APPRAISAL AND PERFORMANCE PREDICTION OF SENAI DESARU EXPRESSWAY CABLE-STAYED BRIDGE SUBJECT TO EARTHQUAKES

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DEDICATION

I dedicate with love and gratitude
To my beloved God, Allah S. W. T.,
Akhawatifillah fid Dakwah,
My husband Mohd Ammar Abu Kassim,
My parents Aizon bin Rahman and Che Wah binti Shafiei,
My siblings, and My in-law Family
For being with me till the very end of my thesis completion

Hopefully this research will be beneficial for the Ummah, Insya-Allah!

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ABSTRACT

Application of cable-stayed bridge types in Malaysia is getting higher demands by the developer due to its cost-effectiveness. However, its high flexibility and low damping behaviour may exhibit a critical response due to earthquake loads. In addition, there are challenges for the bridge authorities to decide the severity of bridge condition in post-earthquake events. Therefore, the objectives of this research are, (i) to assess the seismic performance of a cable-stayed bridge under the earthquake time history loading in terms of dynamic behaviour and acceleration response, (ii) to establish fragility curves as guidelines of potential damage level of the cable-stayed bridge components under various earthquake loadings, and (iii) to investigate the applicability of Artificial Neural Network (ANN) as a prediction tool of damage level for cable-stayed bridge's intelligent decision-making tool in Bridge Health Monitoring System (BHMS). The seismic performances of cable-stayed bridge were obtained by developing the 3D Finite Element Model (FEM). Two types of seismic analyses were implemented in this research, Free Vibration Analysis (FVA) and Non-Linear Time History Analysis (NTHA). Earthquake loads scaled to Peak Ground Acceleration (PGA) with low, moderate, and strong earthquake loads were utilised. The obtained results from the NTHA was then fed to the Feedforward Artificial Neural Network model to obtain a damage level prediction model for the cable-stayed bridge. The acceleration data of structure response were used as input in the ANN model. Meanwhile, the output of training network used the damage levels from the analysis which were Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). Data used for the ANN training was 70% of total data, while data used for testing and validation were 15% of the whole data, respectively. The results showed that the proposed artificial intelligent prediction model could provide prediction of up to 83.54% rate of accuracy and the least mean squared error of 0.1549. Next, the fragility curves of each component subjected to earthquake time history parameter were determined. Scaling factors for 14 time histories were calculated to generate IDA curves, which were needed to develop fragility curves. The pushover analysis and NTHA also needed to build the IDA curve. From the fragility curves, it was concluded that different bridge components have different probabilities of damage level occurrence due to specified earthquake time history parameters. This research was verified using on-site modal testing to compare the modal parameter with the FEM. The studied dynamic behaviour of cable-stayed bridges, as well as damage assessment through fragility curves and ANN approach, will greatly assist authorities in maintaining the structural integrity of their bridges by detecting and predicting the likelihood of damage under earthquake loads.

ABSTRAK

Aplikasi jenis jambatan kabel-penahan di Malaysia mendapat permintaan yang lebih tinggi oleh pemaju kerana keberkesanan kosnya. Walau bagaimanapun, kelenturannya yang tinggi dan tingkah laku redaman yang rendah mungkin menunjukkan tindak balas kritikal kerana beban gempa. Di samping itu, terdapat cabaran bagi pihak berkuasa jambatan untuk menentukan tahap kerosakan jambatan dalam kejadian pasca gempa. Oleh itu, objektif kajian ini adalah (i) untuk mengkaji prestasi seismik jambatan kabel-penahan akibat dari beban sejarah masa gempa, dari segi tingkah laku dinamik dan tindak balas pecutan, (ii) untuk membina lengkung kerapuhan sebagai garis panduan untuk jangkaan tahap kerosakan komponen jambatan kabel terhadap pelbagai muatan gempa demi, dan (iii) untuk menyelidik kebolehgunaan Rangkaian Saraf Buatan (ANN) untuk meramalkan tahap kerosakan jambatan kabel-penahan sebagai alat membuat keputusan pintar dalam BHMS. Prestasi seismik jambatan kabel penahan diperoleh dengan membina Model Elemen Terhingga 3D (FEM). Dua jenis analisis seismik yang dilaksanakan dalam kajian ini adalah Analisis Getaran Bebas (FVA) dan Analisis Sejarah Masa Bukan Linear (NTHA). Beban gempa yang diskalakan dengan Pecutan Tanah Maksima (PGA) rendah, sederhana, dan kuat digunakan. Hasil yang diperoleh dari NTHA kemudian dimasukkan ke Model Rangkaian Saraf Suap-Hadapan untuk mendapatkan model ramalan tahap kerosakan untuk jambatan kabel-penahan. Data tindak balas pecutan struktur digunakan sebagai input dalam model ANN. Sementara itu, output untuk latihan ANN adalah tahap kerosakan dari analisis iaitu ringan (IO), sedang (LS), dan teruk (CP). Data yang digunakan untuk latihan ANN adalah 70% dari jumlah data, sementara data yang digunakan untuk pengujian dan pengesahan masing-masing adalah 15% dari keseluruhan data. Hasil kajian menunjukkan bahawa model ramalan cerdas buatan yang dicadangkan dapat memberikan ramalan kadar ketepatan sehingga 83.54% dan ralat kuasa dua min terendah adalah 0.1549. Seterusnya, lengkung kerapuhan setiap komponen yang dikenakan parameter sejarah masa gempa ditentukan. Faktor penskalaan untuk 14 sejarah masa dikira untuk menghasilkan lengkung IDA, yang diperlukan untuk membina lengkung kerapuhan. Analisis pushover dan NTHA juga diperlukan untuk menghasilkan lengkung IDA. Menuju lengkung kerapuhan, dapat disimpulkan bahawa komponen jambatan yang berlainan mempunyai kebarangkalian tahap kerosakan berlainan kerana parameter sejarah masa gempa yang ditentukan. Kajian ini disahkan menggunakan pengujian modal di lokasi untuk membandingkan parameter modal dengan FEM. Tingkah laku dinamik kajian jambatan kabel-penahan, serta penilaian kerosakan melalui lengkung kerapuhan dan pendekatan ANN, akan lebih membantu pihak berkuasa dalam mengekalkan integriti struktur jambatan mereka dengan mengesan dan meramalkan kerosakan terhadap beban gempa.

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LIST OF ABBREVIATIONS

ANN	-	Artificial Neural Network
CP	-	Collapse Prevention
FEM	-	Finite Element Method
FFA	-	Feed Forward Algorithm
FVA	-	Free Vibration Analysis
GA	-	Genetic Algorithm
IDA	-	Incremental Dynamic Analysis
IO	-	Intermediate Occupancy
LM	-	Levenberg Marquardt
LS	-	Life Safety
MMD	-	Malaysian Meteorology Department
MSE	-	Mean Squared Error
NDA	-	Nonlinear Dynamic Analysis
NGA	-	Next Generations Attenuation
NSA	-	Nonlinear Static Analysis
NTHA	-	Nonlinear Time History Analysis
PBSD	-	Performance Based Seismic Design
PEER	-	Pacific Earthquake Engineering Research
PGA	-	Peak Ground Acceleration
PGV	-	Peak Ground Velocity
POA	-	Pushover analysis
SDE	-	Senai Desaru Expressway
SHM	-	Structure Health Monitoring
UTM	-	Universiti Teknologi Malaysia

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Bridges are essential parts of urban infrastructure that play a vital role in the development of an effective transport network around the globe. They exist in different types and designs where each serves a specific purpose. For instance, the arch, simply supported, simple beam, and cantilever bridges typically connect shorter distances using short to medium bridge spans. Meanwhile, cable-stayed and suspension bridges use longer spans to connect longer barriers. Certain circumstances, such as site geological and environmental conditions, aesthetic value, and economic aspect, also determine the type of bridges that are built. Since the late 20th century, cable-stayed bridges have risen to prominence in major cities around the world. They are the most cost-effective options for engineers when a longer span is required, but the span is short enough that the suspension bridge becomes economically impractical. Figure 1.1 shows the illustrations of basic cable-stayed elements, which consists of span, main span, pylon or tower, stayed cables, and pier. With a longer main span, the bridges can carry a large amount of traffic, consisting of automobiles, trucks, bicycles, and pedestrians, daily.

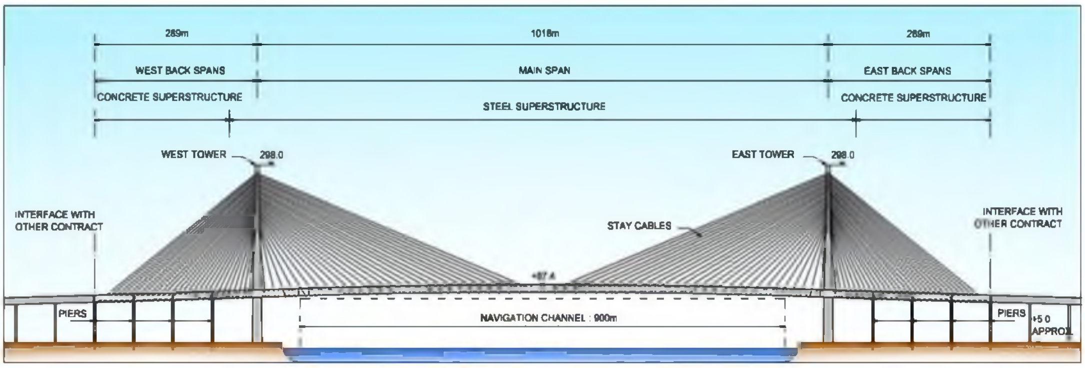


Figure 1.1 Cable Stayed bridge elements,(Sham and Wyatt, 2016)

Usually, continuous usage from the bridge users causes the bridge structure to consequently experience a degradation process during its service life. Besides that, there are several types of loading acting on bridge structures that can induce deterioration phase, as shown in Figure 1.2.

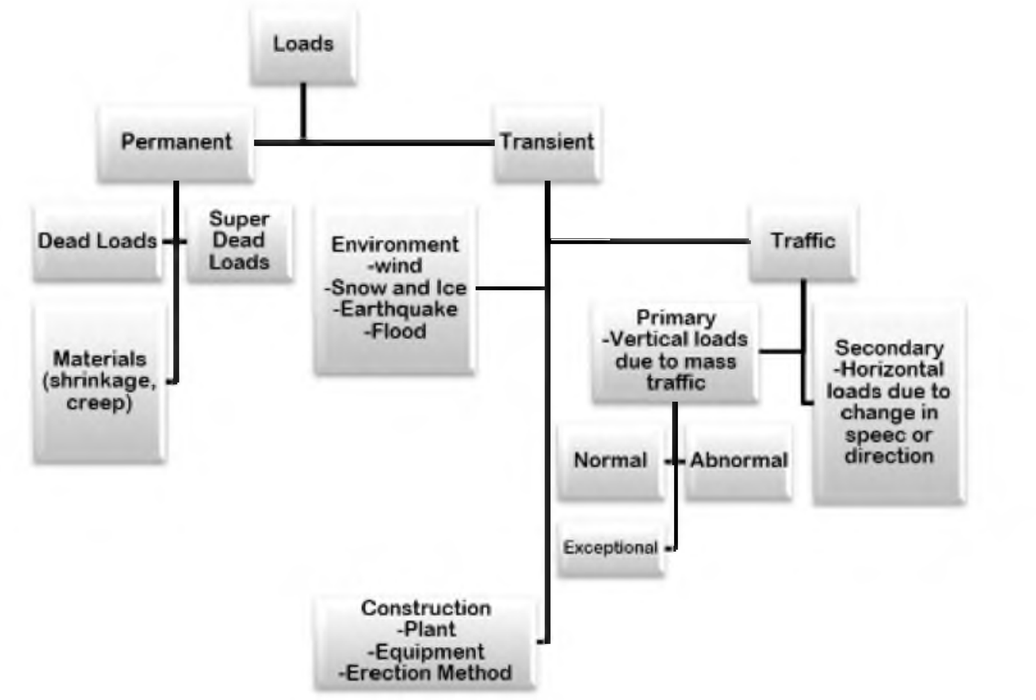
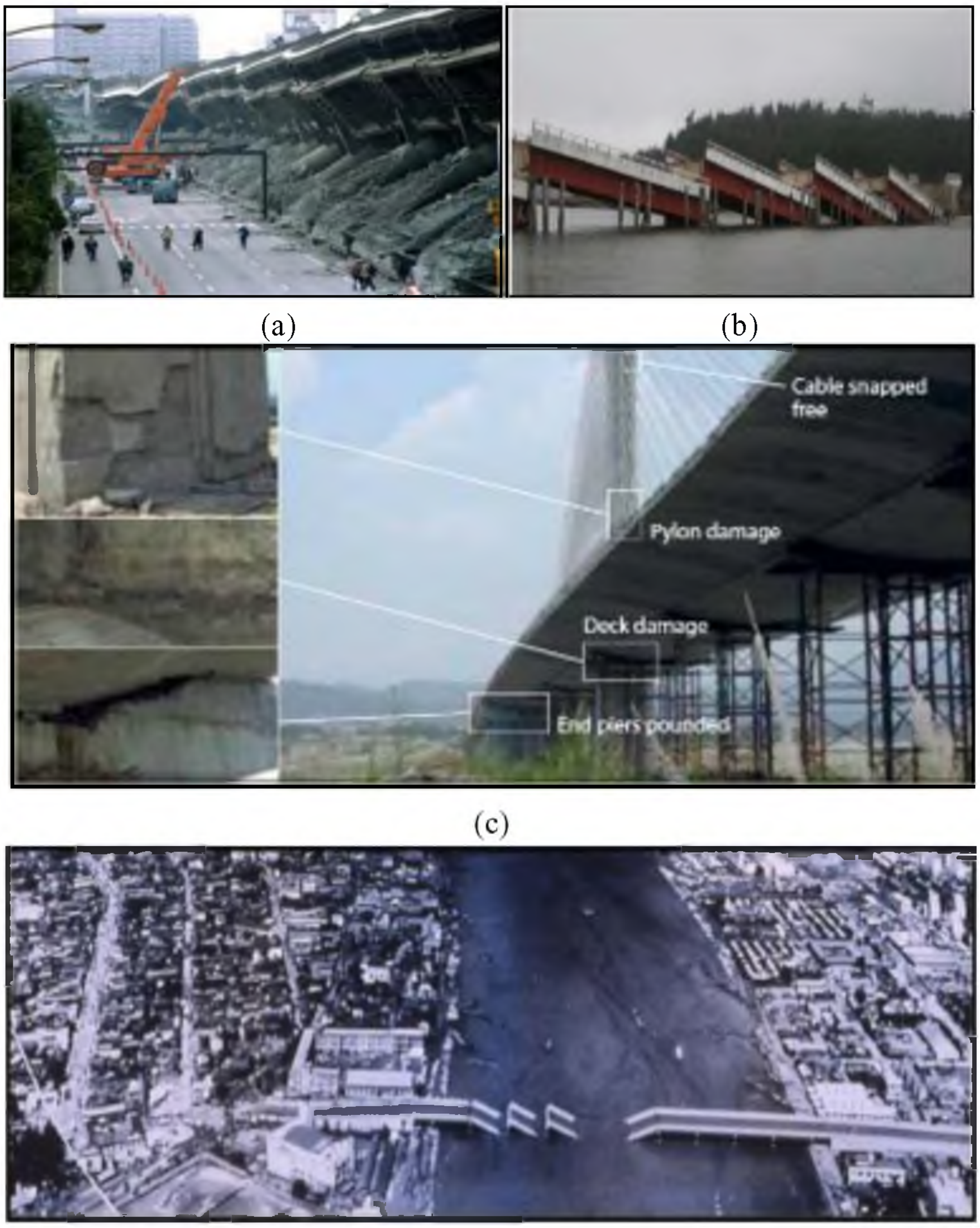


Figure 1.2 Types of loads on a bridge (Ryall, 2009).

It can be seen from the figure that when bridges are often subjected to severe conditions such as earthquakes, some of their critical structural elements, particularly cables, could collapse. In general, earthquake load is known as one of the transient loadings, and its effects are the most disastrous. Figure 1.3 depicts some of the bridge failures due to earthquake loads: (a) Hanshin Expressway failure due to Kobe, Japan earthquake in January 1995 (a) Hanshin Expressway failure due to Kobe, Japan Earthquake in January 1995. (Venton and Writer, 2016), (b) Tubul Bridge failure due to Chile Earthquake on 27th February 2010. (Yen et al., 2011), (c) Chi Lu Cable-Stayed Bridge failure due to Chi-Chi, Taiwan earthquake on 19th September 1999 (Wenzel et al., 2011), and (d) Showa Bridge collapse during the 1964 Niigata Earthquake (Bhattacharya et al., 2014). Overall, these series of bridge failures emphasised the importance of seismic criteria (as a baseline design) and performance updates (throughout the service life) of bridges.



(a) (b)

(c)

(d)

Figure 1.3 (a – d) Bridge failures due to earthquake loads

During the San Fernando earthquake in 1971, the most disastrous damage occurred to the overpass structures at three major interchanges in the region of strong shaking. A total of 42 bridges were tremendously affected by the tremors. As a result, the National Earthquake Hazard Reduction (NEHRP) was established in 1977 by the US Congress after the earthquake event (Sims, 2000). Meanwhile, the Kobe earthquake in 1995 affected up to 325 bridges, out of which about 27 were severely damaged, as reported by the Japan Road Association (JRA). During this tremor, the famous Shinkansen railway and three expressways were completely interrupted by some collapsed viaducts (Wang, Zhu and Cui, 2017). During this tremor, the famous Shinkansen railway and three expressways were completely interrupted by some collapsed viaducts (Wang, Zhu and Cui, 2017). Known as the greatest earthquake of September 21, the Chi-Chi earthquake caused a number of bridges to collapse in the central region of Taiwan, while several others underwent structural damages. Finally, during the Loma Prieta earthquake on October 17, 1989, the two Caltrans-designed structures were severely damaged, a segment of the San Francisco-Oakland Bay Bridge was knocked down, and a long section of the double-deck Cypress viaduct in Oakland was devastatingly demolished (Sims, 2000). It was reported that 41 people were killed due to the collapse of Cypress viaduct structures (ims, 2000).

In Malaysia, the construction of cable-stayed bridges to connect two significant locations across the stream, rivers, and ocean has increased. For example, the Langkawi Sky Bridge, Muar Second Bridge, Penang Bridge, Prai River Bridge, Seri Saujana Putrajaya Bridge, Seri Wawasan Putrajaya Bridge, Sultan Abdul Halim Muadzam Shah Bridge, and Senai Desaru Bridge. The Senai Desaru Bridge, for instance, was built as an expressway bridge across a significant distance (500 m) of Johor River. It is also the longest single plane cable-stayed bridge. In general, the cable-stayed bridge structures in Malaysia are not designed to withstand seismic loading but are designed solely for gravity loading. As reported by Ramli and Adnan, (2016), in Malaysia, only two bridges have considered the long-distant earthquake effect in their baseline designs: the Penang Bridge, which officially started to operate for public on 14th September 1985, and the Second Penang Bridge, which has a total length of 13.5 km, making it the longest bridge in Malaysia to apply seismic design criteria.

Even though Malaysia is not in the Pacific Ring of Fire and the chances of earthquake occurrence are remote, there is still a possibility of moderate to strong earthquakes hitting Malaysia (Noorliza Lat and Ibrahim, 2009 and Abas, 2001). Malaysia is considered at risk because it is surrounded by active and moderately active tectonic plates, with the highest threat from far-field ground motion from Sumatera earthquakes (Adnan, Marto and Hendriyawan, 2004). Moreover, Peninsular Malaysia is situated about 400 km from Sumatera and is a neighbour to Borneo, which are regions of the Pacific Ring of Fire with high seismic activities. Thus, theoretically, the high magnitudes of seismic waves from the Sumatran earthquake would shake the structures that have high natural period including long bridges and high-rise buildings in Penang, Kuala Lumpur, Putrajaya, and Johor Bahru. In November 2007, Peninsular Malaysia felt a series of tremors in Bukit Tinggi, recorded by the Malaysian Meteorological Department's seismic stations, which ranged in local magnitude from 2.5 to 3.5 (Noorliza Lat and Ibrahim, 2009). Therefore, seismicity in Malaysia is categorised as low to moderate, with uncommon damaging earthquakes. However, in recent years, East Malaysia (Sabah) has witnessed a rise in low to moderate seismic events due to a few active local fault lines, including Belait, Crocker, Jerudong Fault, Mensaban, Mulu, and Pegasus Tectonic Line (Harith and Adnan, 2017).

The importance of monitoring the existing bridges in Malaysia should not be disregarded since the structures' vulnerability to earthquake tremors can cause catastrophic damages. Therefore, a substantial study on a long cable-stayed bridge's vulnerability is essential to understand the potential seismic responses under earthquake loading. At present, numerous finite element models have been developed to assess the seismic response of bridge structures. However, little work has been carried out to understand the seismic response of cable-stayed bridges. A common approach for evaluating bridge seismic vulnerability is the generation of vulnerability function in the form of fragility curves. Fragility curve is a conditional probability that gives a likelihood in which a structure will meet or exceed a specified damage level for a given ground motion intensity measure. It is a useful tool for estimating the extent of structural damage of a specified bridge and assessing the capacity of a bridge structure under the earthquake load. Furthermore, fragility study is crucial to identify the vulnerable parts of a bridge structure. Hence, this type of bridge assessment could provide beneficial information to bridge authorities when deciding on retrofitting and other rehabilitation works.

Meanwhile, a properly structured health monitoring of long cable-stayed bridges is crucial since an earthquake event would not only threaten the users, but also cause economic losses. Regular monitoring, like site inspection, is thereby required, but it is highly challenging and costly for large-scale bridges because of the high complexity of their structure. Generally, inspection is essential for ensuring safety, maintaining inventory, and collecting statistics on planning in Malaysia. Robert and King (1984) highlighted the importance of inspection and strength assessment of existing bridges in Malaysia. The study noted that the scheduled inspection carried out by qualified personnel and assisted by design data, including drawings of structure, is necessary to get proper results for future road planning and upgrading. The results of inspection provide useful data for bridge authorities and designers to resolve the recurrent causes of problem. Later on, Public Works Department (PWD) performed a series of bridge inspection studies. King, Heng and Mahamud (2000) reported on the study of Annual Mandatory Bridge Inspection (AMBI) from bridge inspections done from 1995 to 1998. The study highlighted the Working Committee of Bridge Inspection formed under the Road Engineers Association of Malaysian (REAM) to develop National Guidelines for Bridge Inspection. The inspection guide was based on PWD's work of practice and has been adopted by all the bridge agencies in the country and has become a national guide for bridge inspection by default (Ng and King, 2010).

Apart from the lack of regular inspection implementation as the effort to monitor bridge conditions in Malaysia, poor decisions (resulting from the lack of proper information), the conventional inspection method is also suffered from inconsistence results due to subjective judgement by the inspectors. Therefore, the application of intelligent bridge assessment method is able to ensure the overcome the problem. As for bridge health monitoring system, some critical decisions are necessary to be precise (for example, the current extent of damage). In essence, the current condition of a bridge should be given the highest priority to ensure its safety and serviceability to the bridge's users. In recent years, the neural network has been widely applied as a decision support algorithm for various ranges of civil engineering problems. The decision-making tools are needed to improve the accuracy of decisions made by a system. The availability of such bridge assessments would help to ensure the safety of bridge users and would also be useful for bridge authorities.

1.2 Problem Statements

Based on the overview and research background discussed in the previous section, there are several problem statements that can be stated as follows:

(i) Application of cable-stayed bridge type in Malaysia is getting higher demands by the developers. Therefore, a few aspects need to be taken into consideration to ensure the safety of bridge users. The important aspect includes the durability, serviceability, structural health, bridge maintenance, and special monitoring of bridges. Limited work has been carried out to study the performance of local structures under various earthquake loads. Thus, the safety of cable-stayed bridge users upon the earthquake effects is neglected.

(ii) Cable bridges are vulnerable to earthquakes due to their high flexibility and low inherent damping. If a cable-stayed bridge collapses in an earthquake or post-earthquake event, it may cause immense loss of life and property. Therefore, the seismic vulnerability of cable-stayed bridges at different levels of damage should be explicitly measured in order to ensure protection.

(iii) Monitoring system equipped with a decision-making tool has not been investigated by researchers in detail. In addition, there are challenges for bridge authority to decide the severity of bridge condition in post-earthquake events. The long cable-stayed bridge usually carries a high traffic load with more users, and the prediction of damage under earthquake loads is thereby important. Thus, this research would help eliminate the difficulty of predicting the damage level of a cable-stayed bridge due to the earthquake load if the conventional method, such as routine inspection, continues to be used.

(iv) The use of a decision tool in machine learning (using MATLAB software) is rather complicated to incorporate in bridge health monitoring systems and requires some modifications before using it in real-time systems. The idea of simplifying intricacies of the tool into equations is thereby crucial.

1.3 Research Objectives

(i) To assess the seismic performance of a cable-stayed bridge under the earthquake time history loading in terms of dynamic behaviour and acceleration response.

(ii) To establish fragility curves as guidelines of potential damage level of the cable-stayed bridge components under various earthquake loadings.

(iii) To investigate the applicability of Artificial Neural Network (ANN) as a prediction tool of damage level for cable-stayed bridge's intelligent decision-making tool in Bridge Health Monitoring System.

1.4 Scopes and Limitations

The outcomes of the study can be affected by several variables and factors involved. Therefore, the scope and limitations should be defined clearly to conduct good experiments as mentioned in the objectives of study. The scope and limitations of this study are:

(i) The case study was the Senai Desaru Expressway (SDE) Bridge, a cable-stayed bridge that is 1708 m long.

(ii) Analysis used was the dynamic non-linear method on CSI Bridge software (version 20). The bridge was analysed based on five earthquake data from Pacific Earthquake Engineering Research (PEER) database and the two time histories were gathered from the Meteorological Department of Malaysia. The local earthquake time histories of Ranau earthquake events, which occurred in June 2015, were obtained from seismic stations in Kota Kinabalu.

(iii) Fragility curves were developed using 14 earthquakes data.

(iv) Damage level occurred was based on Federal Emergency Management Agency (FEMA) 356. The damage levels were Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) and all used Non-Linear Time History Analysis.

(v) Development of damage level prediction on bridge structure used feedforward ANN to train the cable-stayed bridge's data.

(vi) Input data for training the feedforward neural networks algorithm were time series, accelerations, and damage level output from the finite-element modelling results. A total of 16620 data samples were used, in which 70% of the total data was used for the training data, while another 15% was for testing and the rest was for validation. Data was trained using MATLAB Programming software (2013 version) under University Technology Malaysia (UTM) license.

1.5 Organization of Thesis

The study is divided into seven chapters. The content of each chapter is summarised as follows:

Chapter 1: Introduction describes the research background, problem statements, and objectives of this study. The scope and limitations of study, organisation of thesis, and outcome of research to be conducted are explained at the end of this chapter.

Chapter 2: Literature Review discusses the seismic behaviour, and seismic vulnerability of a cable-stayed bridge, and applications of damage prediction model for civil structures. In addition, the chapter provides a review of the available information, research gaps, and answers to the issued problems. The end of this chapter is a summary of the literature works in similar research area.

Chapter 3: Research Methodology explains the step-by-step solution to the problems which is required to achieve the objectives of the study.

Chapter 4: Cable-Stayed Bridge's Seismic Performance and Vulnerability describes the bridge model's response from earthquake excitation data obtained from Pacific Earthquake Engineering Research Centre (PEER) and Malaysian Meteorology Department (MMD). This chapter includes behaviour of the bridge model that was analysed based on non-linear time history analysis to find the bridge acceleration response and the result of vulnerability study of cable-stayed bridge.

Chapter 5: Decision Support Tool Development explains the development of prediction model using ANN. This chapter includes description of the trial-and-error experiments and investigation to get the best model prediction for cable-stayed bridge, and the final damage-level prediction equation based on the weightages and biases obtained by the ANN model.

Chapter 6: Field Modal Testing as Validation explains the field modal testing carried out to validate the finite element method and numerical analysis accuracy. This chapter includes the methods used to execute the testing and results of the field modal parameters.

Chapter 7: Conclusions and Recommendations concludes and summarises the results of previous chapters and explains the advantages of feedforward-backpropagation in bridge monitoring software. The end of the chapter consists of recommendation for further study.

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