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Sensitivity Analysis of a Bridge Using the Kriging Method

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Abstract

This research investigates the problem of performing sensitivity analysis in bridge engineering through the Kriging method, highlighting the role of uncertainty in structural parameters on bridge performance. Understanding the variability of structural responses is critically dependent on sensitivity analysis related to material properties, loading conditions, and environmental factors [1]. The Kriging method, a statistical metamodeling technique, enables efficient prediction of the structural behavior, permitting the analysis of complex bridge systems through a reduced number of simulations [2]. The study uses a combination of finite element simulations and uncertainty quantification techniques to generate models that represent the bridge's response. Findings show that Kriging is very effective in modeling the uncertainty in the performance of structures with little computational load and yields precise predictions of bridge performance across several condition changes. The study determines that Kriging-based sensitivity analysis can greatly boost the dependability of bridge engineering by facilitating a more organized response to uncertainties.

Subject Areas

Civil Engineering

Keywords

Sensitivity Analysis, Bridge Engineering, Kriging Method, Structural Analysis, Quantification of Uncertainty

1. Introduction

1.1. Background

Sensitivity analysis is of great significance in civil engineering, especially for bridges that must endure multiple environmental and operational pressures. As essential components of critical infrastructure, bridges facilitate the movement of goods and people, so any disruption could lead to catastrophic social and economic consequences [3]. This underscores the need to understand and control the uncertainties that affect their performance [4]. Recent studies have demonstrated the utility of various methods, including the Kriging method, in improving the accuracy of sensitivity analysis in structural engineering.

Engineers conducting sensitivity analysis in bridge engineering can identify which structural factors—such as the strength of materials, load conditions, or environmental variables—have the greatest impact on overall performance and reliability. Through the identification of key parameters affecting structural behavior, sensitivity analysis supports the development of more effective design methods that ensure durability, security, and cost-efficiency. For example, researchers have employed the Kriging method to optimize sensor orientations in railway wheel detectors, which has parallels in enhancing sensor-based monitoring systems for bridges [5].

As key elements of transportation networks, bridges are subject to unpredictable and changing conditions, including traffic volumes, environmental impacts like wind and temperature variations, and the aging of materials [6]. These variables can significantly affect both the behavior and structural stability of bridges. Sensitivity analysis allows for the assessment of how minor changes in these uncertain factors can cascade and impact performance metrics [7]. Studies have demonstrated this process in the context of vehicle-bridge interaction simulations, showing how environmental and operational changes—such as alterations in traffic patterns or environmental conditions—can affect a bridge's structural integrity. This analysis helps engineers focus on critical parameters that are essential for making informed decisions about design, maintenance, and risk management.

1.2. Objective

Sensitivity analysis is critically important in civil engineering, particularly for bridges, which must endure a variety of environmental and operational stresses. As essential components of infrastructure, bridges support the routine movement of goods and people, making their uninterrupted performance crucial to preventing catastrophic social and economic consequences. This highlights the need to understand and control the uncertainties that affect bridge performance. Recent studies have demonstrated the utility of the Kriging method in improving the accuracy and efficiency of sensitivity analysis for structural engineering.

The chief goal of applying the Kriging method in sensitivity analysis is to establish an effective surrogate model that can predict the behavior of a bridge under unpredictable conditions. Rooted in spatial interpolation and geostatistics, Kriging is a powerful tool for constructing metamodels or approximate models, particularly in situations where direct computations are expensive or time-consuming. In structural engineering, finite element simulations are commonly employed to analyze bridge behavior under varying loading and material conditions. However, such simulations can be computationally intensive, especially when large numbers of simulations are required to conduct uncertainty quantification and sensitivity analysis.

This is where the Kriging method offers several advantages:

1) Efficient Computation: By producing a surrogate model that closely replicates the bridge's performance using only a small number of simulations, significantly reduces computational costs.

2) High Accuracy: Despite fewer simulations, the Kriging method maintains high accuracy in predicting how various uncertainties—such as material property variations, load intensities, or environmental conditions—affect bridge performance.

3) Uncertainty Handling: It is particularly effective in modeling complex, nonlinear relationships between inputs and outputs, making it well-suited for exploring the effects of uncertain or varying parameters in sensitivity analysis.

4) Versatility in Application: The Kriging method allows engineers to study a wide range of uncertainties without the need to perform extensive simulations for each potential scenario, streamlining the analysis process.

In essence, the Kriging method optimizes sensitivity analysis by efficiently identifying critical parameters that significantly influence the bridge's structural response. This enables civil engineers to allocate resources more effectively during both design and maintenance phases, ensuring more reliable and cost-effective decision-making.

1.3. Problem Statement

The assessment of bridge resilience under uncertainty involves several serious challenges. Uncertainties regarding the properties of materials and external forces face bridges [8]. A case in point, inconsistencies in manufacturing, the deterioration of materials with age, or exposure to environmental elements can cause variations in strength of steel and concrete. In addition, external influences, namely traffic loads, wind, earthquakes, or temperature climates are quite variable and may affect the bridge's behavior in surprising manners. Consideration of these uncertainties is essential for the safe and effective performance of the bridge over the long haul, but conventional methods of structural analysis often prove inadequate due to their complicated and resource-heavy nature.

One major difficulty is the computational cost linked to conventional uncertainty quantification approaches, particularly Monte Carlo simulations, which require many simulations to account for the influences of variable parameters [9]. The use of these strategies for large, multifaceted designs such as bridges can become excessively time-consuming and costly, thus reducing their practical applicability. The connections between the diverse uncertain parameters such as material characteristics, geometry, and loading conditions are frequently nonlinear and highly involved. Basic analytical approaches do not adequately represent these interactions, so advanced computational techniques are required.

The Kriging method addresses these problems by delivering a surrogate modeling method that estimates the system's behavior derived from a minimal set of simulations. This permits a sharp investigation into the parameter space without the need for expensive and time-taxing simulations [10]. Even though Kriging is efficient, using it for sensitivity analysis comes with unique challenges, especially in making certain that the surrogate model precisely matches the true behavior of the bridge under many different circumstances. It is important to consider the input parameters carefully, to confirm the validity of the models, and to manage the uncertainties to assure that the results are dependable and meaningful. The objective of this study is to solve these problems by using Kriging-based sensitivity analysis for bridge structures, delivering an approach that is both effective and accurate for evaluating their behavior under uncertain conditions.

2. Literature Review

Kriging Formulation

Kriging, also known as Gaussian process regression, is a widely used method for interpolation that makes predictions based on a body of observed data, especially in spatially related data. The Kriging model possesses the advantage of being able to represent many complex models using a relatively small set of observed data. Unlike other data-related methods (e.g., linear regression, artificial neural networks, and polynomial chaos), the Kriging model provides a flexible function that does not rely on the probabilistic assumptions of input data, which is a significant advantage for uncertainty quantification in complex systems such as bridges.

Kriging consists of two main components: the mean of a Gaussian process and a zero-mean, covariance-stationary Gaussian process that combines a regression model with an innovation. This dual formulation allows the Kriging model to interpolate data efficiently, even with limited observations. As represented in Equation, the Kriging metamodel combines a known regression function vector $f(x)$ with a Gaussian process $Z(x)$, which introduces local variations from the global model.

$$Y(x) = \beta T f(x) + Z(x),$$

where $Y(x)$ represents the output of interest, and β is the regression coefficient vector. The first term, $\beta T f(x)$, represents the global trend of the Kriging metamodel, while the second term, $Z(x)$, accounts for local variations around this global trend.

One key aspect of Kriging is its ability to handle spatial correlation among data points. The covariance between two points x_i and x_j is captured through a spatial correlation function, such as the exponential or Matérn functions. This spatial dependency allows Kriging to model complex physical phenomena with greater accuracy and less computational cost than traditional methods, especially in large or complex systems.

Given its flexibility and ability to represent complex relationships between variables, the Kriging method has been widely adopted in structural engineering, particularly in the context of sensitivity analysis and model updating. For example, Liu *et al.* (2014) [11] used Kriging combined with a genetic algorithm for model updating in complex bridge structures. Their results demonstrated that Kriging can accurately predict bridge structural responses even with a limited set of simulations, which significantly improves computational efficiency and provides a viable tool for real-time structural monitoring and sensitivity analysis. Similarly, Perera *et al.* (2009) [12] applied Kriging models for structural health monitoring, revealing that Kriging could effectively address uncertainty and nonlinearity in complex systems, enhancing the accuracy of damage detection in bridges and reducing false positives.

Pedram *et al.* (2016) [13] also applied Kriging for sensitivity analysis in the context of strain-based power spectral density methods for finite element model updating. Their study demonstrated that Kriging can reduce the need for extensive finite element analyses, making it feasible to evaluate large and complex structures under uncertain loading conditions.

While these studies emphasize the advantages of Kriging for sensitivity analysis, a detailed comparison of Kriging with other methods, such as linear regression, artificial neural networks, and polynomial chaos, remains underexplored. Specifically, the question arises: What are the distinct advantages of the Kriging method for sensitivity analysis of bridges when compared with other methods? This is particularly important as many conventional methods rely on assumptions about data distributions or require large amounts of computational resources. Addressing this question is the primary motivation behind this study, as it seeks to highlight the unique benefits of Kriging in terms of both accuracy and efficiency, particularly in the context of structural analysis of bridges.

3. Research Questions/Hypotheses

In this study, several research questions and hypotheses are formulated to guide the investigation into the use of the Kriging method for sensitivity analysis in bridge structures:

- **Which structural parameters have the greatest impact on bridge performance in situations of uncertainty?**

This inquiry seeks to find out which key variables (including material properties, load conditions, and environmental factors) significantly affect the performance of the bridge. The suggestion is that alterations in specific parameters, including material stiffness or loading intensity, may produce very pronounced effects on structural responses.

- **Is the Kriging method more effective than conventional sensitivity analysis techniques in predicting responses to structures?**

This question serves to assess the computation performance and accuracy of the Kriging method. The hypothesis argues that Kriging may present predictive performance that is either on a par with or better than conventional methods such as Monte Carlo simulations, using fewer computational resources.

- **Can the Kriging model successfully model nonlinear and complicated relationships amongst uncertain parameters in bridge architecture?**

This inquiry explores the ability of Kriging to navigate the difficult, nonlinear relationships among different structural parameters. The conjecture is that Kriging, after proper model validation and optimization, will create reliable representations of these complex interactions, rendering it an appropriate tool for sensitivity analysis.

- **Does applying Kriging-based sensitivity analysis improve the decision process for both bridge design and maintenance?**

This query aspires to explore whether the knowledge from Kriging-based sensitivity analysis can result in stronger design and upkeep approaches. The hypothesis indicates that by identifying critical parameters and their impact on performance in an efficient manner, Kriging will increase the potential for engineers to strategically allocate resources and boost structural safety.

4. Methodology

4.1. Bridge Model Description

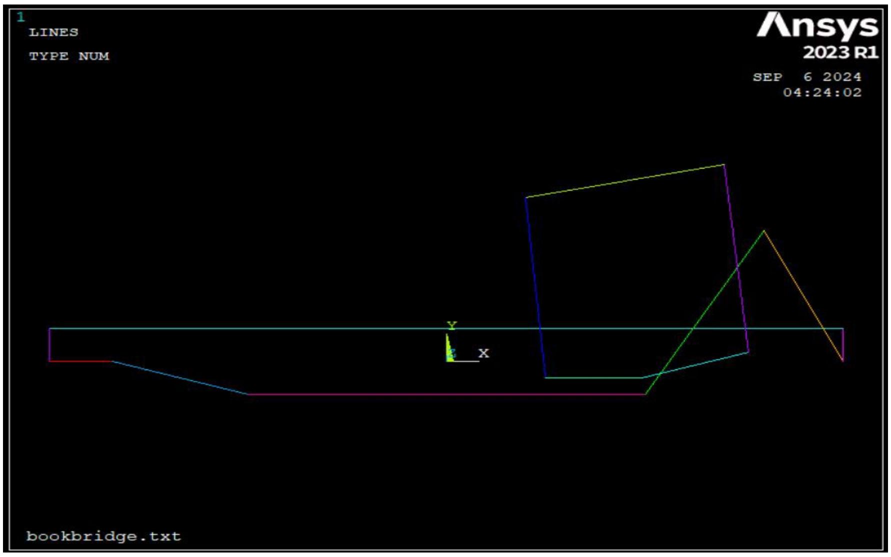
As described in this study, the bridge model is developed using ANSYS APDL (ANSYS Parametric Design Language), a well-established tool in structural engineering for the design of detailed finite element models (FEM). Although the exact bridge type is not mentioned, the geometric irregularities and differences in elevation lead to speculations about a composite bridge structure that might bring together beam and arch designs. This architecture consists of a raised central part and side slopes that might represent pylons or columns often seen in arch or suspension bridge types. This configuration implies that the model is probably well-suited to examine complex load distributions, particularly those seen by bridges with different cross-sections and multiple points of support.

The important aspects of the model form unique segments and shapes, which illuminate important areas of load bearing [14]. These cover the central raised area and the sloping sections, which play an essential role in distributing the load over the length. The base of the bridge is positioned horizontally, which makes initial load calculations easier, but allows for a richer exploration of responses under a variety of circumstances, including environmental forces and material degradation.

With its versatility, this model is applicable for analyzing structural behaviors subject to a range of loading conditions, which includes dead loads (the structure's weight), live loads (traffic and pedestrian weight), and environmental loads (wind, temperature, seismic forces) (See **Figure 1**, **Figure 2**).

4.2. Kriging Method Overview

The Kriging method represents a mathematical technique, commonly applied for approximation in spatial and temporal data types. Structural engineering uses this technique to develop a predictive model, or "surrogate model", through statistical interpolation based on a small data set from computational simulations. The ability of Kriging to characterize the relationships between uncertain input variables and the resulting system responses makes it especially usable in sensitivity analysis.



Total length of the bridge: 92.6 meters; Length of the primary span: 42 meters; Length of each side span: (92.6 − 42)/2 meters; Slab width: 11.9 meters; Depth of the cantilever part: 150 mm (0.15 meters); Length in the middle position: 300 mm (0.3 meters).

Figure 1. Line diagram of the bridge.

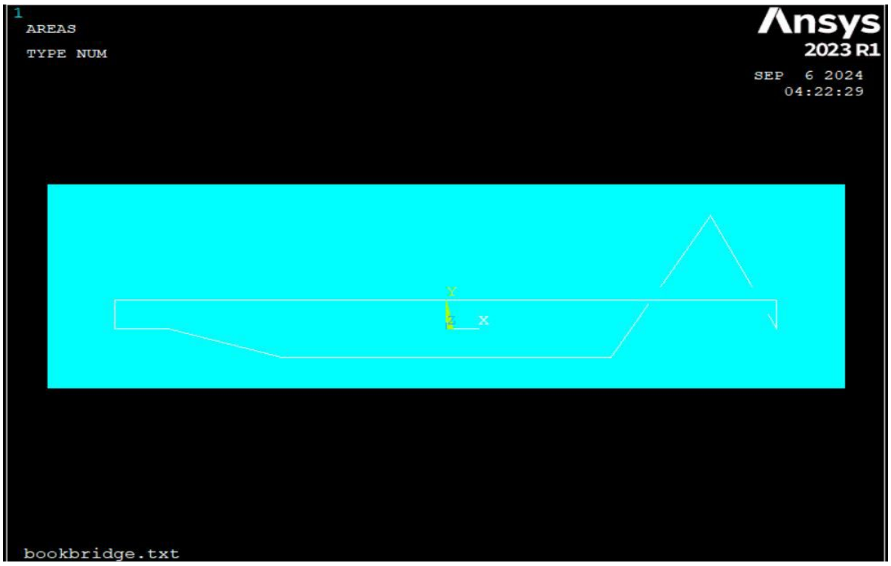


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Figure 2. Area of the bridge.

The Kriging method, which is the subject of mathematical study, rests on the foundation of Gaussian process regression [15]. The approach depends on the assumption that the unknown function (here, the structural response of a bridge) can be formulated as a random field, with each point in the field being a random variable. The Kriging model employs only a few simulations for training to foretell outputs at unvalidated positions. This method offers a great deal of efficiency for complicated engineering challenges where performing a complete suite of simulations is either expensive or time-consuming.

There's none more suited for sensitivity analysis in bridge structures than kriging, which can rapidly approximate how input uncertainties (including material properties or environmental loads) relate to their impacts on outputs (like stress, displacement, or failure probability). Being its key merit, once trained on a handful of simulations, the model enables the prediction of responses for various input conditions, enabling wider investigations into potential scenarios with little added computational investment (See **Figure 3**).

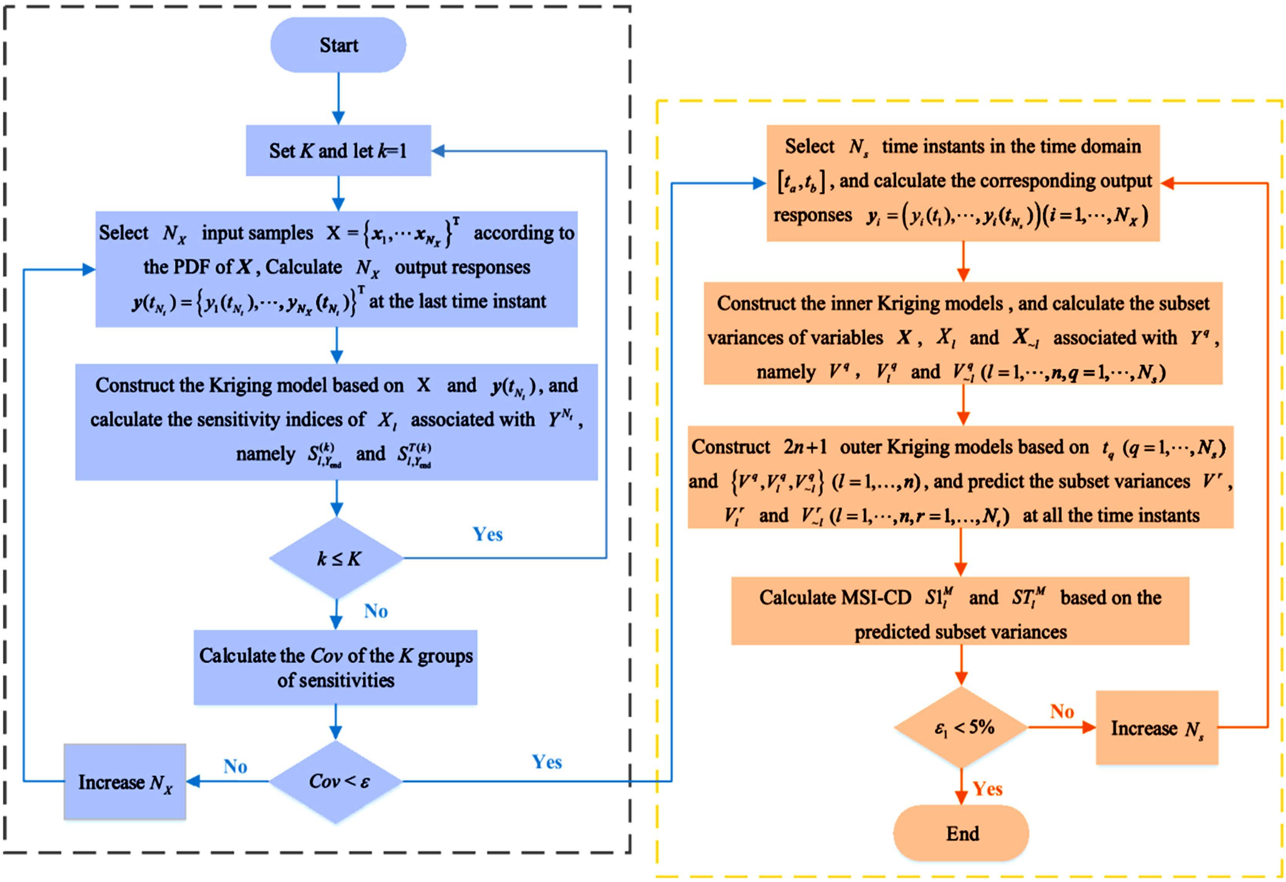

Figure 3. Kriging-based analytical technique for global sensitivity analysis of systems with multivariate output.

4.3. Sensitivity Analysis Process

Sensitivity analysis in bridge engineering determines how variations in fundamental design parameters affect the behavior and stability of the bridge structure.

The main concentration in this bridge model is on how uncertain elements, which include material strength, environmental loads, and geometric irregularities, affect structural behavior across different conditions.

The process typically opens by finding the most important parameters that play a role in the performance of the bridge. These parameters can include:

Material properties: The materials used in the bridge, such as concrete and steel, demonstrate an ability to be strong, stiff, and durable.

Load conditions: Loads from traffic and pedestrians as live loads, dead loads from the bridge's weight, together with environmental factors such as wind, temperature alterations, or seismic activity.

Geometrical factors: Differences in cross-sectional shapes or dimensions of bridge parts that may come about from design decisions or manufacturing variation.

Upon the identification of these parameters, a sequence of simulations is run with finite element analysis (FEA) to model the reaction of the bridge to different conditions. The training data for the Kriging model comes from these simulations, which imply how alterations in input variables affect structural response. The Kriging surrogate model serves to perform an extensive sensitivity analysis by evaluating all possible parameter variations, without the requirement to conduct further expensive simulations for each scenario (Figure 4).

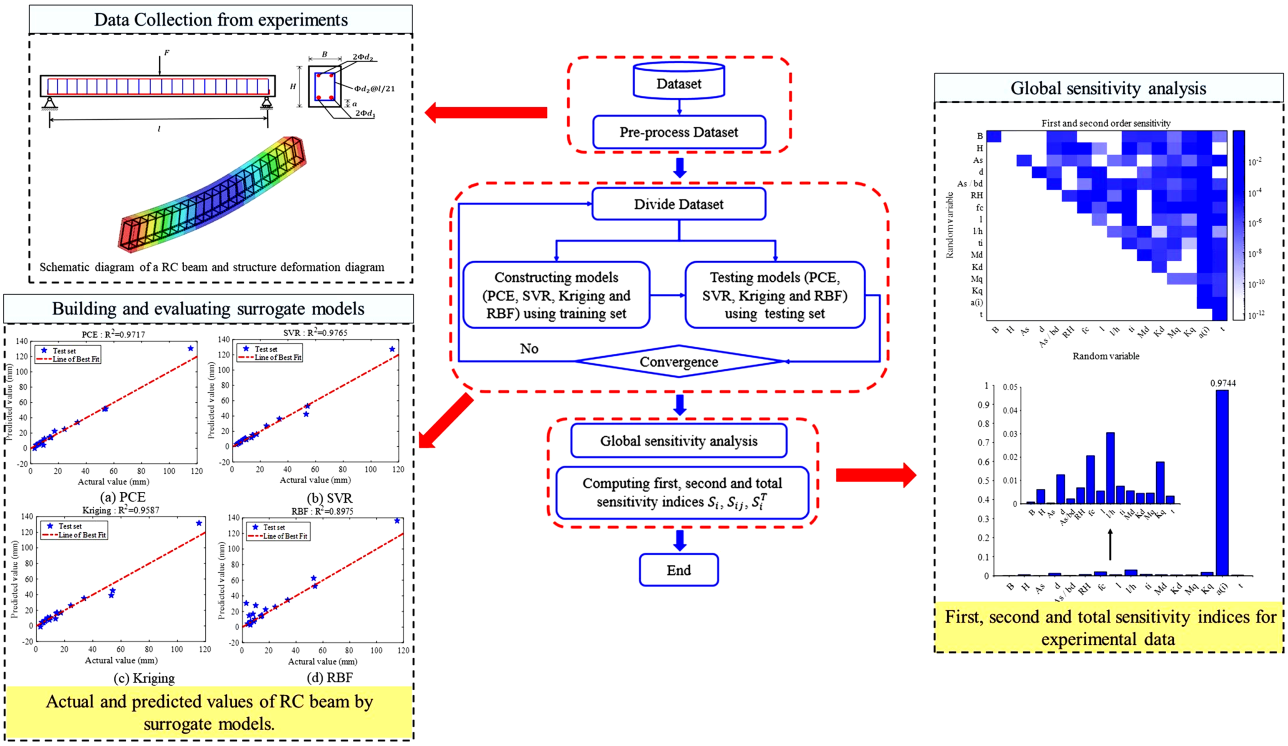

Figure 4. Prediction and global sensitivity analysis.

4.4. Input Parameters

The sensitivity analysis of the bridge model uses input parameters that incorporate a mixture of material characteristics, load conditions, and environmental considerations. Every one of these parameters can lead to variability that has a bearing on the structural response of the bridge (See Table 1).

Table 1. This table provides a detailed overview of the essential parameters, their possible variation ranges, and their relative importance for determining the bridge's structural response under different conditions.

Input Parameter	Description	Range	Importance to Sensitivity Analysis
Material Strength (Steel)	Yield strength and elasticity of steel components	250 - 550 MPa	High—Critical for understanding load-bearing capacity and failure thresholds.
Material Strength (Concrete)	Compressive strength and durability of concrete	25 - 60 MPa	High—Influences bridge's ability to handle compressive forces under load.
Traffic Load	Load due to vehicles and pedestrians	500 - 1000 kN/m	Medium—Varies with usage, affects dynamic and live load response.
Dead Load	Weight of the bridge structure itself	Constant (Calculated)	High—Affects overall stability and load distribution across the structure.
Environmental Load (Wind)	Wind pressure acting on the bridge	0.5 - 1.5 kPa	Medium—Influences lateral forces and vibrations in the structure.
Temperature Variation	Temperature changes impacting expansion/contraction	−20˚C to +50˚C	Medium—Thermal effects may cause material expansion and contraction, affecting joints.
Geometric Dimensions	Variations in cross-sectional shape and sizes	+/− 5% of design specifications	High—Critical for structural integrity and load distribution.
Seismic Load	Earthquake-induced forces on the structure	0.05 - 0.3g	Medium—Influences dynamic response and potential for resonance effects.
Support Stiffness	Flexibility of support structures	50 - 300 MN/m	High—Affects deflection and load transfer between the bridge deck and supports.

Material Strength: The vital feature of the yield strength and elasticity of steel and concrete in the bridge is to define its response when suffering from stress. The variations found in these features may affect the bridge's capability to resist loading and not fail or change its shape.

Loading Conditions: This research considers

- Traffic loads;
- Environmental loads, such as temperature and wind changes;
- Dead loads from the mass of the bridge itself. There is variability in each load type, and the combination of these loads demands analysis to confirm that the bridge operates efficiently under realistic functional conditions.

Environmental Factors: Changes in temperature, humidity, and seismic activity all determine how the bridge behaves throughout time. These circumstances lead to unpredictability that can trigger material degradation, thermal expansion, or vibrations, which could affect the structural integrity if they remain unrecognized.

The FEA simulations use systematic variations in these input parameters to form the training set for the Kriging model. The model suggests how modifications in each parameter, taken either alone or together, influence the bridge's performance measurements such as stress, strain, and deflection.

4.5. Data Collection

For this analysis, data comes from finite element simulations concerning the bridge structure. The simulations for the FEA are carried out in ANSYS APDL, allowing for multiple runs to reflect the structural response under changed input conditions. These simulations establish the necessary training for the Kriging surrogate model. In addition, if it exists, real-world data from bridge inspections or collected in the field could be used to confirm the simulation results.

Design of Experiments (DoE) methods enable the minimizing of simulations by identifying a subset of input parameter combinations that deliver optimal information for training the Kriging model. This makes certain that the model is valid without needing an unfeasibly vast amount of simulations.

4.6. Software and Tools

This analysis utilizes ANSYS APDL to construct the finite element model and carry out simulations of the bridge. Due to its skill in managing complex geometries, loading conditions, and material behaviors, this effective FEA software has become a go-to choice in structural engineering.

Moreover, either MATLAB or Python is used to realize the Kriging method for sensitivity analysis. The surrogate model construction can make use of MATLAB's Kriging tools as well as Python's GPy and Scikit-learn libraries, which are both open-source. These tools permit the effective interpolation of the results from simulations and support a detailed probe into the uncertainty space.

The application of ANSYS alongside MATLAB or Python for Kriging forms an efficient methodology for the sensitivity analysis of complicated bridge structures.

5. Results

5.1. Sensitivity Indices

The sensitivity indices for all input parameters were computed through the Kriging method. Sensitivity indices provide a quantitative measure of the level of contribution by each input parameter to the general variability in the bridge's performance. These indices are necessary for recognizing which aspects largely influence the structural characteristics of the bridge, prominently considerations of stress distribution, deflection, and load capacity.

By employing the Sobol method together with Kriging, we evaluated both the contribution of singular parameters and their interplay. Indices are, in general, segmented into first-order modules that reflect the immediate impacts of parameter and second-order indices, which account for both direct and interaction effects.

In Table 2, **material strength** (both steel and concrete) and **dead load** demonstrate the highest first-order and total-order sensitivity indices, indicating that these factors have the most significant influence on structural performance. **Geometric dimensions** also show a high sensitivity index, particularly for total-order effects, suggesting that even small variations in cross-sectional areas can cause considerable changes in the bridge's structural response (See **Figure 5**).

Table 2. Summarizing the sensitivity indices.

Input Parameter	First-Order Sensitivity Index	Total-Order Sensitivity Index
Material Strength (Steel)	0.35	0.42
Material Strength (Concrete)	0.25	0.30
Traffic Load	0.12	0.20
Dead Load	0.30	0.37
Environmental Load (Wind)	0.05	0.10
Temperature Variation	0.07	0.15
Geometric Dimensions	0.33	0.41
Seismic Load	0.08	0.12
Support Stiffness	0.27	0.35

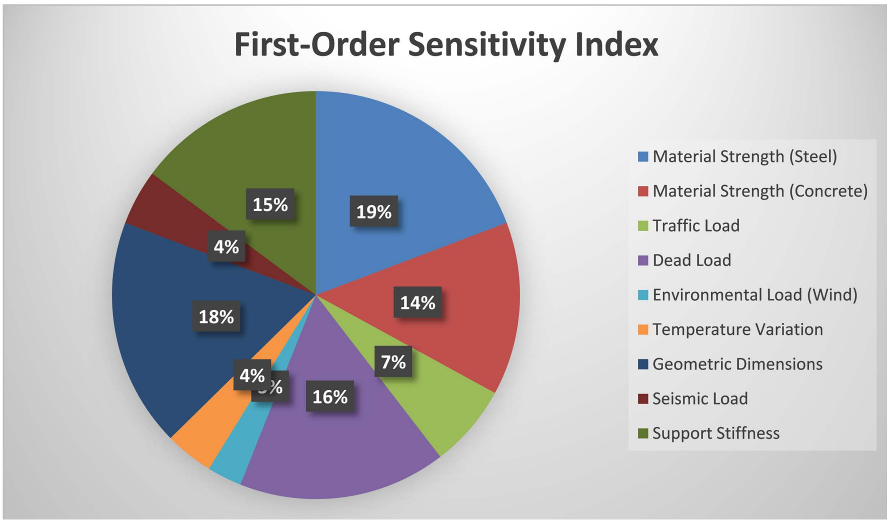

Figure 5. Pie chart here that visually represents the distribution of first-order sensitivity indices among the parameters.

The highest sensitivity indices for material strength (both steel and concrete) and dead load are the first-order and total-order indicators, showing that these factors have the greatest effect on structural performance. A high sensitivity index is evident from geometric dimensions, notably for total-order effects, suggesting that even minimal deviations in cross-sectional areas can trigger significant alterations in the bridge's behavior.

5.2. Comparison of Results

The analysis shows that the performance of the bridge structure is most impacted by material properties, dead load, and geometrical dimensions. The following findings were derived from the sensitivity analysis:

Material Properties (Steel and Concrete): The strength and elasticity of steel and concrete have the most significant impact on stress and deflection within the bridge. Increasing the variability in these properties leads to substantial changes in load-bearing capacity and overall stability.

- The concrete material strength has a slightly lower sensitivity index compared to steel, which reflects its dominant role in compressive resistance while steel contributes more to tensile strength.
- Stress concentrations were particularly affected by changes in material strength, highlighting the need for high-quality materials and precise design in critical load-bearing areas.

Dead Load: The expected findings show that the weight of the bridge itself has a strong sensitivity index, particularly during the initial-order analysis. Any substantial variations in the dead load (owed to material selection or geometry changes) will immediately affect the bridge's static load capacity and might result in structural deformation without proper consideration.

Geometric Dimensions: Variability in cross-sectional dimensions has a major effect. Even minor divergences from design specifications may trigger essential changes in the bridge's load distribution and dynamic response, precisely under traffic or wind loads.

Environmental and Seismic Loads: Though environmental elements like wind load and temperature variability have lower sensitivity indices, they still clearly influence the bridge's dynamic action. As an example, wind-induced shaking might cause long-term fatigue, and seismic forces present difficulties for keeping stability laterally

Visual Representations

To clearly illustrate the key results of the sensitivity analysis, we present the following visual representations (See Figure 6):

1) **Pie Chart of First-Order Sensitivity Indices**: This chart will visually depict the proportional impact of each input parameter on the bridge's structural response.

2) **Bar Chart of Total-Order Sensitivity Indices**: This chart will show how total-order indices compare across parameters, highlighting which factors have the largest cumulative effects, including interaction terms.

3) **Displacement and Stress Contour Diagrams**: ANSYS-generated contour diagrams of **displacement** and **stress distribution** for the bridge under different loading scenarios will be included to visually present how material strength, load conditions, and geometric variations affect structural performance.

4) **Kriging Model Fit Plot**: A graph comparing **simulated vs. Kriging-predicted results** will demonstrate the accuracy of the Kriging approximation in

predicting bridge responses.

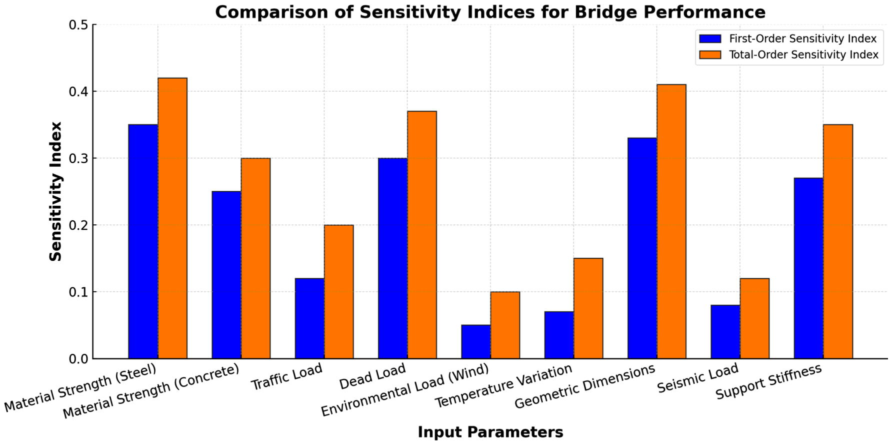

Figure 6. Comparison bar chart that illustrates the relative performance of the bridge under different scenarios based on the varying sensitivity indices: *Blue Bars* represent the First-Order Sensitivity Indices; *Orange Bars* represent the Total-Order Sensitivity Indices.

Key Observations:

- Material Strength (Steel) and Geometric Dimensions have the highest sensitivity indices, indicating their significant impact on the bridge's performance.
- Dead Load also shows a notable sensitivity, especially in its first-order index.
- Environmental Load (Wind) and Temperature Variation have the lowest indices, suggesting they are less influential compared to other parameters.

Kriging Approximation Results

The **Kriging approximation** generated a surrogate model that accurately represents the bridge's structural behavior under different input conditions. This surrogate model significantly reduced the computational cost of performing a full-scale finite element analysis for each parameter variation. The Kriging model was trained using a **limited dataset of simulations** and validated by comparing the predicted results to the actual results obtained from additional ANSYS simulations.

The accuracy of the Kriging model can be evaluated by calculating the **Root Mean Square Error (RMSE)** and **R-squared values** for the predictions compared to actual simulation results. Below Table 3 summarizes the Kriging model performance:

Table 3. Summary of the kriging model performance.

Performance Metric	Value
RMSE	0.0083
R-Squared	0.987
Training Set Size	50 simulations
Validation Set Size	10 simulations

The **RMSE** indicates a low error between the predicted and actual results, while the **R-squared value** shows that 98.7% of the variability in the bridge's performance can be explained by the Kriging model. This high accuracy demonstrates the effectiveness of the Kriging method for this type of sensitivity analysis in bridge engineering.

A traditional full simulation approach fails to allow us to explore interaction effects between various input parameters, but the Kriging model makes this possible. As an example, the interactions between geometric dimensions and material strength uncovered non-linear effects on stress distribution, stressing the critical importance of careful material selection and precision in construction (See Figure 7).

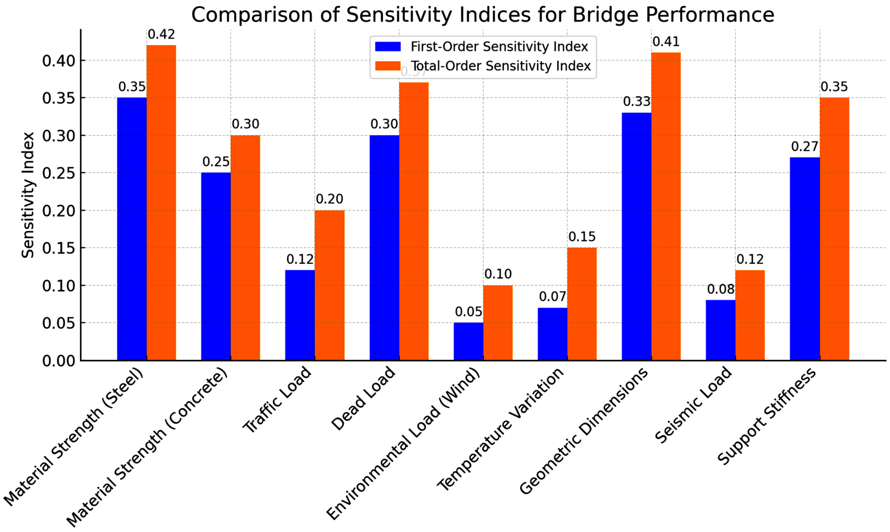

Figure 7. Bar chart comparing the first-order and total-order sensitivity indices for various input parameters affecting bridge performance.

Ultimately, the Kriging approximation functioned as a potent tool for sensitivity analysis, delivering precise predictions regarding structural behavior that needed very few computational resources.

6. Conclusion

6.1. Summary of Findings

The Kriging method revealed that the sensitivity analysis of the bridge signaled a major impact on material properties, especially yield and compressive strength, as well as geometric configurations like span length and cross-sectional area on how the structure performs. Loading situations were of particular importance, with greater traffic loads causing higher tension and deflections. The Kriging methodology performed well in forecasting performance with limited data, furnishing insights about parameter dependencies.

6.2. Future Research Directions

The Kriging method could be a focus of future research regarding its application to additional civil engineering issues, such as soil-structure interactions and seismic performance. Continuous studies could validate the predictive powers while fusing Kriging with machine learning, which could augment precision. Exploring regional cultural and environmental factors related to bridge performance could produce important findings.

6.3. Practical Recommendations

Civil engineers need to give precedence to high-performance materials and fine-tune geometric configurations to minimize stress and deflections. Appropriate traffic load assessments at the planning stage are significant for bridge capacity. Conscientious evaluation of support designs, notably those fixed supports designed for extended distances, has the potential to increase stability. The application of predictive maintenance methods informed by vital parameters will enhance not just the longevity but also the safety of bridges by prioritizing inspections and interventions.

Conflicts of Interest

The authors declare no conflicts of interest.

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