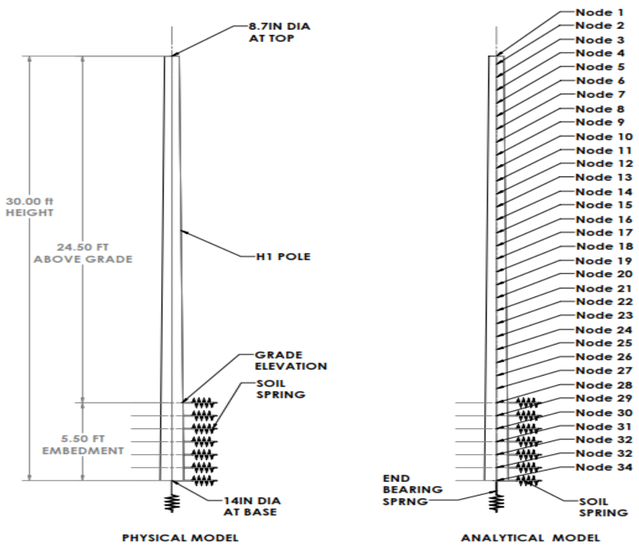

Fig. 2. Soil Embedment for a Class H1 utility tapered wood pole and Finite Element Analytical model.

The lateral spring constants for sand vary linearly with depth of the embedment in soil. In contrast, the lateral spring constants for clay and granite remains constant over the depth of embedment in soil. This variation in the spring constants are presented in Tables 1 through 3.

TABLE 1: SOIL SPRING CONSTANTS OF SANDY SOIL
[γ_{SOIL} = 110 PCF; POLE END BEARING CAPACITY = 0.54 KIPS; $A_{E,Z}$=660 PSI/FT]

Node Number	Depth of Soil, ft	$E_{s,z}$, ksi	k_x, k_y, kip/in	k_z, kip/in
28	0	0.00	0.00	0.00
29	1	0.66	15.84	0.04
30	2	1.32	31.68	0.15
31	3	1.98	47.52	0.35
32	4	2.64	63.36	0.62
33	5	3.30	79.20	0.97
34	5.5	3.63	43.56	1.17

The rotational stiffness of the soil is small and therefore neglected in this study. The soil spring constants reflect only the compression stiffness since typical soils (except rock) have negligible tension capacity. The lateral and vertical soil springs are hence axially loaded compression-only elements. The lateral spring constants are typically based on the compressive load displacement test data. Similarly, the vertical spring constants are based on the shear load versus displacement test data. Standardized formulas are provided in geotechnical textbooks to calculate the soil spring constants which agree very closely with experimental data. The lateral and vertical spring constants given in Tables 1, 2 and 3 were determined based on equations that utilize the various soil properties such as soil density, moisture content, compressive strength, shear strength, etc.

The analysis model utilized a total of 34 nodes, with 6 nodes spaced at 11 inches and the 7th node at 6 inches in the soil, and 27 nodes above the ground level spaced at 10.89 inches. The number of nodes used was found to be sufficient to provide accurate results for a varying mass and stiffness system involving soil-structure interaction. Essentially, the pole is modelled as a multi-degree-of-freedom system. The Young's modulus of wood is taken as E_{wood} = 1000 ksi. Tables 1, 2 and 3 show the soil spring constants in the x, y, and z directions for Sandy, Clayey soils, and Granite (rock). At node 34, an additional spring was added to account for the end bearing capacity of the poles in the respective soils.

TABLE 2: SOIL SPRING CONSTANTS OF CLAYEY SOIL
[γ_{SOIL} = 90 PCF; POLE END BEARING CAPACITY = 0.44 KIPS, $A_{E,Z}$ = 3920 PSI/FT]

Node Number	Depth of Soil, ft	$E_{s,z}$, ksi	K_x, k_y, kip/in	k_z, kip/in
28	0	0.00	0	0.00
29	1	3.92	94.08	0.03
30	2	3.92	94.08	0.13
31	3	3.92	94.08	0.29
32	4	3.92	94.08	0.51
33	5	3.92	94.08	0.79
34	5.5	1.96	23.52	0.96

TABLE 3: SOIL SPRING CONSTANTS OF GRANITE (ROCK)
[γ_{SOIL} = 140 PCF; POLE END BEARING CAPACITY = 4.47K KIPS, $A_{E,Z}$ =29000 PSI/FT]

Node Number	Depth of Soil, ft	$E_{s,z}$, ksi	K_x, k_y, kip/in	k_z, kip/in
28	0	0.00	0	0.00
29	1	29.00	696	0.05
30	2	29.00	696	0.20
31	3	29.00	696	0.44
32	4	29.00	696	0.79
33	5	29.00	696	1.23
34	5.5	14.50	174	1.49

III. Numerical Results

The numerical results were generated with SAP2000 finite element software [8] using the soil-structure interaction model created for this study. Tables 4 and 5 summarize the frequencies for modes 1 through 10, and modes 11 through 20, respectively. The tables list the soil types starting from the smallest soil spring constants to the largest based on known stiffness values of the soil. The modal response of the soil types agrees with the well-established understanding that the sandy soils exhibit smallest stiffness whereas rock provides the largest highest stiffness. It is observed that only the first, second modal frequencies for the fixed based were larger than those with the three types of soil. All the modal frequencies starting from the third mode are larger for the various soil types than those for the fixed based condition and continued to increase up to the 20th mode.

The fundamental frequency of the Class H1 pole with fixed base was 5.6 Hz as compared to 2.7 Hz, 3.5 Hz, and 5.5 Hz for Sandy, Clayey soils, and Granite. Poles embedded in Granite showed a larger natural frequency compared to Sandy and Clayey soils, but less than the fixed base. The fundamental frequencies of the class H1 poles embedded in Sandy, clayey soils and granite are 51.5%, 36.7%, and 2.8% lower when compared to the fixed base. These are significant variations and can led to errors in dynamic response evaluations of poles if the proper soil parameters are not included in the dynamic analysis. Poles embedded in granite or rock has the fundamental natural frequency very close to that of the fixed base model.

The results in Tables 4 and 5 are plotted graphically and shown in Figures 3 and 4. Figure 3 shows the graph of mode numbers versus the corresponding modal frequencies. Figure 4 shows the percentage decrease or increase in frequencies for various modes. Rock exhibited signification increase the frequencies between the 2nd and 10th mode before convergence with sand and clay. The decrease in the frequencies for sand was only in the first 3 modes, however, there was significant increase in the frequencies from the 4th mode. It was observed that convergence or stabilization of the frequency gain occurs at about the 14th mode. However, there is divergence of the frequencies compared with a fixed based beyond the 4th mode for all types of soil.

TABLE 4: Frequencies for Modes 1 through 10 with Various Foundation Soil Types, and Percent Modal Frequency Deviation from Fixed Base Condition

Modal Frequencies										
Mode Number	1	2	3	4	5	6	7	8	9	10
Sand	2.7	3.6	13.5	33.7	58.9	81.2	115.8	163.6	171.6	220.2
Clay	3.5	15.2	37.1	66.4	86.0	116.2	164.5	171.6	221.0	284.1
Rock	5.5	18.2	43.1	78.6	123.4	171.7	175.2	222.2	244.4	300.0
Fixed Base	5.6	6.1	22.4	27.0	53.1	65.2	96.9	118.8	126.1	152.7
% Modal Frequency Deviation from fixed base										
Sand	-51.5	-40.7	-39.7	25.0	10.9	24.5	19.5	37.7	36.1	44.2
Clay	-36.7	148.6	65.7	146.4	62.0	78.2	69.8	44.4	75.3	86.1
Rock	-2.8	197.3	92.4	191.5	132.4	163.2	80.8	87.0	93.8	96.5

TABLE 5: Frequencies for Modes 11 through 20 with Various Foundation Soil Types, and Percent Modal Frequency Deviation from Fixed Base Condition

Modal Frequencies										
Mode Number	11	12	13	14	15	16	17	18	19	20
Sand	283.5	320.1	352.3	425.6	468.1	502.5	582.1	615.5	663.0	744.0
Clay	284.1	320.1	352.8	426.0	468.2	502.8	582.3	615.6	663.2	744.3
Rock	300.0	320.1	364.3	433.8	468.2	508.5	587.4	615.5	668.4	749.3
Fixed Base	185.6	218.9	263.4	294.1	300.2	349.6	376.3	442.1	464.1	479.8
% Modal Frequency Deviation from fixed base										
Sand	52.7%	46.2%	33.8%	44.7%	56.0%	43.7%	54.7%	39.2%	42.9%	55.1%
Clay	53.1%	46.2%	34.0%	44.9%	56.0%	43.8%	54.7%	39.2%	42.9%	55.1%
Rock	61.6%	46.2%	38.3%	47.5%	56.0%	45.5%	56.1%	39.2%	44.0%	56.2%

Stiffness and mass are the two parameters that determine the natural frequencies at various mode. The soil proprieties clearly influence the frequencies in the following manner:

1. increase the effective stiffness of the system, or
2. decrease the effective mass of the system.

Additional research is required to further study the effect of stiffness and mass to explain the observed phenomenon, which was outside the scope of this investigation.

Rock exhibited significant increase in the modal frequencies between the fourth and tenth mode when compared to Sandy, and Clayey soils. The trend towards frequency convergence appear to start after mode 10, and apparent convergence after the twentieth mode. However, there is a 54.2% average difference in the frequencies between the fixed base and the various soil types.

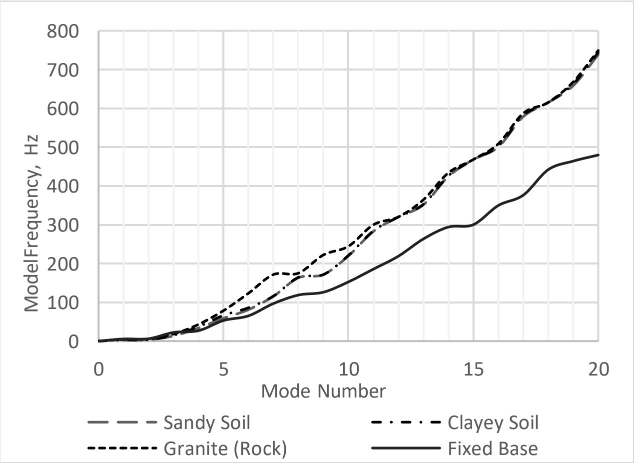

Fig. 3. Frequency versus Mode Number for Various Foundation Soil Types.

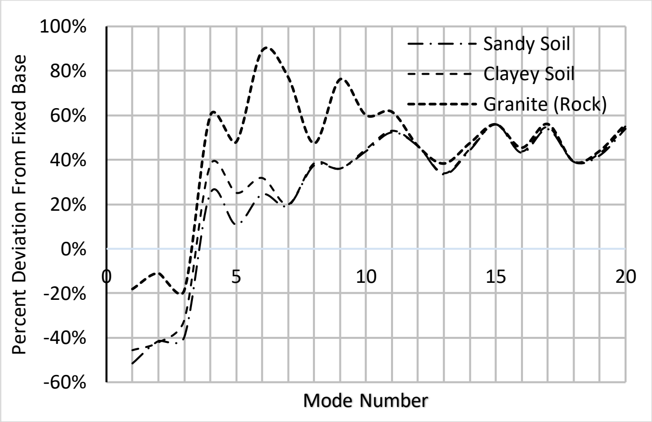

Fig. 4. Frequency Deviation Vs Mode Number for Various Foundation Soil Types.

IV. CONCLUSION

The study shows that the natural frequencies of wood transmission and utility poles are significantly influenced by the type of soil in which they are embedded. The fundamental frequencies of poles embedded in Sandy, Clayey and Granite foundation soil types are lower than those for a pole with fixed base. However, there is an increase in the modal frequencies after the first mode. Apparent modal frequency convergence occurs at about the 20th mode but is about 54% larger than that of a fixed base pole. The results indicate that soil properties are an important factor in the dynamic response of wood transmission poles and must be incorporated in the design of such structures. However, the type of soil has little influence on the frequencies at higher modes. A fixed base model is not representative of actual soil foundation conditions and gives inaccurate modal frequencies of poles. Significant errors are introduced in the dynamic characterization of poles embedded in soil, particularly sandy and clayey soils, if the soil-structure interaction is ignored. The study reveals deviations of 52%, 37% and 3% in the natural frequencies of the pole studied, in the presence of sandy, clayey and granite soil types, respectively, in comparison to that based on the assumption of a fixed base.

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