sustainability

MDPI

Article

An Intelligent Evaluation Method for Service Safety of Cable Net Structures under Multiple Factors

Zhansheng Liu [1,2,*], Zehua Zhang [1,2] and Chao Yuan [1,2]

[1] Faculty of Architecture, Civil and Transportation Engineering, Beijing University of Technology, Beijing 100124, China; 1454299969@emails.bjut.edu.cn (Z.Z.); yuann@emails.bjut.edu.cn (C.Y.)
[2] The Key Laboratory of Urban Security and Disaster Engineering of the Ministry of Education, Beijing University of Technology, Beijing 100124, China
* Correspondence: liuzhansheng@bjut.edu.cn

Abstract: Various uncertainties often influence the serviceability of cable net structures, which can impact their structural safety performance. The accurate identification of sensitive factors during the structure's service life and the determination of its serviceability state is crucial for achieving intelligent serviceability safety. In this paper, based on the digital twin model, a multi-factor-based assessment method for the serviceability safety of cable net structures was proposed. Firstly, the assessment method for serviceability safety under multi-factor influence was described in detail, outlining the specific workflow. Secondly, key indicators that affect the structural safety state are selected, and their range of variation is determined. Subsequently, a comprehensive dataset of sample data, considering long-term multi-factor influence, was constructed, through combined simulation using MATLAB 2021 and ANSYS 15.0. Finally, a support-vector-regression-based structural safety assessment model was established and validated.

Keywords: cable net structures; digital twin; factor indicators; safety assessment model

check for updates

Citation: Liu, Z.; Zhang, Z.; Yuan, C. An Intelligent Evaluation Method for Service Safety of Cable Net Structures under Multiple Factors. *Sustainability* **2023**, *15*, 15633. https://doi.org/10.3390/su152115633

Academic Editor: Gianluca Mazzucco

Received: 12 September 2023
Revised: 17 October 2023
Accepted: 26 October 2023
Published: 5 November 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Cable net structures, as a prominent structural system within prestressed steel structures, have experienced rapid development and wide application in recent years, attracting extensive attention and research interest from scholars. In the field of structural analysis, most studies typically combine model experiments and simulations to investigate the mechanical performance and safety of cable net structures under different influencing factors [1–3]. Experimental methods are the most effective approach in structural analysis research, as they consider various initial errors, environmental factors, and human factors. However, model experiment methods often suffer from drawbacks such as long equipment-installation and testing cycles, significant environmental influences, and high human-resource costs. Conducting multiple model experiments can be cost-prohibitive and impractical [4].

The emergence and widespread use of finite element analysis software have significantly increased the complexity of problem-solving in engineering structures, particularly in the construction of large-span, high-rise, and large-scale buildings. Nevertheless, classical numerical calculation methods, similar to finite element analysis, are not always suitable for practical engineering and have certain limitations. Firstly, the accuracy and computational efficiency of these methods depend heavily on the precision of various constitutive models, which can be theoretically challenging and require a high level of expertise. Developing and refining corresponding constitutive models can be time-consuming. Secondly, traditional numerical calculation methods are not only slow in computation speed but also costly when applied to fine-grained unit simulations. Thirdly, although there are mature commercial software platforms available in the industry and academia, such as ANSYS and ABAQUS, it is challenging to achieve efficient conversion between different platforms,

and the quality of simulation results often relies on the operator's proficiency. Lastly, due to inherent limitations in numerical calculation methods, it is difficult to accurately determine sensitive indicators that affect the structural safety state during the service life of the structure. It is also challenging to classify the safety condition of the structure and provide guidance for maintenance strategies. In summary, classical numerical calculation methods still heavily rely on manual operations, and there is significant room for improvement in areas such as parameterization, computational efficiency, and cost savings [5].

Furthermore, as the service lives of cable net structures extends, key structural components, such as prestressed tendons, experience continuous deterioration in material properties and mechanical performance due to adverse environmental factors such as tendon relaxation, corrosion, and temperature variations. This degradation significantly affects the structural safety performance. Fang et al. [6] analyzed the effect of partial tendon relaxation on both static and dynamic structural performance. Shi et al. [7] studied tendon prestress loss and anchor failures' influence on cable net structures, rigorously validating the accuracy and reliability of numerical models using finite element methods. Shi et al. [8] studied the influence of damage factors, including connection node failure, prestress loss, and anchor damage on the static load-carrying capacity and displacement variation rate in cable net structures. Wang et al. [9] investigated stress and deformation characteristics of high-vanadium sealed tendons subjected to 100-year return period wind loads, focusing on their fatigue durability performance. Zhou et al. [10] examined the impact of prestress losses on anchor failure in cable net structures, analyzing mechanisms under long-term loads. Li et al. [11] investigated the influence of uncertain factors like elastic deformation, thermal deformation, and measurement uncertainty on the accuracy of cable net structure analysis, and established a surface adjustment optimization model. Yue et al. [12] studied the deflection evolution patterns of large-span cable-stayed bridges under temperature effects and employed deep learning to predict temperature-induced deflection. Currently, most research and analysis of structural mechanical and safety performance are conducted under the influence of a single factor. Even when considering the combined effects of two or more factors, it is often challenging to assess the long-term structural safety performance due to limitations in experimental conditions and time. Therefore, it is necessary to find an alternative method to traditional serviceability safety assessment—one that can effectively evaluate the serviceability safety of cable net structures over the long term while considering the influence of multiple factors.

This study focused on the intelligent assessment of the structural safety state of cable net structures under the influence of multiple factors during their long-term service. A digital twin-based intelligent assessment method for the serviceability safety of cable net structures under multi-factor influence was proposed. Compared with the existing research, this method can overcome the limitations of test-cost and time. On the premise of ensuring high fidelity of the model, a variety of influencing factors are fully considered to evaluate the safety state of the structure. Firstly, key factors that affect the structural safety during the service life of cable net structures were selected, and the range of variation for these key factors was determined. Secondly, using a high-fidelity finite element model of the structure, Monte Carlo simulation and random sampling methods were employed in combination with MATLAB and ANSYS to generate a large dataset of sample data over the long-term under the influence of multiple factors. Subsequently, a support vector regression (SVR) structural safety assessment model was established, trained, and validated based on the generated dataset. Finally, using the trained structural safety assessment model, the safety of the structure was evaluated under real experimental conditions to validate the feasibility and effectiveness of the proposed method.

2. Structural Service Safety Assessment Method

As the service lives of building structures continues to increase, the prestressed cables, which are key structural components in cable network structures, experience continuous deterioration of material properties and mechanical performance due to factors such as

cable relaxation, corrosion, and temperature fluctuations. This deterioration severely affects the safety performance of cable network structures [13–15]. Currently, most studies and analyses of the mechanical or safety performance of prestressed steel structures are conducted under the influence of a single factor. Even when considering the combined effects of two or more factors, it is difficult to determine the structural safety performance in long-term conditions due to limitations in experimental conditions and time constraints.

In the structural safety analysis of cable network structures, various methods, such as theoretical analysis, numerical simulation, and model testing, have been widely applied to the structural analysis process, enabling comprehensive and systematic evaluation of the safety performance of cable network structures [16]. Nonetheless, given the intricate nature and complex structural configuration of cable network structures, they often present several challenges. For instance, theoretical analysis methods often rely on assumptions, simplifications, and analyzing and calculating under ideal conditions, which may not apply to real engineering cases. Numerical simulation methods, such as finite element analysis, can accurately simulate and capture structural responses. However, the extensive knowledge base and complex operational difficulties associated with these methods hinder their further promotion and application [17]. Model testing methods are generally considered the most effective structural analysis method in the field of civil engineering. However, they have limitations such as high costs, long cycles, and demanding requirements, making it difficult to meet the need for rapid analysis in the study of new structural systems [18].

Therefore, there is an urgent need to find or establish an effective alternative to traditional structural safety assessment methods that can meet the practical requirements of rapid structural assessment and achieve long-term planning for safe structural operation under the influence of multiple factors. This emerges as the primary task at hand. Consequently, based on the aforementioned digital twin model, this paper proposes a method for assessing the safety of cable network structures considering the influence of multiple factors. The specific workflow of this method is illustrated in Figure 1 and consists of the following four steps: (1) selection of multi-factor indicators; (2) establishment of a sample dataset; (3) development and validation of a structural safety assessment model; (4) application of the assessment in practical scenarios.

Step 1: Key sensitive factors that affect the structural safety of cable network structures during service are determined through extensive review of literature and adherence to empirical standards. Due to the unique spatial forms and materials of cable network structures, these factors mainly include load conditions, material quality, design and construction quality, cable relaxation, cable corrosion, temperature, etc. Among them, the load, material, design, and construction quality cannot be changed or can be changed little after the building is formed; cable relaxation, corrosion, and temperature changes occur continuously during the service period of the structure. Relaxation and corrosion will become more and more serious with time, and the temperature will change with the season at any time. Therefore, these are mainly discussed [9–12]. The parameter variation ranges for these key sensitive-factor indicators during service are subsequently determined based on relevant standards and existing literature [19–22].

Step 2: Firstly, a high-fidelity finite element model of the structure is established based on given geometry, materials, loads, and boundary specifications. The geometric shape and size of the cable net structure are determined, including the overall shape of the cable net (such as plane, arc, etc.) and the arrangement and connection of the cable net elements (such as cable lines, nodes, etc.). The mechanical properties of the materials used are determined, including the elastic modulus, yield strength, fracture toughness, and other parameters of the cable net material. The cable net structure is discretized and decomposed into many small finite element elements, such as triangular or quadrilateral elements. More dense grids are used in the key parts and deformation areas of the structure to better capture the distribution of stress and deformation. The boundary conditions are applied to the model to simulate the constraints and loading conditions of the cable net structure, including cable relaxation, corrosion, temperature change, and so on. Considering the nonlinear behavior

and contact force of the material, the appropriate material model and contact algorithm are selected to accurately simulate the mechanical behavior of the cable net structure. Finally, the numerical solution method is used to analyze the model, and the mechanical response information, such as stress, deformation, and displacement of the cable net structure, is obtained to evaluate its performance and safety.

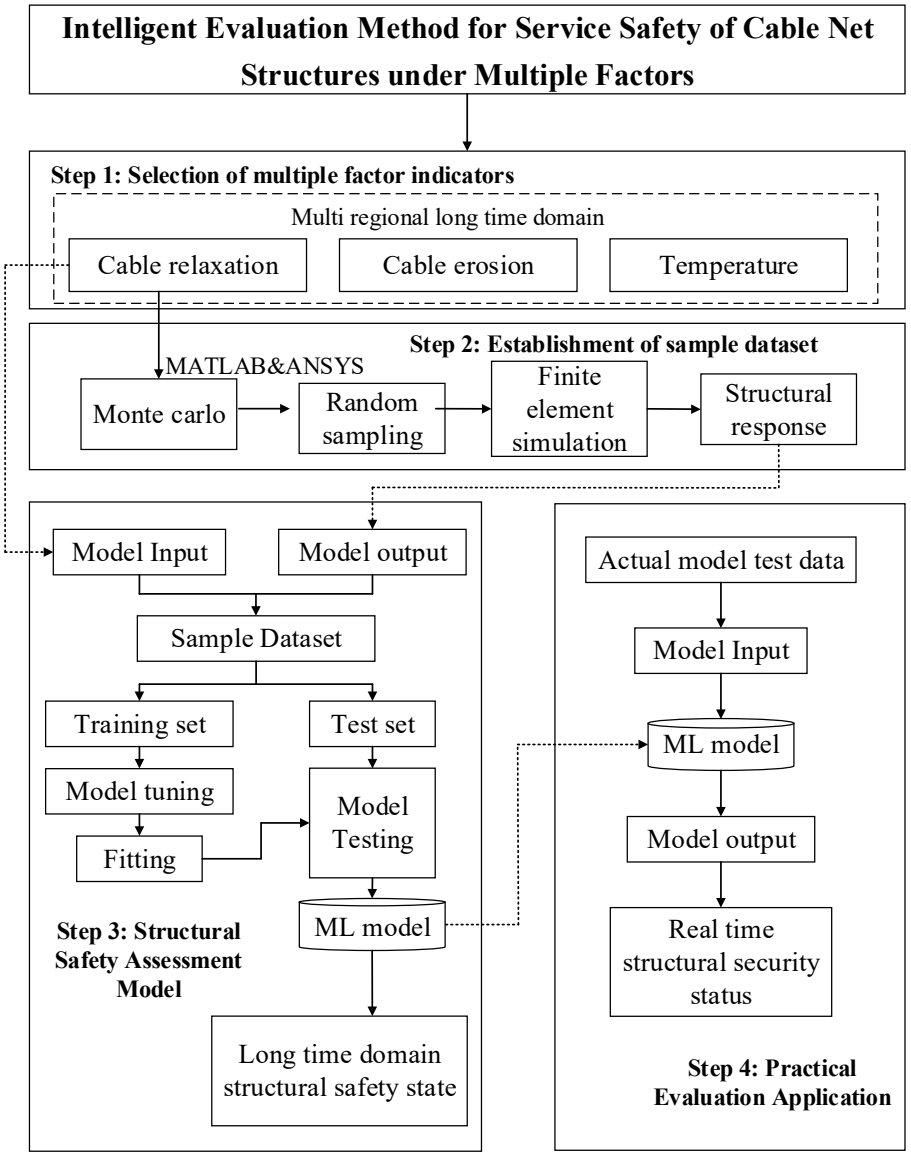


Figure 1. A method of structure service safety evaluation of a cable net under the action of multiple factors based on a digital twin.

Next, using the determined indicator ranges from the previous step, MATLAB is used to randomly generate values for input parameters. Subsequently, a large dataset of structural responses under various operating conditions is generated using the combined simulation application of MATLAB and ANSYS. This dataset contains the safety states of cable network structures across numerous operational scenarios over the long term. The dataset records the cable relaxation, cable corrosion, temperature, and structural responses (such as deflection and cable forces) under different operating conditions.

Step 3: Building upon the established dataset, the multi-factor indicators are used as input parameters, and the corresponding structural responses are used as output parameters. A well-established structural safety assessment model is trained to accurately evaluate the safety performance of cable network structures during service. The key to the success

of this step lies in constructing an accurate dataset that authentically represents the real conditions of engineering structures.

Step 4: The trained structural safety assessment model is used to evaluate the safety of structural model data generated under actual experimental conditions to validate the feasibility and effectiveness of the proposed method.

This workflow framework, as depicted in Figure 1, is not confined to cable network structures during service but also holds the potential for further exploration and application as a versatile framework for assessing the safety of various types of structures in service.

3. Selection of Multiple Factor Indicators

3.1. Cable Corrosion

To validate the effectiveness and applicability of the proposed method and establish the model, it is important to consider the varying corrosion rates of cables in different regions [23], especially in coastal and high-humidity areas where cables are more susceptible to corrosion. In contrast, in inland and dry regions, the corrosion rate of cables tends to be lower [19]. To demonstrate this, this study selects the corrosion rates of cables in four key cities in China for comparison.

The assumed minimum effective diameter of the cable after corrosion is denoted as $d_{\min,0}$. The effective cross-sectional area of the corroded cable can be calculated as $A_w = \pi d^2_{\min,0}/4$. The equation for calculating the diameter of the cable after corrosion, denoted as $d_{\min,0}$, is as follows:

$$d_{\min,0}(t) = d_0 - 2D_{\mathrm{cor}}(t) \tag{1}$$

In the equation, $D_{cor}(t)$ represents the cumulative corrosion depth after t years, following a power function law: $D_{cor}(t) = V_{\mathrm{steel}}\, t^{w}$. Here, V_{steel} represents the corrosion rate in the first year, and w is the long-term corrosion index that characterizes the corrosion development trend. The corrosion rate parameters for cables in different regions in China under various climatic conditions are provided in Table 1 [24]. Therefore, based on this information, the present authors can calculate the remaining cross-sectional percentage of cable corrosion over a certain number of years, in this case, a 50-year period.

Table 1. Cable corrosion parameters in different regions.

Parameter	Beijing	Wuhan	Qingdao	Shenzhen
Climatic characteristics	Temperate semi humid	Subtropical Moist	Temperate ocean	Humid and hot areas
V_{steel}/(mm/a)	0.032	0.047	0.058	0.024
w	0.45	0.39	0.57	1.03

3.2. Cable Relaxation

Due to their high tensile strength and low transverse stiffness, cables are widely used in major engineering fields such as cable-stayed bridges and prestressed spatial structures [20]. In China, most structures or buildings that use high-strength cables are public works with a typical design life ranging from 50 to 100 years. As key structural components carrying high tensile loads, the tensile and holding capacity of cables significantly affect the overall stiffness and strength of the structure. Thus, the service performance of cable network structures is closely related to the long-term characteristics of these structural components [6,25]. High-strength cables composed of high-strength steel wires, experience permanent strain and undergo stress relaxation and stiffness reduction under long-term loading. However, in practical engineering, obtaining precise relaxation rates is challenging due to the continuous variations in temperature and internal forces.

According to experimental results in reference [26], for ordinary cables with a ratio of initial stress to ultimate stress not exceeding 0.55, the stress relaxation rate in a 1000-h relaxation test does not exceed 1.5%. For low-relaxation cables, the stress relaxation rate

does not exceed 0.8%, and the majority of stress relaxation occurs within 1000 h. Moreover, in actual engineering, the design value of cable stress typically falls within 55% of the ultimate stress, and the majority of cable lifespans typically operate at room temperature. Referring to the experimental results of Wang Xiaoxiang, Chen Zhihua, et al. [21], the long-term relaxation rate of high-strength steel wires is below 3%, and the recommended value for a 50-year relaxation rate is 2.6606%. Therefore, this study assumes the long-term relaxation rates of cables as presented in Table 2.

Table 2. The long-term relaxation rates of cables.

Time	100 h	1000 h	10 Years	30 Years	50 Years
Cable relaxation rate (%)	1.27	1.56	2.3	2.54	2.66

3.3. Temperature Effects

Temperature is an important factor that affects the safety state of cable network structures during service and must be considered [22]. Similarly, through literature research and data collection, this study has collected the highest and lowest temperatures within 50 years for four regions: Beijing, Wuhan, Qingdao, and Shenzhen, as shown in Table 3.

Table 3. Temperature changes in different regions.

Parameter (°C)	Beijing	Wuhan	Qingdao	Shenzhen
maximum temperature	36	37	33	35
minimum temperature	−13	−5	−9	8
average temperature	10	15	12	22

4. Establishment and Process of Structural Service Safety Assessment Model

4.1. Establishment of Sample Dataset

The availability of an adequate training dataset is crucial for improving the performance of machine learning models [27]. However, due to the lack of a structural safety database specifically for cable network structures during service, it is challenging to find a sufficient amount of training data. Therefore, generating a large dataset of samples from finite element models is a key step in training the safety assessment model. To address this issue, this study utilizes MATLAB and ANSYS along with Monte Carlo simulation and random sampling methods to generate a substantial dataset. When generating the learning data using Monte Carlo simulation, probability models with corresponding random variables or parameter ranges should be employed. Referring to the results from Liu Zhansheng [28], the probability distribution types for cable corrosion and cable relaxation are assumed to be normal distributions, with a coefficient of variation of 0.2888 for both. For simplicity, the temperature is considered at its highest and lowest values. Furthermore, considering the data requirements of machine learning models, this study initially focuses on exploratory research on the cable forces of ring cables in cable network structures. As ring cables are critical components of cable network structures, their deformations typically occur before local or overall structural failure.

When generating data from a finite element model, it is necessary to repeatedly solve the model by changing multiple physical parameters. Performing these operations solely within the ANSYS operating environment not only involves significant repetition but also requires considerable time and effort. As a result, this study uses MATLAB in conjunction with ANSYS for combined simulation and solution. MATLAB serves as the main control program, wherein all parameters and options are configured and passed to ANSYS. The calculations in ANSYS are then performed using the batch processing mode invoked by MATLAB. Following the completion of ANSYS calculations, MATLAB processes the output files, allowing for the generation of a substantial dataset comprising the safety states of cable net structures under various operating conditions in the long-term domain. This

dataset serves as a foundation for subsequent structural safety assessments. The process of using MATLAB to call ANSYS and generate a dataset can be divided into the following three modules:

(1) Initial Parameter Configuration

The initial parameter configuration module involves setting up the structural parameters and external environmental parameters. The structural parameters include the dimensions and material properties of the structure. However, this study focuses on exploring the structural safety performance under multiple factors, so the dimensions and material properties of the structure are quantified in this research.

Regarding the external environmental parameters, the previous section determined the indicators and their corresponding ranges for various factors. In this module, MATLAB generates random values using a random sampling approach. These random values are assigned to input variables using assignment statements. Subsequently, the assigned values are written to a .txt file for easy access by the ANSYS software in the subsequent steps.

(2) MATLAB Call Module

The main purpose of this module is for MATLAB to call the ANSYS software, perform finite element calculations, and output the results to generate the dataset. The key aspect of the MATLAB and ANSYS combined simulation is the ability of MATLAB to automatically invoke ANSYS for computations, thereby fulfilling the requirement of time efficiency.

In this study, MATLAB achieves this by using the SYSTEM function to call ANSYS in batch mode for processing and analysis. Under ANSYS's batch mode, a macro file written in the APDL language can be used to retrieve data from the .txt file, perform finite element calculations, and conduct post-processing. The results of these calculations are then output to a .dat file.

(3) Data Exchange Module

The data exchange module's purpose is to facilitate data processing and calculations between MATLAB and ANSYS. Both MATLAB and ANSYS can read and write files, enabling data exchange between the two programs. Files with the .txt extension are used for data interchange between MATLAB and ANSYS. The data exchange process is depicted in Figure 2.

The specific steps for data exchange are as follows:

Step 1: MATLAB writes the numerical values generated through random sampling into the input file "datain.txt".
Step 2: MATLAB uses the SYSTEM function to invoke ANSYS in batch mode and performs finite element analysis calculations by reading the data from the "datain.txt" file.
Step 3: ANSYS extracts the computed results of the structural model and writes them into the output file "dataout.txt".
Step 4: MATLAB reads the array data from the "dataout.txt" file and checks if the computation requirements have been met.
Step 5: If the requirements are not met, the process continues; if the requirements are met, the computation stops.

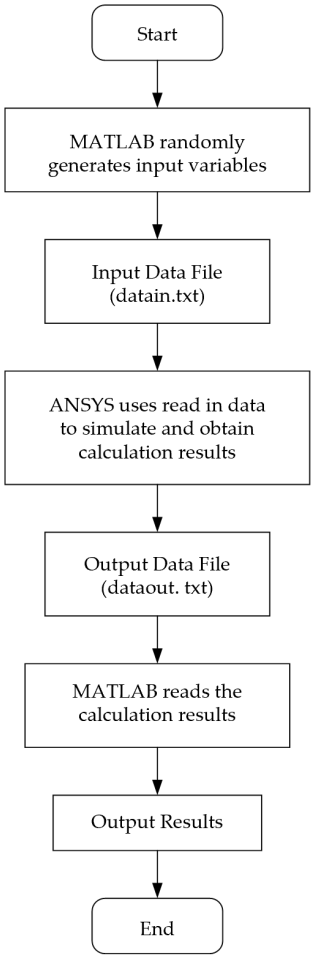


Figure 2. Data interaction between MATLAB and ANSYS.

4.2. Process of Service Safety Assessment Using SVR

Support vector regression (SVR) is a classical machine learning model known for its good generalization performance and robustness [29,30]. Since SVR is a well-established machine learning model with mature theory, a detailed explanation of its principles is omitted [31]. To achieve an accurate assessment of structural safety, this study uses the SVR algorithm to evaluate the service safety of cable net structures under the influence of multiple factors in the long-term domain. A well-developed SVR-based structural safety assessment model is trained using the generated sample dataset. These models are utilized to accurately determine the safety state of cable net structures during their service. The specific process of SVR-based structural safety assessment for cable net structures is illustrated in Figure 3, and the steps involved are as follows:

(1) Importing and processing the sample dataset: The sample dataset is generated as described in Section 4. Additionally, since the influencing factors may have different scales and significant numerical differences, it is necessary to normalize the data in the sample dataset. This study mainly employs the method of min–max normalization for data processing.
(2) Division and selection of training and testing sets: To avoid overfitting and underfitting, 80% of the data are used for training, while 20% are reserved for model testing. The samples are randomly divided into training and testing sets.
(3) Model training: The key to SVR model training lies in selecting appropriate kernel functions and parameters. The radial basis function (RBF) kernel outperforms other kernel functions in terms of accuracy and computational performance. Therefore,

this study adopts the RBF kernel. The penalty coefficient C and the kernel function parameter g are determined through k-fold cross-validation.

(4) Model testing: The testing process uses a randomly sampled testing set, and the SVR model provides predicted values. By comparing the predicted values with the actual values, the coefficient of determination R^2 is calculated. The closer the R^2 value is to 1, the more accurate the prediction. The larger the discrepancy between R^2 and 1, the lower the accuracy. Therefore, the above steps (3) and (4) should be repeated.

(5) Structural safety assessment: Using the established machine learning model, the collected data can be input into the model to obtain real-time safety state probabilities of the cable net structure at a given time.

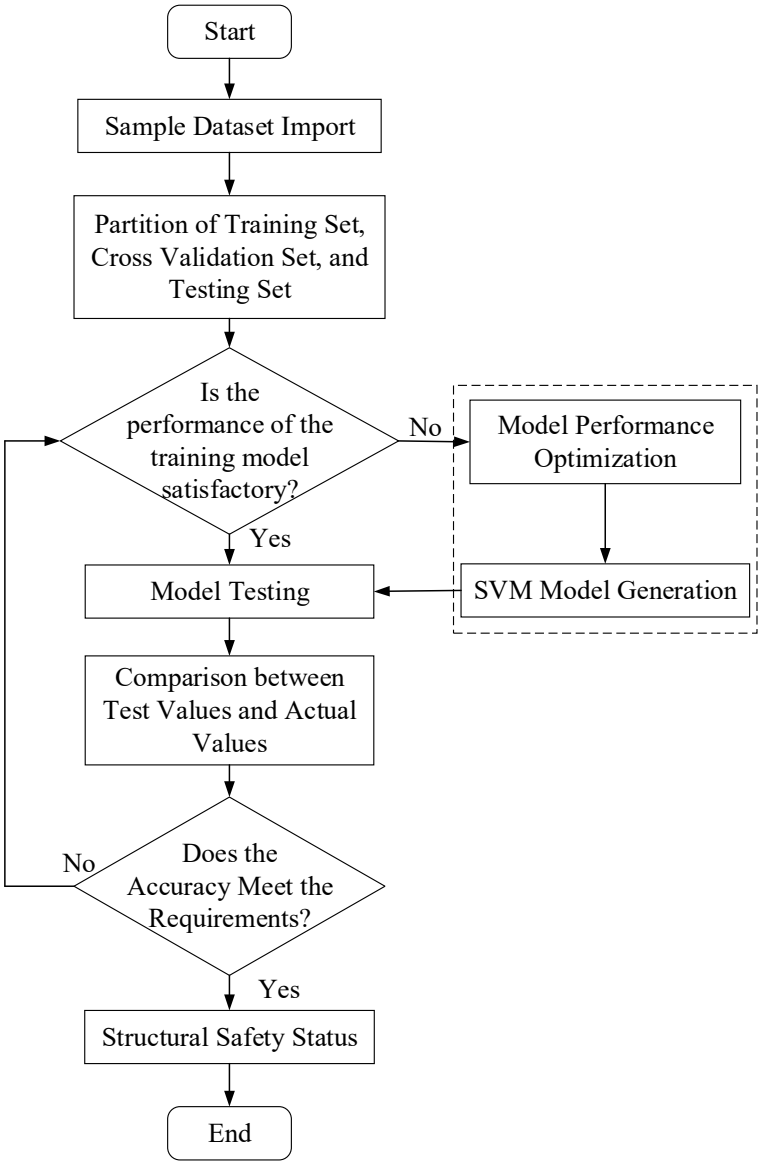


Figure 3. Service safety assessment of cable-net structure based on SVR.

5. Verification of Structural Service Safety Assessment Model

5.1. Establishment of Structural Service Safety Assessment Model

To account for the random combination of multiple factors under different operating conditions, this study conducted tests on a cable net structural model. Three service safety-sensitive parameters, as discussed in Step 4, were used as input variables in the finite element model. A total of 2000 different combinations of operating conditions

were analyzed, with 1400 combinations used as training data for the subsequent safety assessment model and 600 combinations used as test data.

Figures 4 and 5 depict the contour plots of internal forces and displacements for one of the designed operating condition combinations in the cable net structural model. It is evident that the tension in the cable net structure, particularly in the cable loops, which serve as critical components, exhibits the highest values for both internal forces and displacements. Therefore, the internal force and deformation of the loop cable are considered important goals for safety assessment.

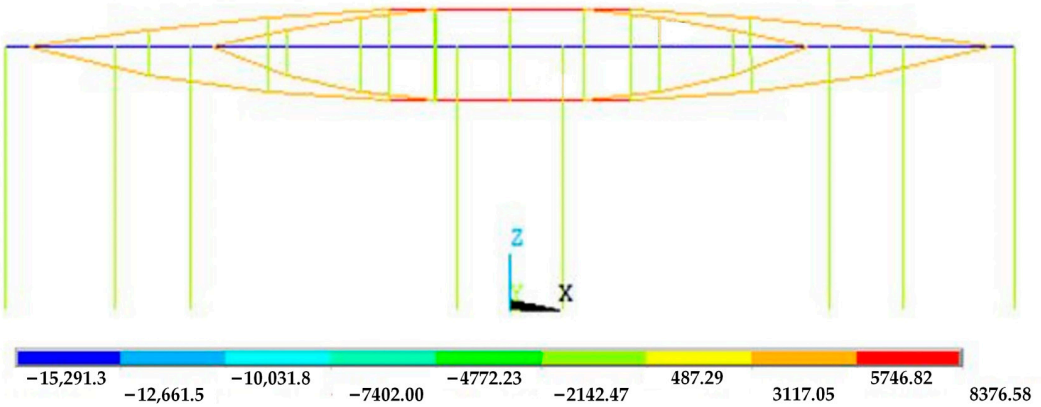


Figure 4. Model internal force diagram.

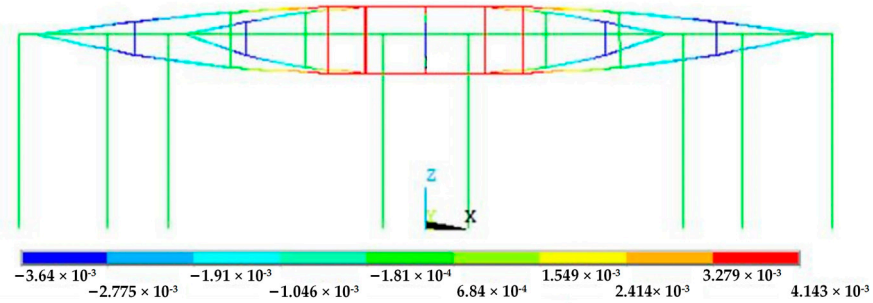


Figure 5. Model displacement diagram.

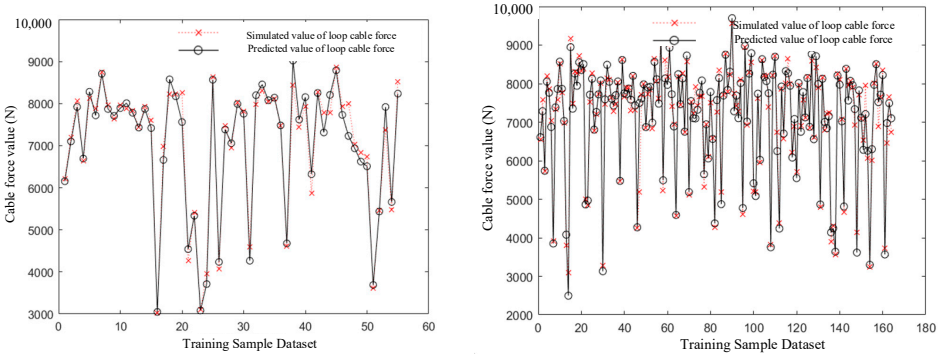
Using ANSYS on a computer with an Intel® Core™ i7-9750 CPU@2.60GHz and 32GB RAM, it takes 20 s to obtain numerical results for one operating condition in the structural model. Taking the cable net structure in this study as an example, the finite element model consists of 136 elements. Typically, as the number of elements increases, the computation time increases significantly. Therefore, the time-cost suggests that the finite element method is not suitable for solving problems that require real-time results.

5.2. Results of Service Safety Assessment

The SVR-based structural safety assessment model was trained using the training dataset of 1400 different operating conditions and tested using the testing dataset of 600 different operating conditions. Table 4 presents the mean squared error (MSE) and coefficient of determination (R^2) for the testing and training sets of the safety assessment models in different regions. Figures 6–9 display some of the evaluation model results.

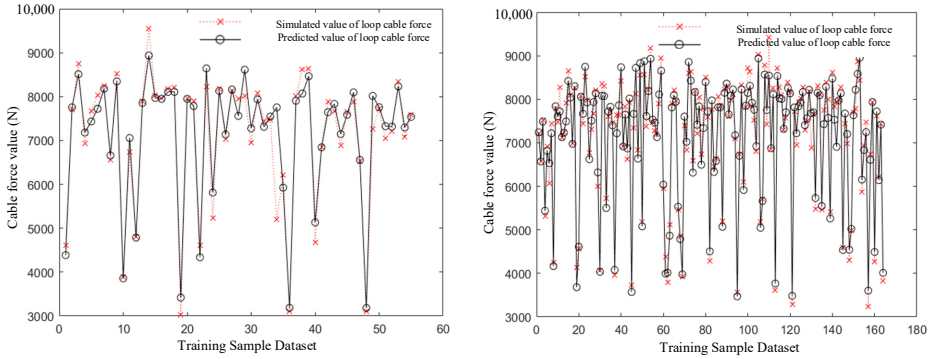
Table 4. Evaluation results of different regional security assessment models.

Region	Training Set		Test Set	
	R^2	MSE	R^2	MSE
Beijing	0.9879	0.452	0.9656	0.759
Wuhan	0.9927	0.387	0.9755	0.632
Qingdao	0.9914	0.349	0.9862	0.546
Shenzhen	0.9921	0.343	0.9867	0.579



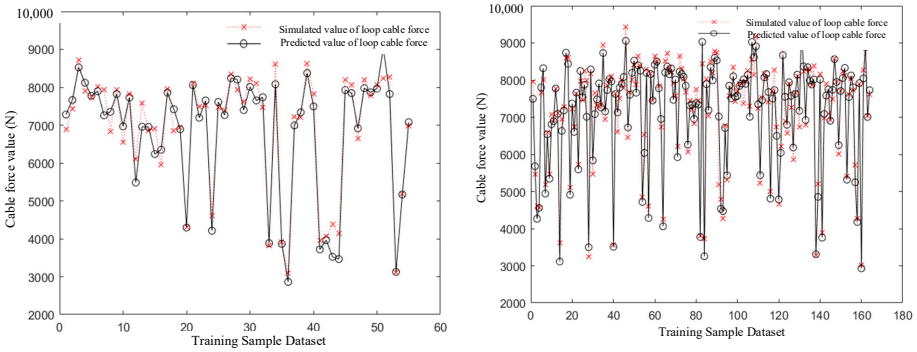
(**a**) Test sample (**b**) Train sample

Figure 6. Model results of samples from Beijing area.



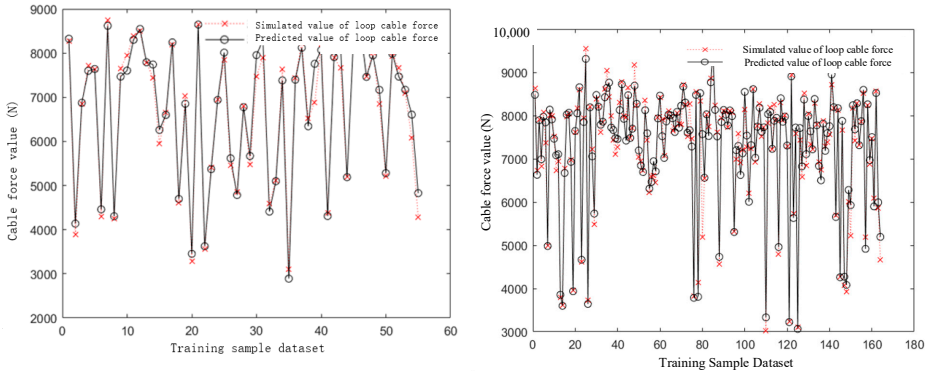
(**a**) Test sample (**b**) Train sample

Figure 7. Model results of samples from Wuhan area.



(**a**) Test sample (**b**) Train sample

Figure 8. Model results of samples from Qingdao area.



(**a**) Test sample (**b**) Train sample

Figure 9. Model results of samples from Shenzhen area.

Despite variations in the range of influencing factors and the structural safety states across different regions, the MSE values obtained from the corresponding databases are small, and the R^2 values are very close to 1. This indicates that the proposed SVR-based structural safety assessment method exhibits good applicability and effectiveness in evaluating the safety states of cable net structures under the influence of multiple factors in different regions. Furthermore, according to the results of the safety assessment models, the safety state probabilities of the cable net structures in different regions consistently exceed 99%.

5.3. Practical Application of Assessment

To validate the performance of the SVR-based structural safety assessment model, actual experimental data were used to assess the model's performance. The trained structural safety assessment model was applied to evaluate the service safety states of cable net structures. The results of the actual experimental data are shown in Figure 10, where the predicted values from the structural safety assessment model closely match the actual values. Furthermore, throughout the evaluation process, the R^2 value is close to 1, and the error values (MSE, MAE) remain at low levels. This indicates that the proposed structural safety assessment method under the influence of multiple factors exhibits good generalization and robustness during practical validation. The SVR-based structural safety assessment model can accurately assess the safety status of cable net structures under various operating conditions.

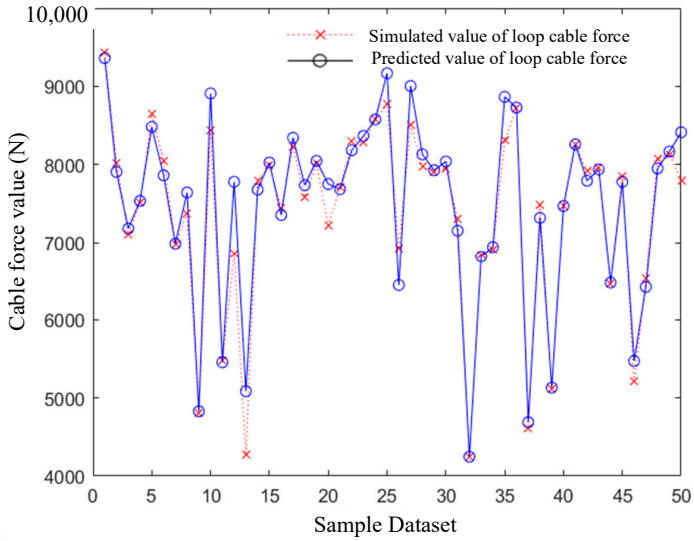


Figure 10. Results of actual test data.

The cable net structure model is a scale model of a project. The structure form is relatively simple, and the force transmission path is also very clear. In addition, in the early stage of the construction of the structure, the construction data are relatively intact. Therefore, the model of the structure is relatively simple, the required data are relatively complete, the training and testing of the evaluation model are also very smooth, and the results are satisfactory. However, in practical engineering, the structural form of the building will be more complex, and the construction data and required data may be lacking. Therefore, the establishment of the finite element model of the actual project and the training of the evaluation model may encounter difficulties.

6. Conclusions

This study proposed a method for assessing the service safety of cable net structures under the influence of multiple factors, based on a digital twin model. The specific steps and application process of the safety assessment method under multiple factors were introduced. MATLAB and ANSYS were used for combined simulation to model the structural response under multiple factors in the long-term domain, creating a sample dataset for cable net structures under numerous operating conditions. Subsequently, a structural safety assessment model was trained using this dataset. The proposed method for assessing the service safety of cable net structures under multiple factors allows for the evaluation of structural safety states using a structural safety model based on a sample database, overcoming the limitations of traditional safety assessment methods in terms of time consumption and high costs under different operating conditions. Compared with the existing research, this method can weaken the constraints of test-cost and time and fully consider various influencing factors to evaluate the safety state of the structure under the premise of ensuring the high fidelity of the model. The main conclusions of this study are as follows:

(1) The results of different regions showed that the proposed structural safety assessment method under the action of multiple factors is suitable for structural safety assessment in multi-region scenarios. At the same time, it has good generalization ability and fault-tolerance ability, which improves the safety assessment of the structure under the action of multiple factors. The predicted value of the structural safety assessment model based on SVR is consistent with the actual value, and the accuracy can be guaranteed above 95%.

(2) The established structural safety assessment model exhibits high potential for application in the assessment of structural safety under multiple factors, both in terms of evaluation accuracy and computational efficiency. It can help staff evaluate the safety performance of structures in various scenarios, fully consider regional factors and structural characteristics, and ensure the accuracy of the results.

(3) There are still some limitations and shortcomings in this study. The applied model example is only a simple cable net structure, whose appearance and size are relatively simple, and the material properties change little. At the same time, this study only considers the effects of cable corrosion, cable relaxation, and temperature on structural safety, which is not comprehensive enough compared with the actual situation of the structure. More factors or parameters can be added to improve the accuracy of the model, such as material aging, environmental vibration, structural reliability, and so on.

(4) The multi-factor structural safety assessment framework proposed in this study is not aimed at a building structure with certain characteristics. In further research, this method can be developed and trained for more building structures. According to the different forms and characteristics of different structures, the corresponding key control factors of structural safety are found. The structural safety assessment framework and model proposed in this paper are appropriately adjusted to explore the applicability of the proposed structural safety assessment model under the action of multiple factors with more diversified and more realistic structural forms and sizes

and to develop structural safety assessment models for various building structures during service.

Author Contributions: Conceptualization, Z.L. and C.Y.; methodology, Z.L.; software, Z.Z. and C.Y.; validation, Z.L. and Z.Z.; writing—original draft preparation, Z.Z. and C.Y.; writing—review and editing, Z.L. and Z.Z.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available for confidentiality reasons.

Acknowledgments: The authors would like to thank Beijing University of Technology for its support throughout the research project.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the study's design, collection, analyses, or interpretation of data, writing of the manuscript or decision to publish the results.

References

1. Sluszka, P.; Gagnon, C.; Rankin, S. Inspection, Evaluation, and Monitoring of Suspension Bridge Cables. In Proceedings of the Structures Congress 2006, St. Louis, MO, USA, 18–21 May 2006. [CrossRef]
2. Teng, J.; Xiao, Y.; Liu, C.; Yu, H.; Liu, H. Practical structural health monitoring systems in large space structures. In *Earth and Space 2012: Engineering, Science, Construction, and Operations in Challenging Environments, Proceedings of the 13th ASCE Conference, Pasadena, CA, USA, 15–18 April 2012*; ASCE: Reston, VA, USA, 2012; pp. 1177–1186.
3. Teng, J.; Zhu, Y.; Lu, W.; Xiao, Y. The intelligent method and implementation of health monitoring system for large span structures. In *Earth and Space 2010: Engineering, Science, Construction, and Operations in Challenging Environments, Proceedings of the 12th Biennial International Conference, 14–17 March 2010, Honolulu, HI, USA*; ASCE: Reston, VA, USA, 2010; pp. 2543–2552.
4. Gil, H.; Choi, Y. Cable erection test at pylon saddle for spatial suspension bridge. *J. Bridge Eng.* **2001**, *6*, 183–188. [CrossRef]
5. Chisalita, A. Finite deformation analysis of cable networks. *J. Eng. Mech.* **1984**, *110*, 207–223. [CrossRef]
6. Fang, Y.; Gao, J. Effect study of cable damage to structural performance of cable-net. In Proceedings of the 2nd International Conference on Modelling and Simulation, Manchester, UK, 21–22 May 2009.
7. Shi, G.; Fan, H.; Bai, Y.; Zheng, J. Damage evaluation of single-layer cable net façade. *Proc. Inst. Civ. Eng. Struct. Build.* **2015**, *168*, 159–173. [CrossRef]
8. Shi, G.; Zuo, Y.; Zheng, J.; Huo, D. Experimental study on the single-layer plane cable net with the influence of damages. *Jianzhu Jiegou Xuebao J. Build. Struct.* **2010**, *31*, 9–17.
9. Wang, Z.; Shi, Y.; Chen, B.; Cheng, Y.; Zhu, Z.; Li, J. Study on fatigue performance of Galfan fully locked coil cable in bending state for National Speed Skating Oval. *J. Build. Struct.* **2023**, *44*, 107.
10. Zhou, Y.; He, S.; Yang, X. Study on prestress loss of anchor cables under long-term loading. *Rock Soil Mech.* **2006**, *27*, 1353–1356.
11. Li, T.; Tang, Y.; Zhang, T. Surface adjustment method for cable net structures considering measurement uncertainties. *Aerosp. Sci. Technol.* **2016**, *59*, 52–56. [CrossRef]
12. Yue, Z.; Ding, Y.; Zhao, H. Deep learning-based minute-scale digital prediction model of temperature-induced deflection of a cable-stayed bridge: Case study. *J. Bridge Eng.* **2021**, *26*, 05021004. [CrossRef]
13. Yang, L.; Shi, G.; Yin, H.; Shi, X.; Guo, Z. Full-scale experimental study on the influence of damages on the static behavior of the single-layer cable net structure. *Structures* **2015**, *3*, 153–162. [CrossRef]
14. Suangga, M.; Hidayat, I. Temperature effect on cable tension forces of cable-stayed bridge. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *195*, 012009. [CrossRef]
15. Fan, F.; Jin, X.; Shen, S. Effect of non-uniform solar temperature field on cable-net structure of reflector of large radio telescope-FAST. *Adv. Struct. Eng.* **2009**, *12*, 503–512. [CrossRef]
16. Branam, N.; Arcaro, V.; Adeli, H. A unified approach for analysis of cable and tensegrity structures using memoryless quasi-newton minimization of total strain energy. *Eng. Struct.* **2019**, *179*, 332–340. [CrossRef]
17. Bedon, C.; Amadio, C. Exploratory numerical analysis of two-way straight cable-net façades subjected to air blast loads. *Eng. Struct.* **2014**, *79*, 276–289. [CrossRef]
18. Shi, G.; Zuo, Y.; Shi, X.; Shi, Y.; Wang, Y.; Guo, Z. Influence of damages on static behavior of single-layer cable net supported glass curtain wall: Full-scale model test. *Front. Archit. Civ. Eng. China* **2010**, *4*, 383–395. [CrossRef]
19. Chen, Z.; Chen, H.; Liu, H.; Yang, S. Corrosion behavior of different cables of large-span building structures in different environments. *J. Mater. Civ. Eng.* **2020**, *32*, 04020345. [CrossRef]

20. Chen, Z.; Yu, Y.; Wang, X.; Wu, X.; Liu, H. Experimental research on bending performance of structural cable. *Constr. Build. Mater.* **2015**, *96*, 279–288. [CrossRef]
21. Wang, X.; Chen, Z.; Liu, H.; Yu, Y. Experimental study on stress relaxation properties of structural cables. *Constr. Build. Mater.* **2018**, *175*, 777–789. [CrossRef]
22. Chen, C.; Wu, W.; Liu, C. Effects of temperature variation on cable forces of an extradosed bridge. In Proceedings of the 6th European Workshop on Structural Health Monitoring, Dresden, Germany, 3–6 July 2012; pp. 1–8.
23. Klinesmith, D.; McCuen, R.; Albrecht, P. Effect of environmental conditions on corrosion rates. *J. Mater. Civ. Eng.* **2007**, *19*, 121–129. [CrossRef]
24. Cao, C. Natural environmental corrosion of Chinese materials. *Inf. Surf. Eng.* **2005**, *5*, 1.
25. Yan, G.; Jemison, S.; Duan, Q.; Feng, R. Detection of Pretension Loss of Cable-Net Structures. In Proceedings of the ASME 2015 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, Colorado Springs, CO, USA, 21–23 September 2015; American Society of Mechanical Engineers: New York, NY, USA, 2015; p. 57304.
26. Buckler, J.; Scribner, C. *Relaxation Characteristics of Prestressing Strand*; Civil Engineering Studies; University of Illinois: Urbana, IL, USA, 1985.
27. Sarmadi, H. Investigation of machine learning methods for structural safety assessment under variability in data: Comparative studies and new approaches. *J. Perform. Constr. Facil.* **2021**, *35*, 04021090. [CrossRef]
28. Liu, Z.; Wang, H.; Li, B.; He, J. Reliability analysis of cable supported barrel vault considering lasso's corrosion and relaxation. *J. Tianjin Univ. Sci. Technol.* **2016**, *49*, 48–54.
29. Hu, H.; Gao, L.; Meng, Y.; Zheng, H. A Support vector regression based operational transfer path analysis method and its application. *Zhendong Yu Chongji J. Vib. Shock.* **2021**, *40*, 285–295.
30. Liu, Z.; Ding, Y.; Yan, J. Frequency Prediction Based on SVR-ARMA Combination Model Improved by Particle Swarm Optimization. *Zhendong Ceshi Yu Zhenduan J. Vib. Meas. Diagn.* **2020**, *40*, 374–380.
31. Luo, W.; Dong, B.; Wang, Z. Short-term Traffic Flow Prediction Based on CNN-SVR Hybrid Deep Learning Model. *J. Transp. Syst. Eng. Inf. Technol.* **2017**, *17*, 68–74.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.