Parametric Study on the Effects of Catenary Cables and Soil-Structure Interaction On Dynamic Behavior of Pole Structures Using the Finite Elements Method & Exprimental Validation

R. Khosravian[1,a)], M. Steiner[1] and C. Koenke[2]

[1]Research Training Group 1462, Bauhaus-University Weimar, Germany

[2]Institute of Structural Mechanics, Bauhaus-University Weimar, Germany

[a)]Corresponding & presenting author: Reza.Khosravian.Champiri@uni-weimar.de

ABSTRACT

Being a typical structural element in infrastructure of transportation systems, the poles are one of the key parts of almost any railway system, carrying the required electricity wires and further side-supplies. On the other hand, numerical simulations have become an inseparable part of any modern engineering task, such that they lead to a deeper insight into the problem and its various perspectives. Pole structures, not being an exception, have attracted significant attention in this regard, especially due to the increase in utilization of railway systems. Therefore, a deep study on diverse modeling aspects of such structures is a necessity to obtain trustable simulation results.

The current study is a survey aimed at investigating the effects of two factors, namely the catenary cables and soil-structure interaction (SSI), on the dynamic behavior of the pole structures which are used in a high-speed train line connecting the cities of Leipzig and Erfurt in the eastern region of Germany. The study is conducted using 3D Finite Element models (FEM). The final goal is to gain an understanding of how the two mentioned factors, from a modeling point of view, affect the eigenfrequencies of the structure.

Initially, the modeling aspects and assumptions used in the study are clarified, and the methods which were used to model the catenary cables and the SSI are briefly explained. Henceforth, the simulation results are presented and discussed. Finally, a parameter study is performed in order to identify the most decisive parameters of the model when calculating the eigenfrequencies, while simultaneously observing the behavior of the model when only one parameter changes. Last but not least, the eigenfrequencies calculated using the acceleration data which are extracted from the sensors installed on an in-service pole are presented, so that a comparison between the modeling results and those of the real-world model would further assist in making a judgment about the prognosis capability and accuracy of the simulations. Such a comparison especially proves to be useful in order to decide about the boundary conditions and the modeling assumptions concerning the SSI and the cables. It is also worth noting that in the course of the parameter studies, the so called *metamodeling* techniques are used after being shortly introduced, to accelerate the analyses.

Keywords: Soil-Structure Interaction, Pole, Catenary Cables, Dynamic Behavior, Sensitivity Analysis, Metamodeling.

Introduction

Poles, either the ones used for luminary posts or electricity cables along railway systems, are nearly identical structures that despite their relative simpleness in shape and dimensions, are subject to various experimental and numerical investigations. Among various reasons, one could name the possibility of consideration of stochastic properties since the experimental data could stem from multiple structures which are commonly considered to be identical when numerically modeled; however, the necessity of accurate simulation of such structures is undeniable due to their importance and vast utilization. Being diverse in dimensions, usage, structural characteristics and building material, the poles investigated in this study are a part of a high-speed railway system which connects the cities of Leipzig and Erfurt in the eastern region of Germany to each other. Made of reinforced concrete, the investigated structures are prestressed spun-cast poles with a length of 10 meters and outer diameter of 40 and 25 centimeters at the bottom and the top respectively. Unlike statically-cast concrete poles, the spun-cast concrete poles are cenrifugally spun with embedded high-strength, prestressed steel strands which are totally enclosed within the concrete. This technique allows the poles to be extremely strong, while improving the resistance against corrosion. Each pole has a floating pile underneath as the foundation, with a length of almost 6 meters.

Being a critical issue in order to ensure the continues supply of energy, the stability of these pole-pile systems is provided using the direct embedment method. This involves creating a cylindrical hole in the ground by a drill and inserting the concrete pole into the open hole, whose gap is then to be filled using grouting materials. This is a common technique especially in cases which are subject to high overturning moments but only moderate vertical loads. The pole studied in this survey, caries only the catenary cables, but not the full electricity system yet.

Figure 1. The pole with the catenary cable

The goal is to initially investigate the effects of the catenary cables and SSI on the eigenmodes of the structure when modeled using FEM. After a brief introduction to the modeling assumptions, techniques, and the method to model the SSI, the simulation results are presented and discussed. Henceforth, a parameter study is performed in order to identify the most decisive parameters when calculating the eigenfrequencies, while simultaneously observing the behavior of the model when only one parameter changes. Finally, the eigenfrequencies calculated using the acceleration data which are extracted from the sensors installed on an in-service pole are presented, so that a comparison between the modeling results and those of the real-world model would further assist in making a judgment about the prognosis capability and accuracy of the simulations. This will also lead to the conclusion, which boundary conditions in the model simulate the reality in a better manner. The survey comes to an end after making the final conclusions, and indicating the open areas related to the problem, which are to be further investigated.

Modeling Aspects

General

Despite the resemblance of the general behavior of the structure to that of a cantilevered beam, in the absence of closed-form solutions, FEM was used to calculate the natural frequencies of the structure. The structure is modeled using the FEM, having almost 55000 quadratic tetrahedral mesh elements. The prestressing effect was neglected due to the fact that the prestressed load is considerably lower than the buckling load of the pole, a fact that makes this effect negligible when calculating the eigenfrequencies [1].

The soil behavior is assumed to stay in linear range since the main concern is the calculation of the eigenfrequencies, although the linear springs modeling the soil are calculated considering the soil characteristics. The methodology which also accounts for SSI is briefly explained. The concrete is also modeled using a linear elastic constitutive law, based on the properties attributed to C80/95 concrete in Eurocode 2.

In the course of the study, a naming convention was used to differentiate the seven different models (six numerical and one experimental) more clearly:

- Ref: The pole with clamped support, no catenary cables, no SSI
- Ca: The pole with clamped support, with catenary cables, no SSI
- S1: The pole with spring support counting for SSI (Constant soil profile), no catenary cables
- CaS1: The pole with spring support counting for SSI (Constant soil profile), with catenary cables
- S2: The pole with spring support counting for SSI (Parabolic soil profile), no catenary cables
- CaS2: The pole with spring support counting for SSI (Parabolic soil profile), with catenary cables
- Exp: The eigenmodes calculated using the acceleration data of the sensors installed on an in-service pole

Last but not least, throughout the entire paper, the X direction represents the direction in which the catenary cables are extended, while Y is its perpendicular direction and Z is aligned with the length of the pole.

Catenary Cables

The catenary cables at service during this phase of the project, were the ones used for electricity grounding only (Figure 1). Having a cross sectional area of $242.5mm^2$, the cables are made of aluminum type 243 AL1 (DIN EN 50182). The distance between each pair of poles is 65 meters which results in a sag of 1 meter in the middle based on field observations.

Modeled using linear elastic material, the cables were assumed to behave geometrically nonlinear, such that after the deformation due to their self weight, they resembled a hyperbolic cosine function ($f(x) = a.\cosh(\frac{x}{a})$); the function's shape is decided by a constant parameter, the so-called *catenary constant* (a), which is the ratio of the horizontal tension to the weight of the cable in the middle and is to be calculated in an iterative procedure since it is initially unknown [2]. A circular cross section with the mentioned cross sectional area was used to model the cables; however, its bending and torsion stiffness was supposed to be only 20% of that of a rigid cross section with the same material properties and cross sectional area.

For modeling simplifications, the cables were substituted by a spring-mass system; however, the stiffness and mass of the system were numerically calculated based on the entire cable system modeled separately. In order to calculate the stiffness ($K = \frac{\Delta F}{\Delta X}$) of the spring which substituted the cable system, only two cables were modeled as explained before, and the change of reaction force (ΔF) was calculated when a known displacement (ΔX) was applied at their intersection point. As illustrated in Figure 2, different values of applied displacement led to different values of stiffness.

Although the stiffness with regard to the displacement of 0.1 meter was adopted for the rest of the calculations, the effect of the chosen value will be discussed in the parameter studies. Finally, the entire cable system was modeled using the linear spring and the mass of the cables acting in X and Z directions respectively.

Soil-Structure Interaction (SSI)

As long as the model concerns the calculation of the eigenmodes, the assumption of not violating the linear range stays valid [3]. Hence, the substructure part in models which simulated the SSI was modeled using seven elastic springs, such that the springs would also count for the interaction between the soil and the floating pile underneath the pole. Proposed by Novak [4], the stiffness values of the springs (three translational, two rotational and two translational-rotational coupling springs) depend on the soil's shear modulus and density, as well as on the pile's modulus of elasticity and radius. Furthermore, the slenderness and bottom condition (floating or end-bearing) of the pile are decisive only in the vertical direction, which is not of great importance in this case due to the relatively low loading in the vertical direction, as was also proven in the parameter studies to be presented. The method eventually leads to four spring stiffness values for horizontal degrees of freedom (DOF), vertical and rotational DOFs as well as the coupling between the rotational and horizontal DOFs. In

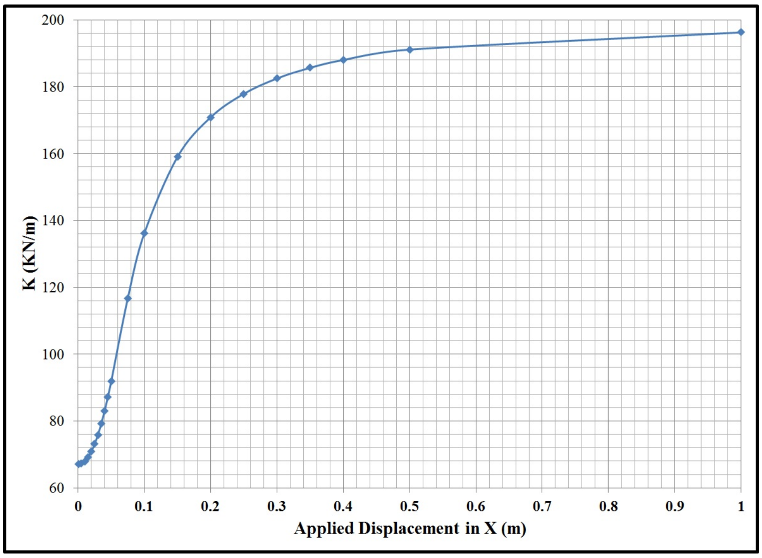

Figure 2. Stiffness of the spring substituting the cables

their work, Novak neglects the torsional behavior around the pile's axis since he states that this motion is not only strongly frequency dependent, but also consequential just for caisson foundations or groups of massive piles.

Moreover, one last critical assumption in the mentioned methodology concerns the soil profile. The soil's shear modulus is considered to be either constant or varying with depth according to a quadratic parabola. Parabolic variation of soil's shear modulus (models S2 and CaS2), versus a constant modulus in the entire soil profile (models S1 and CaS1), represents the physically homogeneous soil stratum with its shear modulus increasing by depth, as the confining pressure enlarges. Each assumption leads to a set of spring parameters which were studied in this work. Full details on this method and the exact formulations could be found in [4].

The spring stiffness values calculated for this problem are shown in Table 1.

Table 1. Stiffness Values of the SSI Springs (GN/m)

DOF	Constant Soil	Parabolic Soil
Vertical (V)	2.472	1.601
Horizontal (H)	1.049	0.382
Rotational (R)	1.548	1.241
H-R Coupling	-0.906	-0.543

It is no surprise that the springs representing the soil with parabolic stiffness profile are softer compared with their constant soil counterparts, due to the loss of stiffness in top layers of the soil.

Test Results: Model vs. Experiment

In order to separately understand the effects of the two factors, the cables and the SSI, on the dynamic behavior of the pole, solely the results of the simulations are initially presented and discussed. Eventually, the experimental results are presented as a measure to judge the precision of the models.

Figure 3 and Table 2 represent the mode shapes and their respective eigenfrequencies for the clamped model (Ref). Moreover, the even modes (2, 4, 6 and 8) represent the modes in the X direction (along the cables), while the odd modes represent those of the Y direction.

To identify the effects of the cables and the SSI, the five numerical models (Ca, S1, CaS1, S2, CaS2) are compared with

Table 2. Eigenfrequencies of the Clamped Pole (Ref)

Mode	f (Hz)
1^{st} bending (1 & 2)	3.4693
2^{nd} bending (3 & 4)	17.113
3^{rd} bending (5 & 6)	44.160
4^{th} bending (7 & 8)	83.423

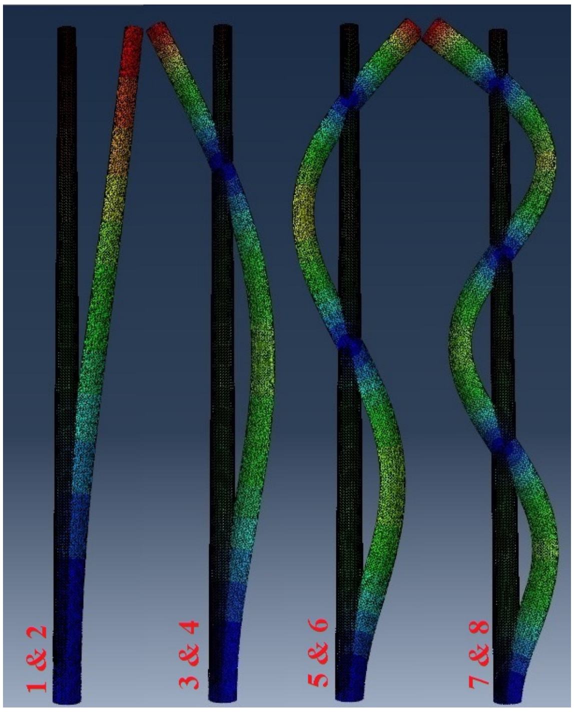

Figure 3. Mode Shapes of the Pole

the model "Ref". Figure 4 illustrates in percentage, how much modeling each phenomenon affects the values of the natural frequencies in the model. The diagram clarifies the effect coming from the inclusion of only SSI (S1 and S2) or the cables (Ca) in the model, while simultaneously showing the overall effect of modeling both phenomena (CaS1 and CaS2).

Based on the diagram in Figure 4, it is possible to state that adding the cable system to the clamped model of the pole results in the reduction of the eigenfrequencies due to the increase in the mass of the system; however, there is a significant increase (over 30%) in the natural frequency of mode 2 (1^{st} bending in X direction) due to the stiffness of the cable system, an effect which is not as influential in higher modes since the action point of the cable stiffness becomes close to the zero-displacement point of the modes (Figure 3). Furthermore, the parabolic soil profile assumption (S2 and CaS2) leads to a softer behavior than the constant soil profile assumption, and the intensity of this difference in behavior becomes more detectable in higher modes, as the structure responds with its stiffer manner.

Analogous to Figure 4, Figure 5 demonstrates the percentage of the difference in eigenfrequencies of the four models (Ref, Ca, CaS1 and CaS2) when compared to those of the experimental data. Having in mind that a positive value in this diagram indicates a stiffer behavior of the model compared to the experimental data, it could be concluded that except the mode 2 and the 4^{th} bending modes, the Ref model (clamped at the bottom) is too stiff to ideally represent the real behavior of the pole, necessitating the simulation of the substructure part and the cable system. Moreover, the cable system has a more dominant effect, similar to Figure 4, compared with the SSI; however, one should not forget that the stiffness of the spring which substituted the cable system plays a significant role here, a parameter which exhibits a large uncertainty due to its nonlinear nature. Furthermore, Figure 5 is a decent basis to judge that the methodology used in this work

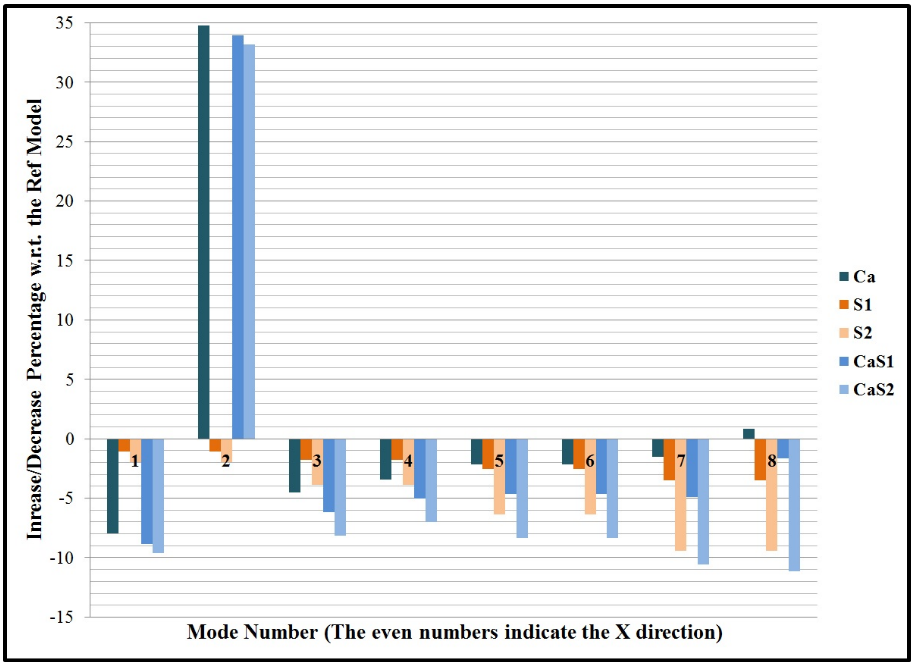

Figure 4. Effect of Catenary Cables & SSI on the Eigenfrequencies

to model the SSI leads to a relatively softer behavior compared to the reality (experimental data), especially with the parabolic assumption for the soil's stiffness profile. It is nevertheless reminded that this methodology has a large field of uncertainties too. Hence, these issues will also be addressed in the parameter studies in order to help to reach a balance between the parameters of the problem, such that a better compromise takes place.

In order to make more supported conclusions, further interpretation of the results is left to be done in the ”Conclusions” section, after a more general viewpoint is obtained from the parameter studies.

Parameter Study

Among all the possible factors each of which could be considered as an uncertain parameter in this problem (e.g. the dimensions, density of aluminum etc.), the following 7 parameters were initially assumed to be the most influential and uncertain ones, with their possible ranges of variation shown in Table 3. The model subjected to the parameter studies accounts for both the cable system and the SSI.

Table 3. The Problem's Initial Parameters (SI Units)

Parameter	Abbreviation	Minimum	Maximum
Concrete's Density	Con_Dens (1)	2200.0	2600.0
Concrete's Young's Modulus	Con_E (2)	$3.36 * 10^{10}$	$5.04 * 10^{10}$
Cable Spring's stiffness	K_Spring (3)	$67.06 * 10^{3}$	$196.28 * 10^{3}$
SSI Spring, Horizontal DOF	SSI_H (4)	$4.71 * 10^{8}$	$1.15 * 10^{9}$
SSI Spring, Rotational DOF	SSI_R (5)	$1.19 * 10^{9}$	$1.67 * 10^{9}$
SSI Spring, Vertical DOF	SSI_V	$1.28 * 10^{9}$	$2.97 * 10^{9}$
SSI Spring, H-R Coupling DOF	SSI_HR (6)	$5.07 * 10^{8}$	$9.69 * 10^{8}$

In order to perceive the general influence of each individual parameter, each parameter was changed from its minimum to its maximum in 15 steps, while the rest were kept constant at their mean value. The foremost conclusion was that the change in SSI_V does not affect the eigenfrequencies at all, hence it was omitted from the list of variables for the upcoming sensitivity analyses.

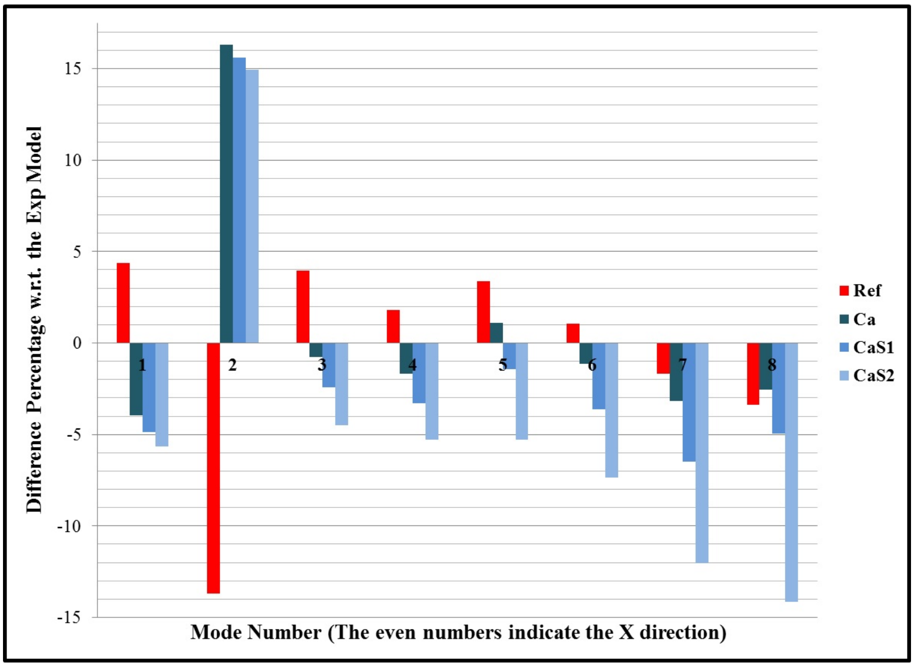

Figure 5. Comparison of the Models with the Experimental Data

Figure 6 shows the results of the parametric study, when the parameters change individually step-by-step in the mentioned range. It is possible to interpret the graph either mode-wise (i.e. judging which parameters affect a specific mode more intensely) or parameter-wise (i.e. concluding which modes a certain parameter affects).

It is understandable from the figure, that $K\_S pring$ affects only the mode 2 (1^{st} bending in X direction) majorly, and mode 4 slightly. Moreover, SSI_R's variation proves to have the least effect on the output, among the soil stiffness parameters, and SSI_H is the most decisive parameter in all modes except 2, in which the $K\_S pring$ plays a more significant role. Eventually, while the Con_E varies the output significantly more than Con_Dens when varying in their mentioned ranges, both parameters remain to be influential in all of the modes.

Despite the benefits of the conclusions made, the complex nature of this problem triggers the need to a sensitivity analysis, since the behavior of the model is highly nonlinear with respect to some parameters (mainly the SSI parameters) on one hand, and the response also depends on the interaction between the parameters (e.g. the relative stiffness of the SSI and the cable system springs etc.) on the other hand. This would allow the simultaneous, but yet random variation of all the parameters, in order to gain a deeper insight into the problem. Last but not least, this would lead to quantitative measures based on which one could judge on the importance of the parameters, rather than just making qualitative comparisons.

Brief Introduction to Sensitivity Analysis

The need to identify the most significant parameters in a multidimensional problem triggers the efforts to develop methods addressing this issue. Sensitivity analysis, as a popular methodology, is a commonly used approach to fulfill this aim. The final output of sensitivity analysis is a measure, based on which one can judge which parameters are more decisive in the final output of the problem, hence a more efficient orientation of time and cost investment could be done to accurately determine only the crucial parameters.

There are various approaches to perform this analysis. The methodology adopted in this work is a variance-based sensitivity analysis proposed in [5]. In this approach, the first-order effect (S_i) and total effect (S_{T_i}) of the parameter X_i on the output Y is calculated for each i in order to get a general impression about the parameter prioritization.

Being a value theoretically always between 0 and 1, S_i is in fact a measure indicating what would happen to the uncertainty of Y if the i'th parameter would be fixed. Hence, a high value represents an important parameter while a small value does not necessarily signal a low importance for the parameter. In fact, to achieve a thorough understanding of the sensitivity pattern for a model with n parameters, one needs the total set of first-order and total effect indices of the parameters.

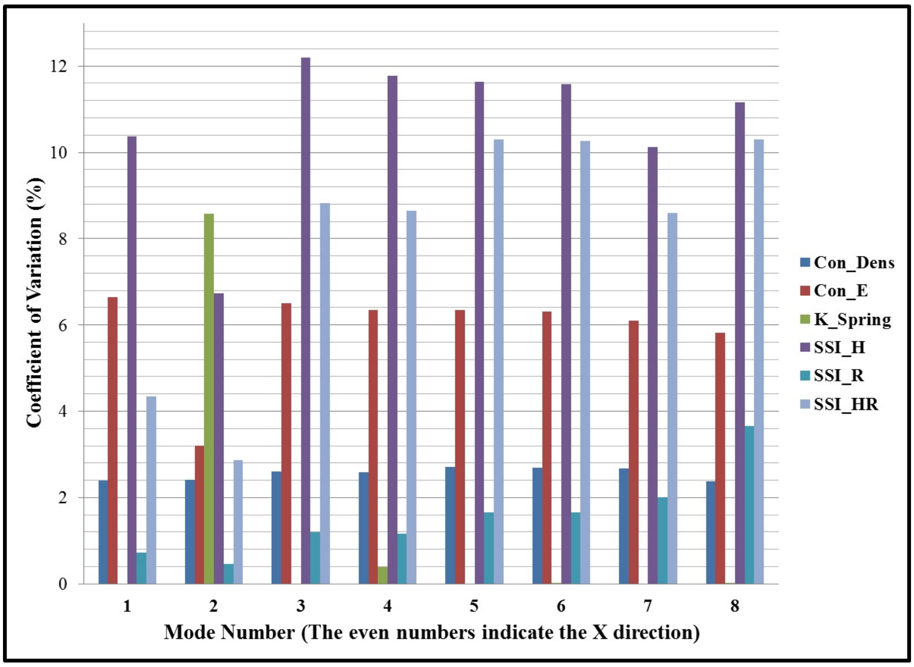

Figure 6. CoV of the Modes When Only One Parameter Changes

Accounting for the total contribution to the output variation due to parameter X_i (that is, its first order effect plus all higher order effects due to interactions among parameters), total effect of this parameter is calculated using a formula which depends on the variances of both the input and the output. The condition $S_i = 0$ is necessary but insufficient to identify parameter i as non-effective, while $S_{T_i} = 0$ is a necessary and sufficient condition for it being non-influential. Accordingly, if $S_{T_i} = 0$, X_i can be fixed at any value within its range of uncertainty without remarkably affecting the variance of the output [5].

Based on the definitions mentioned, S_{T_i} is larger than or equal to S_i, where the latter case happens only when X_i is not involved in any interaction with other parameters. Therefore, the difference, i.e. $S_{T_i} - S_i$ indicates how much parameter i is involved in interactions with other parameters. It is worth mentioning that $1 - \Sigma_i S_i$ is an indicator of presence of interactions among the model's parameters. Moreover, $\Sigma_i S_{T_i}$ is always greater than 1 or, in case that the model is perfectly additive w.r.t its variance, equal to 1 [5].

In spite of the efficiency of variance-based methods to perform sensitivity analysis, high computational costs due to the relatively large number of required samples remains a major drawback of such methodologies, a disadvantage which is to be addressed in this work using the metamodeling techniques.

Brief Introduction to Metamodeling

A common approach to reduce the computational cost of calculating the required outputs for a sensitivity analysis is the application of the so-called *Metamodels*. A metamodel is generally an approximation function which adapts the behavior of a set of input-output data (in this case, the parameters of the FEM model as the input, and the eigenfrequencies as the output). In order to build a metamodel, a support data set $\mathbf{x}_1, ..., \mathbf{x}_n \in \mathbb{R}^k$ and the respective evaluations $\mathbf{y} = [y_1, ..., y_n]^T = [f(\mathbf{x}_1), ..., f(\mathbf{x}_n)]^T$ of the original function $f(\mathbf{x})$ are used. Polynomial Regression [6][7], Moving Least Squares [10] and the Kriging approximation [8][9] are examples of common metamodeling approaches mentioned in the literature. The various techniques differ significantly in their calculation time and approximation quality, which, however, depends on the nature of the observed problem. Accordingly, the optimal metdamodel choice is mainly a case-dependent issue to be addressed.

In this research, various metamodeling techniques were compared and the two optimal models were used as approximation functions. The first one, the Polynomial Regression, is a common and simple approach to adapt a function. There, the original function is approximated by a polynomial function that results in the best fit with respect to the sum of least squares criterion [11]. This results in the approximation function

$$\hat{f}(\mathbf{x}) = p^{\mathrm{T}}(\mathbf{x})\hat{\mathbf{w}} = p^{\mathrm{T}}(\mathbf{x})(\mathbf{X}^{\mathrm{T}}\mathbf{X})^{-1}\mathbf{X}^{\mathrm{T}}\mathbf{y} \tag{1}$$

with $p(\mathbf{x})$ denoting the g-dimensional polynomial basis of $\mathbf{x}$ and $\mathbf{X} = [p^{\mathrm{T}}(\mathbf{x}_1), ..., p^{\mathrm{T}}(\mathbf{x}_n)]^{\mathrm{T}}$ being the matrix containing the basis vectors of the support points. The approximation can be optimized by varying the degree g of the polynomial function. A higher polynomial degree often leads to a better result; nevertheless, there is a risk of over-fitting and extreme increase of the computation time.

The second approach, Kriging approximation, uses a completely different concept since it interprets the data as the output of a stochastic process $\hat{f}(\mathbf{x}_i) = \mu + \varepsilon(\mathbf{x}_i)$ with an unknown constant trend μ and correlated residuals $\varepsilon(\mathbf{x}_i)$. By application of the maximum Likelihood criterion [9][11] the approximation function

$$\hat{y} = \hat{\mu} + \boldsymbol{\psi}(\mathbf{x})\,\boldsymbol{\Psi}^{-1}\,(\mathbf{y} - \mathbf{1}\hat{\mu}), \tag{2}$$

can be reached, where $\boldsymbol{\Psi}$ describes the correlation matrix of the support points and $\boldsymbol{\psi}(\mathbf{x})$ is the correlation vector between the support points and the examination point $\mathbf{x}$. [8] and [9] contain full details on derivations and specific formulations of this method.

Compared with the Polynomial Regression, the Kriging method is much more flexible in the fitting procedure, so that usually a higher approximation quality could be expected; however, it is one of the most complex, and hence expensive metamodeling approaches.

In order to make a decent model selection between the possible metamodeling approaches, a meaningful error criterion should be chosen. For the observed data set related to the problem studied here, the coefficient of determination (R^2) [12] with a validation data set was taken as a reference for the model selection. This error measure could be determined with

$$\mathrm{R}^2 = 1 - \frac{\sum_{i=1}^{m}\left(y_i^{val} - \hat{f}(\mathbf{x}_i^{val})\right)^2}{\sum_{i=1}^{m}\left(y_i^{val} - \overline{y}^{val}\right)^2}, \tag{3}$$

where $\overline{y}^{val}$ is the mean value of the functions' evaluations $y_1^{val}, ..., y_m^{val}$. To avoid an over rating of the model quality, a set of untrained data is used.

During the comparison process of various metamodels, the results of different methods with different number of support points (number of samples, $n = 200, 500$ and 1000) were tested and the coefficient of determination was calculated with a validation data set of $m = 4000$ points. Based on the calculated values, a separate decision for each of the first four eigenfrequencies was made. Eventually, for the frequencies $f1$, $f2$ and $f4$ the Polynomial Regression with $g = 2$ and $n = 200$, and for $f3$ the Kriging method based on $n = 500$ support points were used. In this work, these metamodels were used to calculate the sensitivity indices of the parameters in the CaS1 model, when the first four eigenfrequences are considered to be the output.

Results of the Sensitivity Analysis (Using the Metamodels)

Using the values mentioned in Table 3, different numbers of samples (n), each containing the mentioned six parameters, were produced using a random procedure, such that they obeyed a uniform distribution. The responses (namely the $f1$, $f2$, $f3$ and $f4$) were calculated using the mentioned metamodels. It is worth mentioning that the same calculation using the original FEM model with the available computation power takes around 10 days for a sample size of only $n = 500$. Increasing the number of samples in this method of conducting the sensitivity analysis, leads each sensitivity index (and hence the sum of the indexes) to converge to a certain value. Figure 7 illustrates this convergence trend for the first order sensitivity indexes, when the output is $f2$ (the first bending in X direction).

Furthermore, Table 4 contains the sensitivity values for $f1$ and $f2$ calculated using the metamodels.

Based on the values in Table 4, it is concluded that the most decisive parameter on the frequency of the first bending mode in X direction ($f2$) is the K_Spring, a conclusion which is also consistent with the results of Figure 6. Furthermore, the concrete's Young's modulus is a more important parameter compared to the density of the concrete in calculation of both frequencies; It is also observed that in the Y direction, Con_E has a relatively large first order effect on the response, a conclusion that physically makes sense due to the absence of the large influence from the cable system; however, the

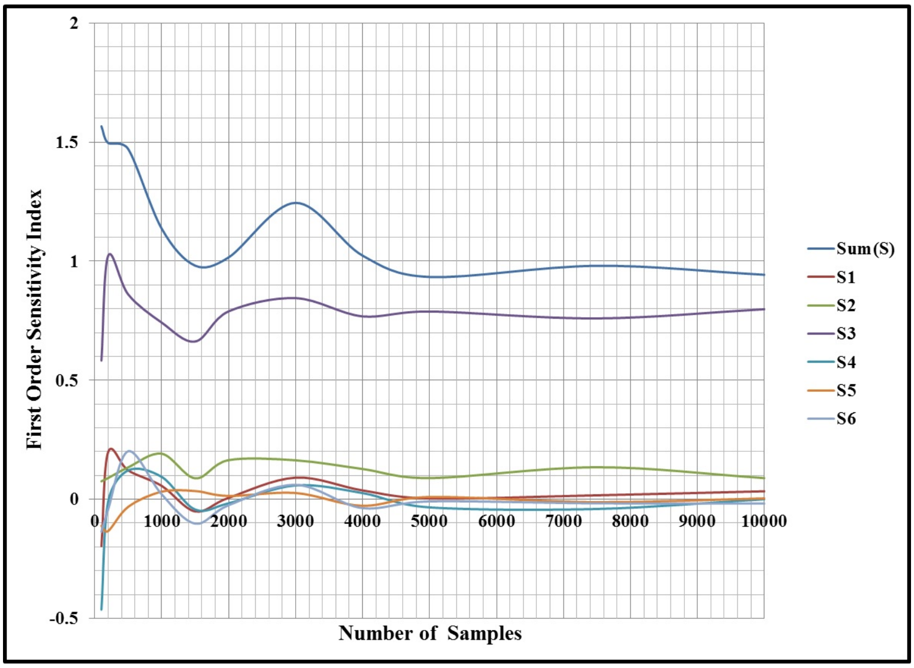

Figure 7. First Order Sensitivity Indexes vs. n for $f2$

Table 4. Sensitivity Indexes for $f1$ & $f2$

Parameter	1	2	3	4	5	6	Sum
$f1(S)$	0.03	0.70	0.00	0.01	0.03	0.00	0.77
$f1(S_T)$	0.07	1.00	0.06	0.09	0.06	0.10	1.38
$f2(S)$	0.03	0.09	0.80	0.00	0.00	0.00	0.92
$f2(S_T)$	0.05	0.21	0.80	0.03	0.02	0.04	1.15

conclusion that Con_E is the most influential parameter on $f1$ contradicts the results shown in Figure 6. Moreover, it was also observed during the studies that the converging trend for the sensitivity indexes would not happen for $f3$ and $f4$, besides the fact that such contradictions in the results of the sensitivity analyses with the metamodels continued to exist. This was nevertheless expected, due to the low quality of the created metamodels (R^2 value of around 0.4).

Conclusion & Outlook

The dynamic behavior of a pole structure used in a high-speed railway system in Germany was studied using the FEM, to identify the effects of the catenary cables and the soil-structure interaction (SSI), and to propose a suitable model for simulation of this structure. The numerical results were compared with results extracted from the data acquired from the sensors installed on an in-service pole, to provide a trustable measure against which the numerical results could be judged. The SSI was modeled using two assumptions for the soil profile, namely a constant and a parabolic profile for the stiffness of the soil, while the cable system was modeled using a spring-mass system. A comparison between Figure 4 and Figure 5 shows that while a clamped boundary condition for the pole (no SSI effect and no cables included) is not a suitable approach, the assumption of a parabolic stiffness profile for the soil also leads to a large modeling error in this case. Based on Figure 6 it is concluded that the spring stiffness values of the SSI for the horizontal direction (SSI_H) and the coupling DOF (SSI_HR) are the most decisive parameters of this problem in all modes, except mode 2 (1^{st} bending in X direction) in which the cable stiffness plays the most crucial role. The results of this parameter study were also supported by sensitivity analyses conducted using the metamodels, although the quality of the metamodels led to shortcomings in some areas. Taking these facts into consideration, one can conclude using Figure 5 that the CaS1 model (the model accounting for both the SSI and the cable system, with a constant soil profile assumption) is the best compromise among all the six numerical approaches used in the study, to simulate the real response of the structure; however, the stiffness of the spring which substituted the cable system should be reduced, while at the same time that of the SSI springs should be increased in order to match the eigenfrequencies of the real pole in service.

However, the eigenfrequencies calculated from the data (the ”Exp” model in this work) exhibit different uncertainties due to existing obstacles in conducting in-site measurements and also the quality of the acquired data. Moreover, despite the structural resemblance of the poles used in this railway system, nonidentical boundary conditions for various poles are practically expected to exist; hence, having a higher number of poles with their eigenfrequencies extracted from the acceleration data would significantly increase the trustability of the conclusions made here. Furthermore, this problem triggers the need to use a more advanced metamodeling strategy, e.g. a combination of metamodels for different ranges of the various parameters, in order to cover a wider range of conclusions. Therefore, overcoming these issues and calibrating the model using the results would remain an open problem to be addressed in an extensive work.

Acknowledgment

This research is supported by the German Research Foundation (DFG) via Research Training Group ”Evaluation of Coupled Numerical Partial Models in Structural Engineering (GRK 1462)”, which is gratefully acknowledged.

References

[1] Blevins, R.D. (1995) *Formulas for Natural Frequency and Mode Shape*, Krieger Publishing.

[2] Costello, E. (2011) Length of a Hanging Cable. *Undergraduate Journal of Mathematical Modeling: One + Two* **4**, Article 4.

[3] Clough, R. W., Penzien, J. (1993) *Dynamics of Structures*. McGraw-Hill Publishing Company, New York, USA.

[4] Novak, M., El Sharnouby, B. (1983) Stiffness Constants of Single Piles. *Journal of Geotechnical Engineering* **109**, 961-974.

[5] Saltelli, A., Ratto, M., Andres, T. (2008) *Global Sensitivity Analysis: The Primer*, John Wiley and Sons, England.

[6] Myers, R.H.(1971) *Response Surface Methodology*. Allyn and Bacon, Boston.

[7] Box, G.E.P., Draper, N.R.(1987) *Empirical Model-Building and Response Surfaces*. John Wiley and Sons, New York.

[8] Krige, D.G. (1951) A Statistical Approach to Some Basic Mine Valuation Problems on the Witwatersrand. *Journal of the Chemical, Metallurgical and Mining Society of South Africa* **52**, 119–139.

[9] Forrester, A.I.J., Sobester, A., Keane, A.J. (2008) *Engineering Design via Surrogate Modelling: A Practical Guide*. John Wiley and Sons, UK.

[10] Lancaster, P., Salkauskas, K. (1981) Surface Generated by Moving Least Squares Methods. *Mathematics of Computation* **37**, 141–158.

[11] Press, W.H., Flannery, B.P., Teukolsky, S.A., Vetterling, W.T. (1986) *Numerical Recipes - The Art of Scientific Computing*. Cambridge University Press.

[12] Schoelkopf, B., Smola, A. (2002) *Learning with Kernels*. MIT Press.