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STUDY ON TECHNOLOGICAL SOLUTIONS FOR DISPLACEMENT MONITORING OF BRIDGES IN VIETNAM

MAJOR: GEODETIC-CARTOGRAPHIC ENGINEERING
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SUMMARY OF Ph.D. DISSERTATION

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The dissertation has been completed at: **The Department of Engineering Surveying, Faculty of Geodesy - Cartography and Land Management, Ha Noi University of Mining and Geology**

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The dissertation can be referred at:
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INTRODUCTION

1. The urgency of the study

Monitoring bridge displacement is carried out to collect data on the displacement of the structure accurately, together with other monitoring data used to calculate the change in internal forces from which to evaluate, predict the level of safety; design check; warning; provide data for the maintenance and repair bridges in the process of exploitation and use. Because the bridge is large, has a complex structure, and must ensure very high accuracy requirements in displacement monitoring, measuring in difficult conditions, and the large volume of monitoring data. It is very necessary and important in researching technological solutions for data processing and data analysis to improve the accuracy and measurement convenience when observing bridges.

2. Target, subject, and scope of the study

The target of the study is to propose technological solutions to improve the accuracy of bridge displacement monitoring. The studied subject is the rigid structure bridge and the cable-stayed bridge. The scope of the study is in the field of bridge displacement monitoring during its operation in Vietnam.

3. The research contents

Research on the standard direction measurement diagram in general form and applying the least squares method to process the general standard direction data in the displacement monitoring of the rigid bridge‘s horizontal direction; Research on the application of GNSS - RTK in vertical displacement monitoring of cable-stayed bridges; Study on the application of Artificial Neural Network (ANN) in establishment a cable-stayed bridge displacement model based on the impact of dynamic load factors.

4. Research methodology

Statistical method, analytical method, experimental method, comparative method, mathematical method, and computer applications.

5. Scientific and practical significance

The dissertation contributes to perfecting the data processing theory of the standard direction control network when monitoring the bridge's horizontal displacement. In addition, it is a scientific basis for developing standards for cable-stayed bridge displacement monitoring when applying GNSS-RTK technology. It also helps to develop the ANN application in building displacement models based on the long-term data of the cable-stayed bridge monitoring system. The obtained results can be used in teaching, researching, and producing reality.

6. The defended points

- *The first point:* Generalizing the standard direction diagram and applying the least squares method to process the standard direction data in this diagram allows the standard direction method in the monitoring of rigid bridge horizontal displacement to be accurate, flexible, and convenient.
- *The second point*: GNSS - RTK technology in cable-stayed bridge displacement monitoring and analysis of monitoring data by ANN allows the establishment of a bridge displacement model with high accuracy.

7. New contributions

- Proposing a general standard direction diagram to build the basic network, monitoring network, and processing measurement data in the general diagram according to the least squares method in the monitoring of the rigid bridge horizontal displacement.
- Studying the accuracy and evaluating the applicability of the cable-stayed bridge's vertical displacement monitoring by GNSS - RTK in Vietnam conditions.
- Research on the application of artificial neural networks to establish a cable-stayed bridge displacement model based on the impact of dynamic loads.

8. Structure of the dissertation: The dissertation consists of three parts: an introduction, 4 chapters of content, and a conclusion.

Chapter 1
OVERVIEW OF BRIDGE MONITORING IN THE WORLD AND VIETNAM

1.1. Overview of bridge

1.2. Overview of bridge displacement monitoring

1.3. Overview of theoretical research and practice of bridge displacement monitoring in the world and Vietnam

1.1.1. In the world

1. Researched measuring methods and processed standard direction data.
2. Researched the application of GNSS - RTK in bridge displacement monitoring.
3. Researched the application of ANN to handle monitoring data.
4. GNSS was integrated into SHMs of cable-stayed bridges.

1.1.1. In Viet Nam

1. Researched standard direction methods in construction displacement monitoring. Studied the general theory on the method of establishing, and adjusting the basic geodetic control network, evaluating the stability of the base control landmark.
2. Researched the accuracy of GNSS – RTK, and applicability of GNSS - RTK in cable-stayed bridge displacement monitoring including guidance on the selection, design, and installation of equipment, and GNSS methods.
3. Researched the application of artificial neural networks in establishment displacement models such as hydroelectric projects, and underground mines.
4. Some cable-stayed bridges installed GNSS belong to the structural monitoring system

1.4. Assessing the research status and orientating for the dissertation

1.4.1. Achievements

- Standard direction method has been applied when monitoring horizontal displacement of construction works under pressure from one side such as hydropower plants, bridges...

- The research evaluates the accuracy and applicability of GNSS-RTK in horizontal and vertical displacement monitoring has been studied a lot, achieving high accuracy.
- ANN is a powerful tool to solve non-linear problems and is commonly used in disaster forecasting, securities, etc.

1.4.2. Disadvantages

- With the requirement of high accuracy and measurement in difficult conditions such as crossing rivers, lakes, etc., the rigid application of one of the four standard directional measurement schemes during the monitoring of the rigid bridge‘s horizontal displacement has proved difficult causing many obstacles to the measurement work.
- There is rarely research and evaluation of the accuracy of monitoring cable-stayed bridge displacement by GNSS-RTK in the vertical direction.
- There has not been an in-depth study on the application of ANN in processing and analyzing a very large number of cable-stayed bridge displacement monitoring data.

1.4.3. The main research direction of the dissertation

- Studied the standard direction measurement diagram in general form and applied the least squares method to process the standard direction measurement data according to this general scheme.
- Studied the accuracy of GNSS - RTK in vertical displacement monitoring of cable-stayed bridges.
- Researched and applied ANN in the establishment displacement model in three directions X, Y, and Z of cable-stayed bridges.

Chapter 2

STUDY ON THE APPLICATION OF STANDARD DIRECTION METHOD IN MONITORING DISPLACEMENT IN THE RIGID BRIDGE ‘S HORIZONTAL DIRECTION

2.1. Structural characteristics, technical requirements in the monitoring of the rigid structure bridges ‘ horizontal displacement

2.2. Horizontal displacement monitoring network system

2.3. Standard direction method in monitoring the rigid structure bridges ' horizontal displacement

2.4. Research on building model's general standard direction

2.4.1. Modeling a measurement in the standard direction method

Assuming the machine location at point k; oriented point j, and the measured point i. Quantity Δ_i, deviation Y_i, the distance between monitoring points S_{ki}, S_{ij}.

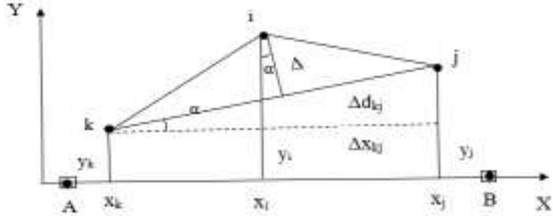

Figure 2.10: General standard direction diagram

In Figure 2.10 relationships between the measure Δ and the y-direction deviation (from the original standard direction) are shown as follows:

$$\frac{\Delta}{\cos\alpha} = y_i - \frac{x_j - x_i}{x_j - x_k} y_k - \frac{x_i - x_k}{x_j - x_k} y_j \qquad (2.11)$$

$$\cos\alpha = \frac{x_j - x_k}{\Delta d_{kj}} \qquad (2.12)$$

$$\Delta = \cos\alpha \left(y_i - \frac{x_j - x_i}{x_j - x_k} y_k - \frac{x_i - x_k}{x_j - x_k} y_j \right) \qquad (2.13)$$

Δ: deviation of i from the kj direction; y_k , y_i, y_j: coordinates of k, i, j

For the m measure there is a corrected numerical equation of the general form:

$$v_m = \frac{\partial \Delta_m}{\partial y_1} \delta y_1 + \cdots + \frac{\partial \Delta_m}{\partial y_t} \delta y_t - \Delta_m$$

$$or \quad v_m = a_{m1} \delta y_1 + \cdots + a_{mt} \delta y_t - \Delta_m \qquad (2.14)$$

Determine the coefficient of the corrected numerical equation: For the unknowns that do not participate in (2.14), there is a coefficient $a_m = 0$. The coefficients a_i, a_k, a_j are determined:

$$a_{mi} = \cos\alpha \qquad (2.15)$$

$$a_{mk} = \frac{\Delta x_{ji}}{\sqrt{\Delta y_{kj}^2 + \Delta x_{kj}^2}} + y_k \Delta x_{ji} \times \frac{y_j - y_k}{\sqrt{(\Delta {y_{kj}}^2 + \Delta x_{kj}^2)^3}} \qquad (2.16)$$

$$a_{mj} = \frac{\Delta x_{ik}}{\sqrt{\Delta y_{kj}^2+\Delta x_{kj}^2}} - y_j \Delta x_{i_k} \times \frac{y_j-y_k}{\sqrt{(\Delta y_{kj}^2+\Delta x_{kj}^2)^3}} \qquad (2.17)$$

For each measured value, an equation of the form (2.14) will be established.

2.3.2. Process standard-directed network data using the least squares method

If the number of measured values is more than the number of unknowns, the system of numerical equations is corrected:

$$A.Y + \Delta = V \qquad (2.18)$$

with $V^T = [v_1 \quad \cdots \quad v_n]_{1\times n}$ $\qquad \Delta^T = -[\Delta_1 \quad \cdots \quad \Delta_n]_{1\times n}$

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1t} \\ a_{21} & a_{22} & \cdots & a_{2t} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nt} \end{bmatrix}_{nxt} \qquad Y^T = [Y_1 \quad \cdots \quad Y_t]_{1\times t}$$

The correction of the monitoring point coordinates along the vertical axis is determined by solving the system of equations by the least squares method. Now there is a standard system of equations:

$$A^T A Y + A^T \Delta = 0 \qquad (2.19)$$

Solve the system of standard equations to get the observation point coordinates (y):

$$Y = -(A^T A)^{-1} A^T \Delta \qquad (2.20)$$

Apply this algorithm to program processing and calculate deviation in construction monitoring by standard direction method.

2.5. Establish a base control network according to the standard direction pattern

2.4.1. Theoretical basis

To improve the accuracy of monitoring by the standard direction, a network of standard directions was established. At this time, the standard direction network will consist of 4 points instead of 2 points at the 2 ends.

Figure 2:11:Diagram of the established network in the standard direction

2.5.2. Calculation process

To evaluate the stability of landmarks and network positioning in the basic network data processing problem in the standard direction, the free network adjustment method with the incremental iterative calculation process is shown in the figure. 2.13.

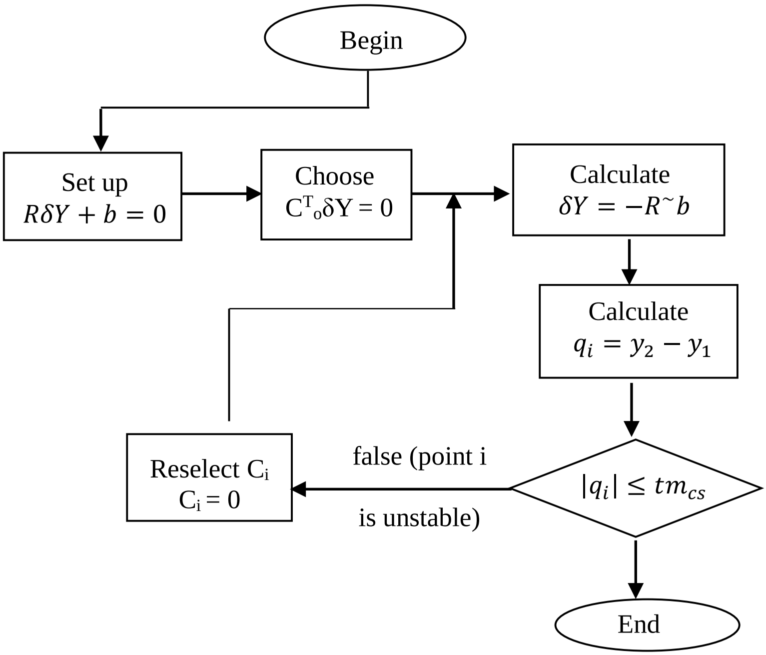

Figure 2. 13: Diagram of basic network data processing

2.6. Horizontal displacement of the rigid bridge according to standard direction monitoring data

2.6.1. Determine the horizontal displacement of the monitoring points

The horizontal displacement of monitoring point m at period i is compared with the first period (period 0) through the following formula:

$$y_m = y_m^{(i)} - y_m^{(o)} \quad (2.40)$$

2.6.2. Horizontal displacement chart, overall bridge displacement assessment

Monitoring n points $X = (x_1, x_2, \ldots x_n)^T$, the horizontal displacement vector in the direction perpendicular to the construction axis $Y = (y_1, y_2, \ldots y_n)^T$, the surface will be established. transverse displacement is the curve of G.

Approximate (G) by a line (L) such that the sum of squares of deviations of the vertices of G from the line L is the smallest $[V_q^2] \rightarrow Min$, then L is called the probability horizontal displacement line.

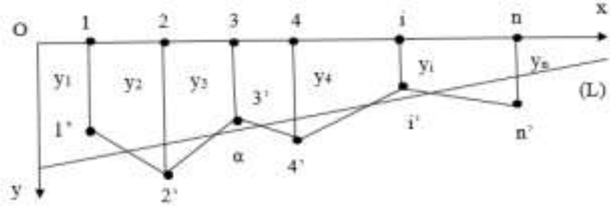

Figure 2. 15: Horizontal displacement parameters

The equation of the line L is written in the form:

$y_i = a.x_i + b$ (with a = tg α) (2.41)

α: The angle of inclination of the line relative to the horizontal

b: Horizontal displacement value of the building at the origin

Conclusion of chapter 2

Proposing a general standard direction measurement scheme and applying the least squares method to process the standard direction measurement data according to this diagram in the monitoring of the rigid structure's bridges' horizontal displacement.

Chapter 3

RESEARCH ON THE APPLICATION OF GNSS - RTK IN CATALOG AND ANALYSIS OF CABLE STAY DISPLACEMENT

3.1. Monitoring the structure of cable-stayed bridges

3.2. Application of GNSS-RTK in bridge displacement monitoring

3.3. Research and evaluate the accuracy of cable-stayed bridges ' vertical displacement monitoring by GNSS-RTK in Vietnam conditions

3.3.1. Monitoring vertical displacement of the cable-stayed bridge by GNSS-RTK method

The height difference measured by GNSS-RTK of a point at two different times considered equal to the standard difference or the resulting amplitude of oscillation (the difference in height of a point at different times of measurement) will not be affected by altitude anomalies [45].

3.3.2. Application of moving average in GNSS-RTK data noise filtering

The moving average value of the displacement measurement result [25]:

$$x = (l_t + l_{t-1} + l_{t-2} + \cdots + l_{t-n+1})/n \qquad (3.4)$$

x is the moving average at time t; lt is the measured displacement value at time t; n is the number of times for calculating the moving average.

3.3.3. Research and evaluate the accuracy of the GNSS-RTK method in vertical displacement monitoring of cable-stayed bridges

3.3.3.1. Evaluation of the GNSS-RTK accuracy in the bridges‘ vertical displacement monitoring – in case the bridge is not open to traffic

To evaluate the accuracy of GNSS-RTK vertical displacement data, the GNSS bridge oscilloscope is compared with the data measured on the slide. The slide is 60cm long, has a precise mm marking, is mounted on a tripod, and can be moved vertically using a handwheel. Before measuring, the slide has been tested and considered to be error-free. The rover is mounted on a slide and is located at specific points of the bridge. At each position of the slide, the machine has received a signal for a certain period of time, and at the same time reads the value on the ruler. GNSS - RTK measurement results are the elevation values of a monitoring point at the positions of the ruler. Next, determine the vertical difference between the value on the slide and the difference in height of a point at two consecutive measurement times. The result measured by GNSS-RTK is the height of a monitoring point at different measurement times, which is evaluated for accuracy according to the following factors:

a. Mean square error of altitude difference of a monitoring point at two consecutive times

The square error of the height difference of a point at two consecutive measurement times is calculated according to the following steps:

+ Average height of GNSS - RTK value at each position of the slider:

$$H_{tb} = \frac{[H_i]}{n} \tag{3.5}$$

H_i: GNSS – RTK height at the i measurement; n: number of monitoring

+ Difference in height of a point at two consecutive measurement times:

$$\Delta H_{(j-1,j)} = H_{tb(j)} - H_{tb(j-1)} \tag{3.6}$$

H_{tbj}, $H_{tb(j-1)}$: Average height at position (j), (j-1) when sliding the ruler.

+ The difference between the measured value on the slide and the difference in height of a point:

$$\Delta D_{(j-1,j)} = D_{ruler(j-1,j)} - \Delta H_{(j-1,j)} \tag{3.7}$$

+ The mean square error is calculated according to the Gauss formula:

$$m_{\Delta H} = \pm\sqrt{\frac{[\Delta D \Delta D]}{t}} \tag{3.8}$$

b. Mean square error of measurement at each time point

- To calculate the mean square error of a measurement, calculate the correct number of the measurement result:

$$v_i = H_{tb} - H_i \tag{3.9}$$

- Determine the mean square error of measurement [4]:

$$m_H = \pm\sqrt{\frac{[vv]}{n-1}} \quad \text{Với n là số lần đo} \tag{3.10}$$

c. Determine the square error of a single in double measurements

When the double measurements are measured independently and with the same accuracy, the range of measurement results is described as follows: $\mathrm{H_1(H_1', H_1''), H_2(H_2', H_2'') \ldots H_n(H_{n1}', H_{n1}'')}$

The error of height difference of a point when measuring away and back:

$$d_i = H_i' + H_i'' \tag{3.11}$$

H'_i, H''_i: Height difference of a point when measuring away and back

The mean square error of each measure in the double measure is calculated

$$m_H = \pm\sqrt{\frac{[dd]}{2n_1}} \quad (n_1 \text{ is the number of double-measure pairs}) \tag{3.12}$$

After calculating the mean square errors, compare the calculated mean square error with the allowed error to conclude the accuracy of the results of the bridge displacement monitoring by GNSS-RTK. The permissible error is 1/10 to 1/20 of the allowable displacement value [7]. The allowable displacement value is taken from the work design.

3.3.3.2.Evaluate the GNSS – RTK accuracy in vertical displacement monitoring of cable-stayed bridges – in case the bridge under operation

When vehicles move on the bridge, the vertical point between the main span of the cable-stayed bridge often fluctuates greatly and continuously, so the moving average value with the time-series is selected to calculate the average value of the measurement results.

-The moving average is calculated according to the formula (3.4).

-The correction number of the measurement result is calculated:

$$v_t = x - l_t \qquad (3.13)$$

-The accuracy of the measurement results is evaluated by determining the mean square error of a measurement according to the formula (3.10).

-The accuracy of GNSS-RTK is evaluated by comparing the mean error of displacement with the allowed error.

3.4. Organize monitoring and establish a monitoring database of cable-stayed bridge structures

3.4.1. Monitoring organization and establishment of bridge structure monitoring database

3.4.2. Operation process of the SHM system

3.5. Artificial Neural Network (ANN) and its application in establishing the displacement model of cable-stayed bridges

3.5.1. The concept of artificial neural network

3.5.2. Structure of artificial neural network

The structure of an ANN is determined by: the number of layers, the connections between neurons, and the number of neurons per layer. Based on the number of layers, it can be classified into single-layer and multi-layer networks; Or based on the connection between the layers in the network, it is divided into Feedforward neural network, Recurrent neural network.

Figure 3.24 is a multi-layer feedforward neural network model (input layer, output layer, hidden layer).

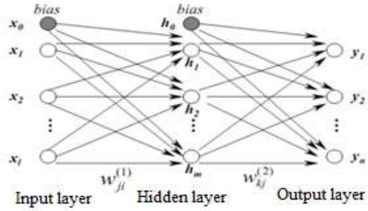

Figure 3. 24: Model of 3-layer feedforward neural network

Neural networks can have more than one hidden layer. However, a single hidden layer is enough for the ANN to compute with any complexity of the non-linear function [23], [37], [56]. The number of neurons in the hidden layer depends on factors such as the number of inputs, the output of the network, the noise of the desired output data, the objective function, the network architecture, and the training algorithm.

3.5.3. Training artificial neural network

Finding the optimal weight must be based on the learning algorithm which is divided into supervised learning and unsupervised learning.

- Supervised learning: The network is trained on a set of samples (pairs of input samples x and actual output d). The difference between the actual outputs and the computational output of the network is used by the algorithm to adjust the weights.
- Unsupervised learning: The training process does not compare with the actual output to show whether the output of the network is true or false.

3.5.4. Back-propagation algorithm

3.5.4.1. Objective function

The most used objective function according to the following formula [6]:

$$E = \frac{1}{2}\sum_{i=1}^{n}(d_i - y_i)^2 \quad (3.20)$$

d_i, y_i: are the actual output and the calculated output data of the network.

3.5.4.2. Back-propagation algorithm (BP algorithm)

BP algorithms and supervised learning are commonly used in multi-layer feedforward neural networks. The BP algorithm will perform two steps of information transmission as follows: First, the input signal x_i is transmitted from the input to the output generating signal y_i. Then the difference between the actual data (d_i) and the calculated output data (y_i) is transmitted back from the output layer back to the previous layer to adjust the weights so that the new set of weights makes the objective function E smaller. The process of finding this set of weights is repeated until the objective function reaches the minimum value.

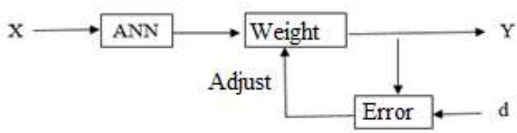

Figure 3.26: Back-propagation process diagram

Based on the above algorithm principle, the back-propagation algorithm is implemented according to the diagram (3.28 Figure).

3.5.4.3. Indicators to evaluate the accuracy of training results ANN

To evaluate the accuracy of ANN training results and displacement modeling results, the following indexes are commonly used [23]:

Mean Square Error:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - d_i)^2 \quad (3.40)$$

Root Mean Square Error:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - d_i)^2}{n}} \quad (3.41)$$

Mean Absolute Error:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - d_i| \quad (3.42)$$

with y_i: Output value from ANN; d_i: Actual output value

Coefficient of determination:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(d_i - y_i)^2}{\sum_{i=1}^{n}(d_i - \bar{d})^2} \quad (3.43)$$

$\bar{d}$: Average actual output value

If the MSE, RMSE, and MAE Errors are smaller, the ANN training results will be better and vice versa. With the coefficient of determination, if the R^2 value is larger, the accuracy of the displacement model will be better.

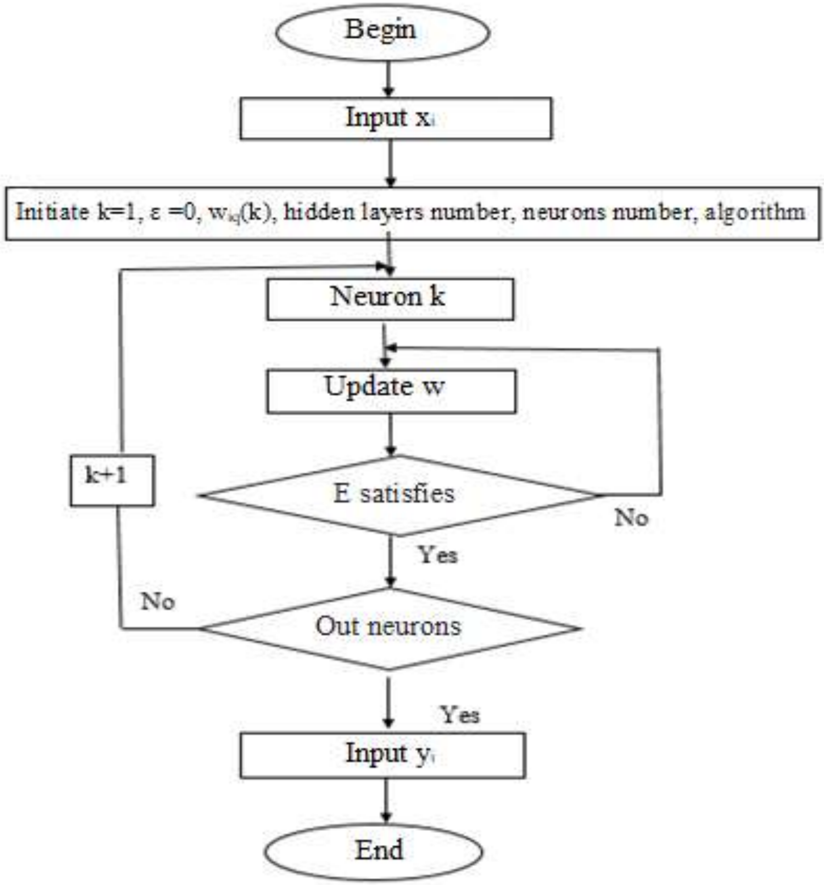

Figure 3.28: Artificial neural network algorithm diagram

3.5.5. ANN application in the establishment of a bridge displacement model

3.5.5.1.General application of ANN

3.5.5.2.Application of ANN in establishing the cable-stayed bridge displacement model

a. Factors affecting the displacement of cable-stayed bridges

The establishment of the cable-stayed bridge displacement model is based on the factors affecting the modeling results. The cable-stayed bridge usually has a long span, small stiffness, plus a high stringing system and tower, so it is sensitive to dynamic loads such as wind, temperature, and live loads of vehicles. Wind velocity and temperature are two environmental factors that greatly influence the displacement of cable-stayed bridges [9], [69]. In addition, the cable-stayed bridge structure is the top of the bridge tower connected to the main girder through cables. These cables are stretched and supported by the main girder. According to documents [42], [43], [69], the vertical displacement of the center main span is also caused by the displacement of the tower tops. Thus, the temperature, the live load of the transport means, and the displacement of the tower top are the main causes of the displacement in the middle of the main span. It will be the input data for the process of establishing the displacement model of the mid-span point.

b. Application of artificial neural networks (ANN) in establishing the cable-stayed bridge displacement model

To determine the bridge state based on a lot of observed data from many different sensors, data mining techniques are applied. The article [57] proves that ANN is used the most, accounting for 30% of the studies in data processing and analysis. Compared with other methods, ANN has outstanding advantages such as building non-linear models, and very fast computation in processing and analyzing big data. In determining bridge failure, multilayer feedforward ANN is also applied to model and predict bridge oscillations. In determining bridge failure, multilayer feedforward ANN is also applied to model and predict bridge oscillations. Scientific publications [44], [45], [60] have proposed this method to detect bridge failure by modeling the change in natural frequency based on machine measurements accelerometer. With the above advantages, multi-layer feedforward ANN excels in displacement modeling, fault detection, etc.

c. The process of establishing the bridge displacement model by the ANN

The process of building a bridge displacement model follows 3 main steps:

Step 1: Data preparation is done as follows:

-Data collection: To train ANN, the collected data includes temperature, wind, stress, and displacement in the X, Y, and Z directions at the midpoints of the main span, the tower top of the cable-stayed bridge. These data must be measured at the same time and over a long period of time.

- Pre-processing of data: Due to simple calculation and keeping the trend of bridge oscillation, a moving average is applied to filter data noise [70].

- Determine the correlation relationship between displacement in directions X, Y, and Z of the midpoint with wind, temperature, stress, and displacement of the tower top. It is the basis for selecting input variables in the process of establishing the displacement model by ANN.

Step 2: Establish a bridge displacement model

-Designing ANN based on input data, network structure, algorithm, and the most optimal parameters adjusted during training. Then the network is trained by adjusting the link weights. The results of the network training process will display the MSE error and the regression coefficient R^2.

Step 3: Evaluate the spherical displacement model.

To ensure the quality of the bridge displacement model, evaluate the model's accuracy. Based on the MSE, RMSE, MAE, R^2 to determine the best model.

Conclusion of chapter 3

- The GNSS-RTK accuracy in the vertical displacement monitoring of cable-stayed bridges is evaluated based on the factors that are the square error of the height difference at two consecutive times, the square error of measurements at each time, the square error of one measurement in the double measure. These errors are compared with the allowable errors in the cable-stayed bridges' displacement monitoring to evaluate the GNSS-RTK accuracy.

- Research on the application of multilayer feedforward Artificial neural network with backpropagation algorithm in establishing cable-stayed bridge displacement model. At the same time, the process of establishing a bridge displacement model by ANN as well as determining the input data to train the network is temperature, stress, displacement in 3 directions of the mid-span point, the tower top, and selecting the moving average method to filter the data noise.

Chapter 4
EXPERIMENT

4.1. Experimental processing of horizontal displacement monitoring data of Chuong Duong rigid bridge

4.1.1. General introduction about Chuong Duong bridge

This is a rigid and straight bridge, so the standard direction method was chosen to monitor the horizontal displacement of the pier by an electronic total station with $m_\beta = \pm 1.5''$. Requirement accuracy when monitoring ±5mm. The accuracy of the weakest point of the network was ±3.5mm, of the base network ±1.1mm, and the monitoring network ±3.3mm.

4.1.2. Layout diagram of landmarks of the basic control network and monitoring network

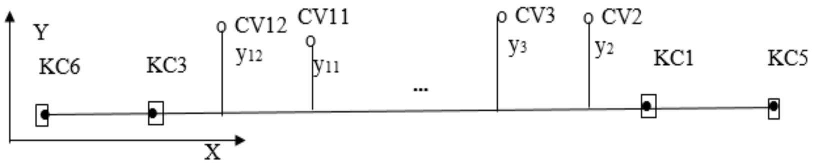

Figure 4.1: Diagram of standard direction of bridge transverse displacement monitoring

Using the general standard directional measurement diagram, the measurement result is the deviation, shown in Table 4.3. Conducted data processing, the results are shown in Tables 4.2, Table 4.3, Table 4.4.

Table 4.2: Result of network accuracy estimation

No	Point	Adjusted coordinates Y(m)	Location error m_Y(m)
1	CV12	200.0132	0.0003
2	CV2	200.0448	0.0009
3	CV3	200.0561	0.0016
…	….	…	…
11	CV11	200.2001	0.0005
12	KC1	200.0391	0.0004
13	KC3	200.0447	0.0001

Table 4.3: Measurement and adjustment of direction deviation

No	Step symbol			Measured value (m)	Correction (m)	Adjusted value (m)
	Machine	Orientation	Measuring			
1	KC5	KC6	CV2	0.0440	-0.0002	0.0438
2	KC5	KC6	CV3	0.0560	-0.0008	0.0552
…	…	…	…	…	…	…
43	KC3	KC5	KC6	-0.0440	-0.0009	-0.0449
44	KC1	KC6	KC5	-0.0412	-0.0006	-0.0418

Table 4.4: Evaluate the offset of the base point coordinates

No	**Point**	**0 cycles coordinates**	**Deviation**	**1 cycles coordinates**	**Evaluation**
1	KC1	200.0403	-0.0012	200.0391	Stability
2	KC3	200.0451	-0.0004	200.0447	Stability
3	KC5	200.0000	0.0011	200.0011	Stability
4	KC6	200.0000	0.0005	200.0005	Stability

Mean square error of unit weight m = ±2.2 (mm)

4.2. Experimental evaluation of the accuracy‘s vertical displacement monitoring of the Bach Dang bridge by GNSS-RTK method

4.2.1. Experiment Description

To evaluate the accuracy of vertical displacement measurements by GNSS - RTK, conduct measurements at Bach Dang cable-stayed bridge. Seeing very small bridge oscillations, Trimble's R8 rover with 1Hz frequency is placed on a slide. GNSS layout diagram includes 1 base station, and 1 rover station located at QT01 and QT02 points, respectively (2 points in the middle of the bridge‘s main span). At each measuring position 1, 2, 3,…, 7 on the slide, the GNSS receives the signal continuously for 5 minutes. According to the bridge design documents, the allowable displacement limit of the main span is ±30cm. The allowable error when monitoring the bridge is selected to be 1/10 of the allowable limit value and equal to ±3cm.

4.2.2. Evaluation of GNSS - RTK accuracy in the Bach Dang bridge‘s vertical displacement monitoring

Calculation results of the mean square error to evaluate data accuracy:

- The mean square error of height difference of one point at two consecutive times at QT01 is ±8 mm. The mean square error at the QT02 point is ±9 mm.
- Mean square error of measurement at each measurement time:

Table 4.8: Elevation mean square error at slider positions (unit: mm)

Location / Point	1	2	3	4	5	6	7	8	9	10	11
QT01	±9	±8	±6	±6	±7	±7	±7	±8			
QT02	±5	±6	±7	±6	±7	±6	±8	±10	±10	±9	±11

- The mean square error of a single measurement is ±5mm.

From that, the values of the squared errors calculated above are all small allowed errors when monitoring the bridge’s vertical displacement.

4.3. Experiment evaluation of the Can Tho bridge‘s vertical displacement monitoring accuracy by GNSS-RTK

4.3.1. Description of the data

The Can Tho bridge has a long main span of 550m, a tower height of 134.7m.

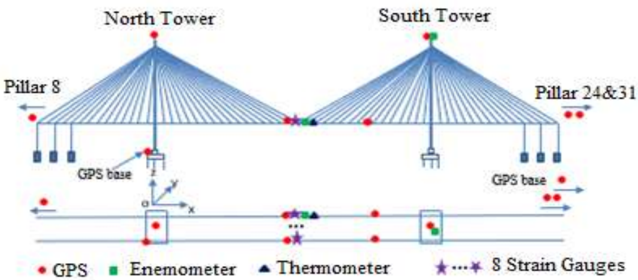

Figure 4. 7: Location diagram of anemometers, temperature, GNSS and stress gauges

The devices for measuring dynamic loads acting on the bridge of SHM such as wind, temperature, stress, and GNSS system using the RTK technique, including 2 base stations and 9 rovers measuring bridge displacement are shown in Figure 4.7. To determine the vertical accuracy, the 1-day main span midpoint displacement observation data (144 data) is calculated.

4.3.2. Evaluation of GNSS-RTK accuracy in displacement monitoring

The square error of a single measurement is ±6mm, which is ±78mm smaller than the allowable error specified in the technical design documents.

Comment: The GNSS - RTK method completely ensures the accuracy of the cable-stayed bridge‘s vertical displacement monitoring.

4.4. Establishment of Can Tho cable-stayed bridge’s displacement model by multi-layer feedforward artificial neural network

4.4.1. Prepare data

- Data collection: Factors such as temperature, wind, stress, and displacement data of the center main span, of the tower top are measured at the same time, and the sampling frequency is every 10 minutes. With continuous measurement time for 07 days, 1008 data of each type is obtained. The data is filtered by moving average, the number of times when calculating the moving average n = 10. Based on the correlation coefficient between the displacement of 1/2 main span point in the X, Y, and Z directions with factors such as Air temperature, wind speed, stress, displacement of the North tower, South tower, and variables with a correlation coefficient greater than ±0.5 will be selected as input data of the ANN training process.

Table 4.10: Correlated coefficients between the center main span and the tower top and environment

Center main span	**Correlated Coefficients (r)**							
	Temperature	**Wind speed**	**North Tower**			**South Tower**		
			X	**Y**	**Z**	**X**	**Y**	**Z**
X	***0.58***	0.25	***0.54***	-0.08	0.05	0.24	-0.13	0.08
Y	0.07	0.02	***0.52***	***0.65***	-0.05	***-0.50***	***0.67***	-0.10
Z	***-0.93***	-0.05	***-0.67***	0.29	-0.18	***0.77***	0.36	-0.31

Table 4.11: Correlated coefficients between center main span and stress data

Center main span	Correlated Coefficients (r)							
	US 1	**US 2**	**US 3**	**US 4**	**US 5**	**US 6**	**US 7**	**US 8**
X	0.09	0.12	0.10	0.19	***0.50***	0.38	0.32	***0.50***
Y	***0.69***	***0.69***	***0.66***	***0.68***	***0.50***	-0.14	-0.25	0.13
Z	-0.14	-0.20	-0.17	-0.33	***-0.93***	***-0.71***	***-0.60***	***-0.88***

So to establish the X direction displacement model of the mid-span point using the data of temperature, stress 5, 8, displacement X direction of the North tower top; in the Y direction put stress data 1, 2, 3, 4, 5, displacement in the X, Y directions at the North tower top, the South tower top; with the Z direction, the data of temperature, stress 5, 6, 7, 8, displacement of the X direction of the North, the South tower top are used.

4.4.2. Establishing the displacement model between the main span

- Design a network with a sigmoid nonlinear training function, supervised learning, and a back-propagation training algorithm. Measurements of temperature, stress, and displacement of the North tower top and the South tower top are input data. The output layer is the displacement value in the longitudinal, horizontal, and vertical direction of the cable-stayed bridge‘s center main span.

Summary of accuracy when training ANN has Table 4. 14 as follows:

Table 4.14: Results of training the artificial neural network

Displacement Direction	X	Y	Z
R^2	0.962	0.995	0.997
MSE (m^2)	$5x10^{-7}$	$4x10^{-7}$	$5x10^{-6}$

The MSE error of the X, Y, and Z directions is very small, approximately zero, and the determination coefficient of the three directions is large, approximately equal to 1. It shows that the training results are very good.

- Establish a cable-stayed bridge displacement model of the center main span in the X, Y, and Z directions in one day using ANN with corresponding input data such as temperature, a live load of vehicles, displacement of the North

tower top, and the South tower top. The output results are the values of the mid-span displacement model of the bridge in all three directions. The results of the displacement model of the cable-stayed bridge‘s center main span in the X, Y, and Z directions are shown in Figures 4. 14, 4. 15, 4. 16.
From Figures 4.14, 4.15, and 4.16, the deviation between the displacement model result and the GNSS-RTK measurement result is quite small.

Figure 4. 14: The establishment results of the X displacement model

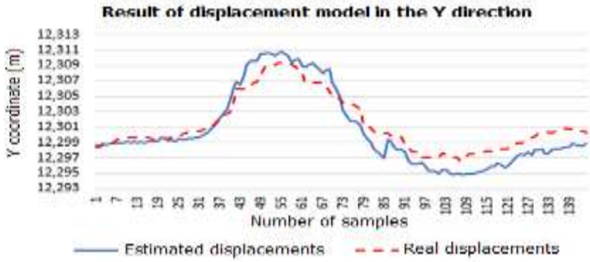

Figure 4. 15: The establishment results of the Y displacement model

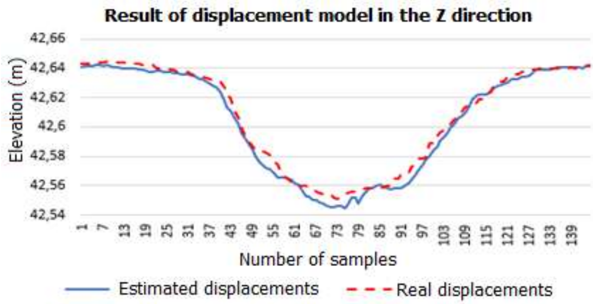

Figure 4. 16: The establishment results of the Z displacement model

4.4.3. Evaluation of the bridge displacement model's accuracy

The accuracy of the bridge displacement model is shown in Table 4.18.

Table 4. 18: Accuracy assessment by RMSE

Direction	**X**	**Y**	**Z**
RMSE (m)	±0.002	±0.002	±0.003

According to Table 4.18, the mean square error when establishing the displacement model of the bridge main span in three directions is small.

Comment: ANN can be used to model the displacement of the cable-stayed bridge based on factors such as temperature, the live load of vehicles, and displacement of the North and South towers top.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

To improve efficiency in bridge displacement monitoring, mainly to improve accuracy, the research content of the thesis has the following conclusions:

1. The application of a general standard direction diagram and data processing according to this diagram by the least squares method allows for improving the accuracy of the standard direction method and at the same time, the application of this method is convenient and flexible when monitoring the horizontal displacement of the rigid bridge.
2. From the results of theoretical research and experimental calculations shows that GNSS - RTK completely meets the accuracy requirements in vertical cable-stayed bridge displacement monitoring, and Z-direction monitoring data has enough reliability for processing, analysis, evaluation, and forecast of cable-stayed bridge displacement.
3. The correlation relationship between stress and point displacement between the main span in all 3 directions was determined in the thesis, thereby determining the traffic load, one of the main causes causing the shift of the center span of the main span. in the Y and Z directions. It is also an

important input of the ANN training process in establishing the cable-stayed bridge displacement model.

4. Due to its high accuracy and reliability (R^2 is greater than 0.962, RMSE error is less than ±0.003m), ANN is applied to model the continuous displacement of the cable-stayed bridge under the influence of temperature, traffic dynamics, displacement of bridge tower tops.

RECOMMENDATIONS

1. Widely apply the standard direction method with a general measurement diagram in the monitoring of the rigid bridge‘s horizontal displacement in Vietnam.

2. Continue to study and process data of cable-stayed bridge displacement monitoring, including in-depth research on filtering noise from GNSS-RTK data to provide reliable data for analysis of the displacement bridge.

3. Proposing agencies and departments to soon have legal documents stipulating accuracy requirements, the selection of types and quantities of equipment, how to design and install machines, measurement methods, processing, calculating, and analyzing bridge displacement data.

SCIENTIFIC WORKS OF Ph.D. STUDENT PUBLISHED RELATE TO THE CONTENT OF THE THESIS

1. H. L. T. Ho, H. V. Le, L. T. Nguyen, (2017), "A Study on Accuracy Evaluation of GPS Vertical Monitoring Outcomes on Main Span of Can Tho Bridge, Vietnam", *The 8th International Conference on Structural Health Monitoring of Intelligent Infrastructure Brisbane, Australia*, pp. 60-67.

2. Thuy Linh Nguyen, Van Hien Le, Minh Ngoc Le, Duc Cong Tran, (2018), "Accuracy assessment of displacement measurements of cable-stayed bridge using GPS-RTK technology", *International Conference on Sustainability in Civil Engineering, Hanoi, Vietnam*, pp.351-354.

3. Khanh Tran, Thuy Linh Nguyen, Kim Thanh Nguyen, (2018), "Study on applying right-angled direction method in Chuong Duong bridge's horizontal displacement monitoring", *Earth Sciences and Natural Resources for sustainable development*, pp. 22-28.

4. Thuy Linh Nguyen, Lan Huong Ho, Van Hien Le, Duc Hai Le, (2018), "Study to evaluate the accuracy of vertical cable-stayed bridge displacement monitoring data by GPS – RTK measurement technique. *Transport and Communications Science Journal* (67), pp. 41-48.

5. Thuy Linh Nguyen, Lan Huong Ho, Van Hien Le, Duc Hai Le, (2018), Study to evaluate the accuracy of vertical cable-stayed bridge displacement monitoring data by GPS – RTK measurement technique, Summary report of the grassroots scientific research project, Code T2018-CT-043, University of Transport and Communications.

6. Thuy Linh Nguyen, Lan Huong Ho, Huu Hung Nguyen (2019), "Research and application of artificial intelligence (AI) to build a

model to predict vertical displacement of cable-stayed bridges". *Transport and Communications Journal*, 12/2019, pp. 72-77.
7. Thuy Linh Nguyen, Huu Hung Nguyen, (2020), "Application of Artificial Neural Network for recovering GPS - RTK data in the monitoring of cable-stayed bridge deformation", *Structural Health Monitoring and Engineering Structure Select proceedings of SHM&ES 2020, Lecture Notes in Civil Engineering*, ISBN 978-981-16-0945-9, pp. 63-76.
8. Tinh Duc Le, Hien Van Le, Linh Thuy Nguyen, Thanh Kim Thi Nguyen, Duy Tien Le, (2020), "Application of correlation and regression analysis between GPS – RTK and environmental data in processing the monitoring data of cable-stayed", *Journal of Mining and Earth Sciences*, 6(61), pp. 59-72.
9. Thuy Linh Nguyen, Lan Thi Huong Ho, Huu Hung Nguyen, Van Hien Le, (2021), "Research on application of neural network to recover GNSS data in cable-stayed bridge displacement monitoring", *Transport and Communications Journal*, 11/2021, pp. 67-71.
10. Thuy Linh Nguyen, Lan Thi Huong Ho, Huu Hung Nguyen, Van Hien Le, (2021), Research on application of artificial intelligence (AI) to recover GPS - RTK data in cable-stayed bridge displacement monitoring in Viet Nam, Summary report of the grassroots scientific research project, Code T2021-CT-033, University of Transport and Communications.