NONLINEAR SEISMIC PERFORMANCE OF INTEGRAL PRESTRESSED CONCRETE BOXGIRDER BRIDGE IN MALAYSIA

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Civil Engineering)

Faculty of Civil Engineering
Universiti Teknologi Malaysia

JANUARY 2011

I dedicate with love and gratitude

to my father, mother, brothers and sister,

for being with me till the very end of my thesis completion.

ACKNOWLEDGEMENTS

In the name of Allah, the Most Gracious, the Most Merciful. I am praised to Allah, Lord of the universe for making me able to undertake this research work.

I would like to express my sincere appreciation to my supervisor Prof. Dr. Azlan bin Adnan, and Dato' Prof. Ir. Dr. Ismail Mohamed Taib for their encouragement, invaluable suggestions, earnest guidance, and motivation.

Special thanks to all SEER members and my dear friends; Ir. Dr. Hendriyawan, Patrick, Reni, Reza, Suryana, Sophia, Suhana, Ahmed Budiea, Kikin, Suzana and Uncle Galingan for their help and support and also being my family and friends during my study years.

I am deeply indebted to my father, mother, brothers, sisters, my uncle, Dr. Dasrilsyah Syahrial and Khadijah C. Alih for providing me the peace of mind to pursue knowledge and at the same time being close at hand to render love, comfort and support to achieve and succeed.

Finally, I want to gratefully acknowledge the technical staffs, especially Mr. Amtral, Mr. Azam and Mr Zul from the Faculty of Civil Engineering for their support throughout my experimental work.

ABSTRACT

Currently integral and continuous concrete box-girder bridges are becoming popular system in Malaysia. The problem occurs in such system is the rigidity connection of column and deck will lead to potential hinge failure. In this research, nonlinear seismic performance for this type of bridge was studied by applying soil – pile interaction and fixed base support system. The study covers numerical and experimental approach. The numerical approach has four steps as follows: (1) investigating material properties of integral prestressed concrete box-girder bridge; (2) modelling integral prestressed concrete boxgirder bridge by considering the interaction of structure, substructure and site condition; (3) studying the soil and pile interaction by applying bridge finite element modelling. (4) Validating experimental modelling with Finite element Modelling. As for the result validation, the four steps in the experimental approach involved: (1) scaling the integral concrete box-girder bridge by implementing Buckingham PI theorem; (2) setting the shaking table, shaker controller, LVDT, strain gauge and accelerometer; (3) analyzing finite element modelling of the scaled integral concrete box-girder bridge and (4) Validating the results by comparing the acceleration, displacement of structure response from instrument and finite element modelling. In this study, it was found that the behaviour and response of integral prestressed boxgirder bridge under seismic loading do not reach the yield level for low intensity earthquake. However, for moderate and high seismic intensity, the bridge response reached the yield level but still was under immediate occupancy level. Furthermore, the effect of soil-pile interaction for integral prestressed concrete box-girder bridge showed that the total displacement at the top of pier is 80% higher than fixed base support under longitudinal earthquake direction, while 87% higher under transversal direction. By conducting experimental shaking table test for integral concrete boxgirder bridge model, the seismic bridge response from finite element modelling (numerical approach) presented the approximate behaviour of integral concrete boxgirder bridge under earthquake loading. The findings in this research suggest that seismic loading effects should be considered in the design of integral prestressed concrete box-girder bridge due to higher displacement value compared to the one of the thermal loading.

ABSTRAK

Dewasa ini, jambatan integral dan bersambung gegalang kotak konkrit prategang menjadi pilihan di Malaysia. Namun, kegagalan engsel ekoran sambungan kaku pada tiang dan lantai jambatan sering terhasil. Dalam kajian ini, perilaku seismik tidak linear jambatan integral gegalang kotak konkrit prategang diselidiki dengan mengambil kira keadaan tiang bawah tanah and penyokong dasar tegar. Kajian ini meliputi pendekatan numerikal dan eksperimental. Empat langkah yang digunakan dalam pendekatan numerikal :(1) Menyelidik sifat bahan dari jambatan integral gegalang kotak konkrit prategang; (2) Memodelkan jambatan integral gegalang kotak konkrit prategang dengan mengambilkira hubungkait antara struktur, substruktur dan keadaan tanah; (3) Mengkaji hubungan tanah dan tiang bawah tanah dengan melakukan analisis unsur terhingga terhadap model jambatan. (4) Mengesahkan model hasil ujikaji dengan model kaedah unsur terhingga. Bagi pengesahan hasil kajian, empat langkah telah digunakan: (1) Menjalankan proses pengecilan dimensi jambatan integral gegalang kotak konkrit prategang dengan menggunakan teori PI Buckingham; (2) Menyelaraskan meja gempa, pengendali penggegar, LVDT, meter terikan dan akselerometer; (3) Menganalisis model kaedah unsur terhingga jambatan integral gegalang kotak konkrit yang telah melalui proses pengecilan dimensi; (4) Mengesahkan hasil kajian dengan membandingkan perilaku kecepatan dan pergerakan struktur dari alat pengesan dan model kaedah unsur terhingga. Sifat dan perilaku jambatan jenis ini di bawah beban gempa tidak mencapai takat alah bagi gempa berintensiti rendah. Namun, untuk gempa berintensiti sederhana dan tinggi, perilaku jambatan telah mencapai takat alah meskipun di bawah takat penghunian segera. Daripada kajian ini, pengaruh hubungan tanah dan tiang bawah tanah untuk jambatan ini menunjukkan jumlah pergerakan pada atas tiang melebihi jenis penyokong dasar tegar kira-kira 0.8 kali untuk arah gempa longitudinal dan 0.87 kali untuk arah gempa transversal. Hasil penemuan dalam kajian ini mencadangkan agar pembinaan jambatan jenis ini sebaiknya mengambilkira kesan beban gempa kerana nilai pergerakan yang lebih tinggi berbanding dengan nilai pergerakan disebabkan oleh beban termal.

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$\ddot{D}_n$ - Acceleration at nth mode

$[k]_i$ - Element i global stiffness matrix

DSHA - Deterministic Seismic Hazard Assessment

$[k]_i$ - Element i local stiffness matrix

$\dot{D}_n$ - Velocity at nth mode

ζ - Damping ratio

α_1 and α_2 - Constants that can be obtained based on the damping ratio

g - Gravity = 9.81 m/s^2

gal - cm/sec^2

E - Modulus of elasticity

α_i - Participation factor

$[K]$ - System global stiffness matrix

$[M]$ - System mass matrix

$\{\varphi\}_i$ - Eigenvector i

$\{1\}$ - A unit vector

fb - Flexural tensile strength

$\{F\}$ - Vector of equivalent nodal forces

MPa - Mega Pascal

$\{U_o\}$ - Vector of amplitudes for various degrees of freedom

PGA - Peak Ground Acceleration (at Bedrock)

PSA - Peak Surface Acceleration

PSHA - Probabilistic Seismic Hazard Assessment

$\ddot{Z}$ - Acceleration of the ground

$[L]_i$ - Element i transformation matrix

$\boldsymbol{a}$ - Acceleration vector

a - Acceleration

A - Acceleration coefficient

$A(t)$ - Pseudo- acceleration

$a_g(t)$ - Ground acceleration at time, t

A_n - Pseudo- acceleration response spectrum

$a^t(t)$ - Total acceleration at time, t

$\mathrm{s_u}$ - Undrained shear strength

Sv - Spectral Velocity

$\mathrm{T_n}$ - Natural period

$\mathrm{T_R}$ - Return Period

$\mathrm{V_S}$ - Shear wave velocity

$\mathrm{V_{S\text{-}30}}$ - The mean shear wave velocity of the top 30 m

Z - Seismic zone factor

σ - Compressive strength

ρ - Mass density

ω - Angular frequency = $2\pi f$

$\mathbf{c}$ - Damping matrix

c - Damping

C - Damping matrix

C_i - i^{th} element of the generalized damping matrix $[\bar{C}]$

D_n - Displacement at nth mode

ϕ - Matrix of corresponding eigenvectors

ϕ_n - Mode shape

f_s - Resisting force

F_x - Force in global x- direction

F_y - Force in global y- direction

F_z - Force in global z- direction

$\mathbf{K}$ - Stiffness matrix

k - Stiffness

K - Stiffness matrix

K_i - i^{th} element of the generalized stiffness matrix $[\bar{K}]$

$\mathbf{1}$ - Influence vector

m - Mass matrix

m - Mass

M - Diagonal mass matrix

M_2 - Moment in local axis-2 direction

M_3 - Moment in local axis-3 direction

$M_b(t)$ - Base moment

M_i - i^{th} element for the generalized mass matrix $[\overline{M}]$

Mp(-) - Negative plastic moment

Mp(+) - Positive plastic moment

M_X - Moment in global x-direction

M_{XX} - Bending force in x-plane and x-direction

M_{XY} - Bending force in x-plane and y-direction

M_Y - Moment in global y-direction

M_y(-) - Negative yield moment

M_y(+) - Positive yield moment

M_{YY} - Bending force in y-plane and y-direction

M_Z - Moment in global z-direction

P - Axial force in local axis direction

$P_{eff}(t)$ - Effective force time history

$q_n(t)$ - Displacement function at time, t

R_X - Rotation in global x-direction

R_Y - Rotation in global y-direction

R_Z - Rotation in global z-direction

S_d - Spectral displacement

S_{MAX} - Maximum membrane force

S_{MIN} - Minimum membrane force

S_v - Spectral pseudo- velocity

S_{VM} - Von Misses membrane force

S_{XX} - Membrane force in x-plane and x-direction

S_{XY} - Membrane force in x-plane and y-direction

S_{YY} - Membrane force in y-plane and y-direction

t - Time

T - Torsion in local axis direction

T_n - Natural period

u - Relative displacement with time

$\mathbf{u}$ - Displacement vector

$\mathbf{u}(t)$ - Displacement vector at time, t

$u(t)$ - Deformation response history

u_0 - Peak value

u_g - Ground acceleration

U_X - Displacement in global x-direction

u_y - Yield deformation

U_Y - Displacement in global y-direction

U_Z - Displacement in global z-direction

$\mathbf{v}$ - Velocity vector

v - Velocity

V_2 - Shear force in local axis-2 direction

V_3 - Shear force in local axis-3 direction

$V_b(t)$ - Base shear

V_r - Shear range

w - Natural angular frequency of vibration

w_1 *and* w_1 - First and second natural frequencies

w_n - Natural frequency i

w_i - Natural angular frequency

$\psi(x)$ - Shape function

$Z(t)$ - Amplitude of motion

ζ_n - Damping ratio at nth mode

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CHAPTER 1

INTRODUCTION

1.1 General

In Malaysia, structural engineers have begun to consider some seismic design considerations ever since tremor effects were felt on local bridge structures. Figure 1.1 shows the 13.6 km length cable stayed box-girder bridge type in Penang. This bridge was the first bridge in Malaysia in which seismic loading was considered during the structural design. Chin (1988) in his reports entitled "The Penang Bridge Planning, Design and Construction Report "(P.15), recognised that the nearest earthquakes source locations to Malaysia were:

1. 4N 99E depth 150km magnitude 6.25; (earthquake occurred on January 20th 1931) and
2. 4N 99E depth 200km magnitude 6.5 (earthquake occurred on July 4th, 1936)

Figure 1.1 First Penang Bridge

According to Chin (1988), a great earthquake in Malaysia is very rare. So, it is more economical to design the structure to resist the maximum seismic input with damage. In other words, the design philosophies should undergo lower level of structural strength at lesser cost to pay for the necessary repairs in the unlikely event of a maximum credible earthquake occurred.

Therefore, it is more preferable for a country like Malaysia to construct a box-girder bridge type compared to the other type of bridge since it has many advantages. The advantages are:

1. Box-girder Bridge has no expansion joint. Normally when earthquake happens, the expansion joint will be damaged due to the movement of the deck and unseating of simple spans will occur (Figure 1.2).

Figure 1.2 Unseating of the bridge deck of Shoowa Bridge in 1964 Niigata earthquake (Moehle and Eberhad, 2000)

2. No bearing for integral bridge type. Normally when earthquake happens, the bearing failure always occurs (Figure 1.3).

Figure 1.3 Nishinomiya-ko Bridge bearing failure in 1995 (Moehle and Eberhad, 2000)

In Malaysia, the concrete box-girder bridge has been constructed in many states. There are two types of concrete box-girder bridge namely continuous box girder and integral box-girder bridge. Some of the existing continuous box-girder bridge types in Malaysia are listed below:

1. Sultan Abdullah Bridge. This is one of the earliest concrete box-girder bridges to be constructed in Malaysia. This bridge crosses the Pahang River near Jerantut on federal Route 64. It has five spans with a total length of 486m. The maximum span length is 115m.
2. Sultan Yussuf Bridge. This bridge which was constructed in1988 is located on Federal Route 5 near the town of Teluk Intan. The bridge crosses the Perak River and has a total length of 1.3km. It has three spans over water, of prestressed concrete box girder design, with a central navigational span of 160m and two side spans of 95m each.
3. Sultan Azlan Shah Bridge. The bridge crosses Sungai Perak and is part of the North- South Expressway. It is 360m long and comprises five concrete box girder bridge spans.
4. Sultan Mahmud Bridge. Figure 1.4 shows the bridge location at the estuary of Sungai Terengganu, connecting the northern and southern sectors of Kuala Terengganu municipality. It comprises three separate structures, the longest of which is the south bridge, 1195m long, connecting the southern bank to Pulau Duyong. The other two structures are the North bridge 1 and 2 which are 220m and 320m long respectively. The five central spans of the south bridge are of balanced cantilever concrete box-girder construction, comprising three 65m long spans and two 40m long spans. The rest of the spans are made up of 40m long prestressed T- beams.

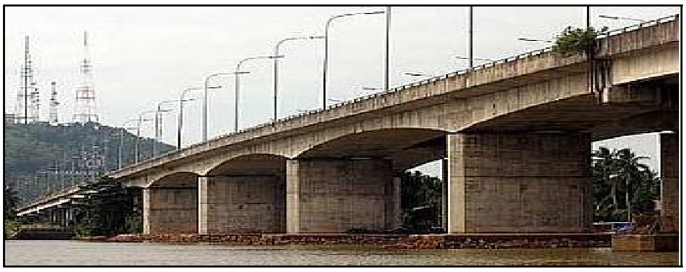

Figure 1.4 Sultan Mahmud Bridge, Terengganu

5. Tanjung Lumpur Bridge. This bridge crosses Sungai Kuantan connecting Padang Lalang and Tanjung Lumpur which provides a direct crossing to the parts of the river from Kuantan Town. The bridge has a total length of 424m comprising of three balanced cantilever double box girder central spans totalling 186m (50m-86m-50m) and three 40m prestressed concrete beam approach spans on each side.

Some of the existing integral box-gider bridges that have been constructed in Malaysia are as follow:

1. Santubong Bridge (Figure 1.5). The main spans of this bridge are of prestressed concrete balanced cantilever box-girder with a central span of 146m. The total span length inclusive of the precast I- beam approach span is 593m. The bridge which is located near Kuching Sarawak was completed in1988.

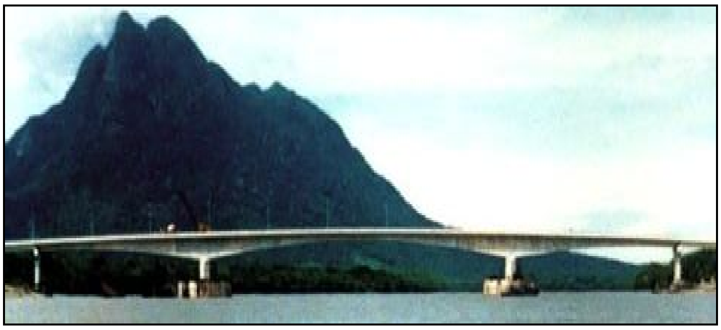

Figure 1.5 Santubong Bridge, Kuching Sarawak

2. Permas Jaya Bridge. Figure 1.6 shows the bridge location over Sungai Tebrau in Johor Bahru which forms the main access to the Permas Jaya New Town. It has a total length of 600m with a central and side spans of 186m and 90m respectively, employing double cantilever box-girder construction method. The symmetrical approach spans on both ends consist of 3spans of 33m and one span of 27m prestressed beams. The bridge was opened to traffic in 1994.

Figure 1.6 Permas Jaya Bridge, Johor

3. Kampung Sawah Bridge. This bridge is located in Kuala Langat in Selangor and is one of the main bridges in Selangor. The bridge is a prestressed box-girder concrete type still under construction, at the casting of the concrete box-girder deck phase. The concrete box-girder bridge is made up of 79m + 110m + 79m (total 268m) span and concrete beam approach spans on each side.

1.2 Problem Background

In recent years, Malaysians are more aware of and concern for the seismic effect on their bridges because the tremors were repeatedly felt over the centuries from the earthquake events around Malaysia. For example, the First Penang Bridge had experienced some minor damage due to Acheh earthquake on 24 December 2004. Fortunately, the First Penang Bridge was designed under seismic consideration.

The seismic consideration for first Penang Bridge has followed the steps as mentioned by Idriss (1985), who identified three presently used methods of obtaining the design ground motion parameters: (1) Use of local codes, (2) Conducting quasi-deterministic seismic hazard evaluation, and (3) Conducting a probabilistic seismic hazard evaluation. Based on Mohammad (1986), in Malaysia, only method (2) is made available with simplified quasi-deterministic seismic hazard evaluation version.

Idriss (1985) also describes the current practice of a quasi- deterministic seismic hazard evaluation as consisting of the following steps:

1. Conducting a geologic and seismologic evaluation to define the sources (faults) relevant to the site.
2. Estimating the maximum magnitude, m_1, on each source. This is the "maximum credible earthquake". The closest distance from the fault zone to the site is then determined.
3. Deriving recurrence relationships for each source using historical seismicity as well as geologic data, and select an earthquake with a magnitude $m_2 < m_1$ for each source such that the recurrence N (m) for $m > m_2$ is the same for all sources; if, for example $N (m^2) = 0.01$ per year is used, corresponding to a recurrence interval of 100 years, this earthquake is then designated the 100 year earthquake.
4. Determining parameters for each source (e.g. peak ground acceleration), using appropriate attenuation relationships, for the maximum earthquake and for the earthquake use the magnitude and distance producing the largest ground motion parameter of interest for design and analyses.

However, based on Chin (1982), there are some data that are collected based on judgmental evaluations probably due to the unavailability or incompleteness of data. The seismic hazard evaluation procedure for the first Penang Bridge can be regarded as a simplified version of the quasi-deterministic approach, in which steps (1) and (2) were followed, but steps (3) and (4) were replaced with judgmental evaluations.

This statement is supported by Mohammad (1986). He reported that the current practice of seismic hazard evaluation in Malaysia is rather subjective, and is limited by the lack of organised data. Research has to be conducted to assemble data and obtain reliable relationships required for rational seismic hazard evaluations.

In 2005, Structural Earthquake Engineering Research (SEER) of Universiti Teknologi Malaysia has carried out seismic zone mapping for peninsular Malaysia and east Malaysia. Azlan et al (2006) has done proper seismic hazard assessment for

Penang Bridge using Deterministic Seismic Hazard Analysis (DSHA) and Probabilistic Seismic Hazard Analysis (PSHA).

From Figure 1.7, the spectral acceleration for the design of the response spectrum of the Penang Bridge carried out by Azlan et al (2006) is two times higher compared to Chin (1988) at period 0.5 – 1.0 second and three times at period 2.0 – 2.5 second. The low values in Chin's result were due to the limitation of organised data in 1980s and the improper deterministic method. Figure 1.7 shows the significance of taking into account the seismic effect in bridge design in Malaysia.

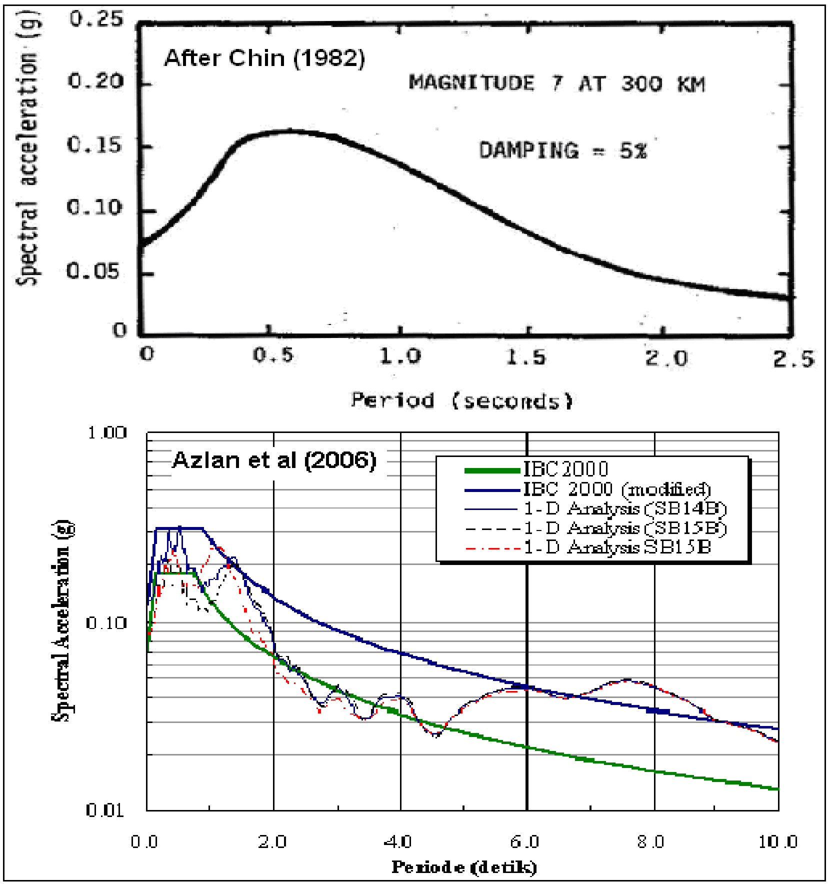

Figure 1.7 Chin (1988) vs Azlan et al (2006) for Design Response spectrum for first Penang Bridge

Seismic performance of existing bridges in Malaysia is very important, particularly for the concrete box-girder type. This type of bridge has good performance for neglecting the effect of earthquake like bearing failure and unseating simple span. Unfortunately, the other problem of this type of bridge that always occurs due to seismic force is plastic hinge failure (secondary stress). The problem occurs into this system after considering the seismic effect where rigid connection of column and deck will produce potential hinge failure. Therefore, the performance of the integral and continuous prestressed concrete box-girder bridges under nonlinear seismic study should be investigated.

Based on Burke (2009), bridge engineers are still willing to relinquish some of their control of secondary stresses for integral prestressed concrete box-girder bridges. It is because integral prestressed concrete box-girder bridge achieves simpler construction, more cost-effective, greater overall integrity, and durability.

Currently integral and continuous concrete box-girder bridges are now becoming a popular choice of system in Malaysia, as the benefit of this system reduces the cost of bridge maintenances. Figure 1.8 shows the problem occurs in such systems when considering the seismic effect where rigid connection of column and deck will produce potential hinge failure (secondary stress).

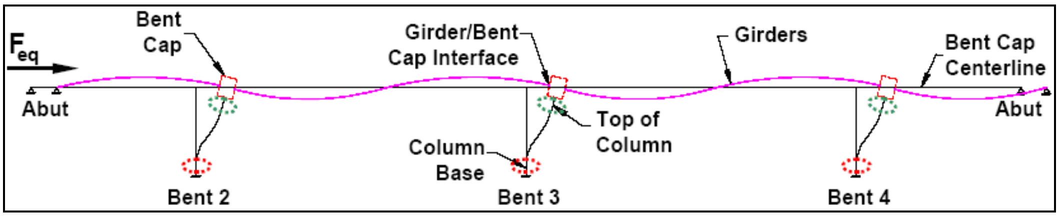

Figure 1.8 Potential Hinge locations (Patty et al, 2002)

In Malaysia, the design of the foundation for integral concrete box-girder bridge abutments have accounted for the expansion and contraction of the bridge due to thermal movement. The resulting soil pressures due to thermal expansion and restraining effects due to jointless construction of the bridge have been recognised as the controlling load for design of integral abutments and piles. Designing and detailing of integral abutments to handle these forces is critical for the proper performance of integral abutments. Based on Kerokoski and Laaksoneen (2005), the passive earth pressure on the integral abutment is estimated to be mobilized after a quite small abutment displacement in the range of 0.005 to 0.05 times height of the wall is adequate. While according to a group of German researcher (Kerokoski, 2006), the displacement equal to 0.025 x H is enough to mobilise half of the passive earth pressure, and that is also the recommended maximum displacement. Due to Weakley (2005), total movement at abutment of fully integral and semi-integral bridge is between 1.5 and 2.25 inch.

Therefore, the seismic performance study of integral concrete box-girder bridge is very important. For low and moderate seismicity areas like Malaysia, the movement of structure due to earthquake loading may possibly be larger than the movement due to thermal loading. In this study, the continuous concrete box-girder bridges are considered since many of this bridge type are constructed in Malaysia.

1.3 Problem Statement

Seismic performance of prestressed concrete box-girder bridge is needed in order to know the level of resistance in existing structures due to ground motion and also the effect of integral system on the bridge. The research will consider the local site response study as part of earthquake loading determination and soil- pile interaction. The performance result of the bridge will be useful for future prestressed box-girder bridge seismic design considerations.

Furthermore, research for determining the level of resistance toward earthquake hazard on the parameters of integral prestressed concrete box-girder bridge such as loading, span etc has not been carried out yet. There were no studies done on the effects of earthquake on integral bridges in Malaysia that are located near high seismic zone countries. Therefore, analysis is required to observe the effect and performance of prestressed integral concrete box-girder bridge toward seismic hazard.

Generally, the overall problems of this study are:

1. Unknown integral prestressed concrete box-girder bridge performance under earthquake loading with respect to Malaysia conditions.
2. Unknown soil-pile interaction effect versus fixed base support effect under earthquake loading for integral prestressed concrete box-girder bridge.
3. How correct is the current nonlinear Finite Element Analysis to perform the actual bridge performance under earthquake loading.

1.4 Objectives

The objectives of this research are as follow:

1. To perform 3D modelling for Integral and Non Integral prestressed concrete box-girder bridges for determining the nonlinear behaviour of bridge component under seismic loading.

2. To perform soil structure interaction effect as a major element in the seismic analysis and forces response impact by considering it.

3. To validate the results of numerical approach by conducting shaking table dynamic test.

1.5 Research Finding/ Expected Outcome

There are three expected outcome in this study. First, the performance of Integral prestressed concrete box-girder bridge can be decided whether the movement due to thermal loading can resist movement due to earthquake loading or vice versa. Second is the impact for considering pile in the integral bridge model and third is the effectiveness of finite element analysis to represent the actual bridge behaviour.

1.6 Scope and limitations

There are many parameters that may have effects on the results of analysis. Therefore the analysis is limited to the following scope:

1. Data collection and preparation:
    - a. Identifying existing continuous and integral prestressed concrete box-girder bridge.
    - b. Obtaining selected bridge drawing and soil data from Public Work department (PWD) and private C&S consultancy companies.
    - c. Obtaining material samples from only one Malaysian precast concrete factory.

2. Mechanical material properties study.
    - a. Conducting the laboratory tests: compressive strength, flexural strength, modulus elasticity, Poisson's ratio and nonlinear stress-strain curves relationship.

3. Parametric study.
    - a. Conducting the nonlinear seismic study for Kampung Sawah Bridge and Nordin Bridge
    - b. Implementing the nonlinear seismic analyses: nonlinear push-over analysis and nonlinear time history analysis by using SAP2000 V14.2.
4. Case study.
    - a. Conducting the case study for Kampung Sawah Bridge only.
    - b. Considering only P-y relationship (lateral soil resistance versus deflection relationship) for soil-pile interaction produced by using LPILE program.
    - c. Analysing soil dynamic properties on Kampung Sawah Bridge location.
    - d. Analysing one dimensional shearwave propagation analysis on Kampung Sawah Bridge Location by using NERA program.

   e. Generating artificial time histories for Kampung Sawah Bridge location for 500 years return period by using EZ-frisk and Simqke.
   f. Implementing the nonlinear seismic analyses: nonlinear pushover analysis and nonlinear time history analysis by using SAP2000 V14.2.

5. Bridge Model Verification of study.
   a. Modelling reinforced concrete box-girder bridge type which in this experimental work, the effect of prestressing tendon is neglected due to the small size of bridge model.
   b. Measuring the bridge responses by using accelerometer, strain gauge and LVDT.
   c. Conducting the tests by using ANCO R51 hydraulic shaking table.
   d. Scaling the bridge becomes 3 meters length.
   e. Conducting the dynamic tests at transversal direction only.
   f. Producing the additional table by using steel plate and stiffener.

1.7 Methodology

The research design of this thesis is shown in Figures 1.9, in which, the symbols I, O, and P stand for input, output and process of the analysis respectively, while the arrows show the flows of input required by the process and the output as a result of the analysis.

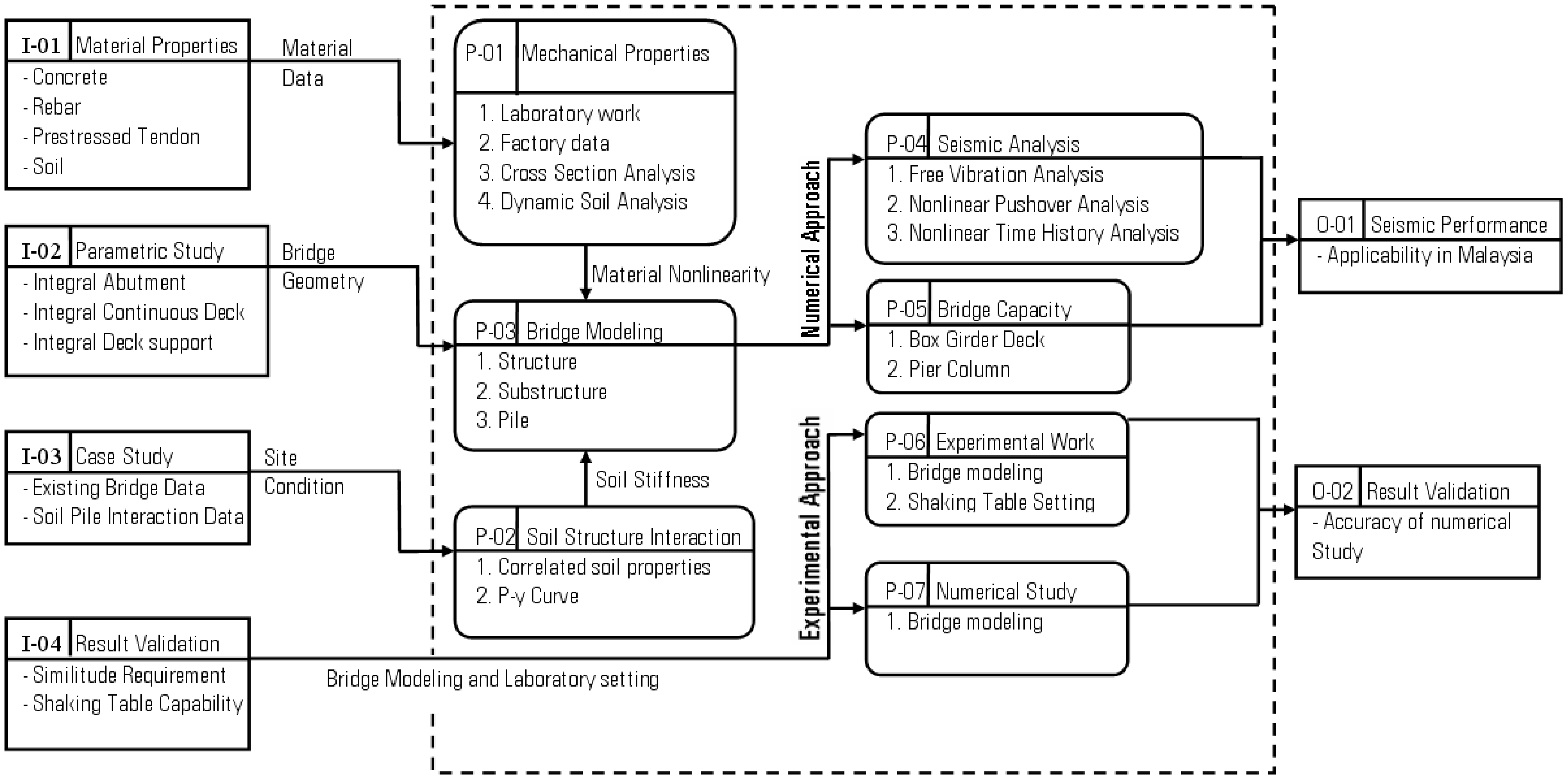

Figure 1.9 Methodology of research.

1.7.1 Data Collection

From Figure 1.9, there are some data collection and information required for the analysis: the sample of structural bridge material, bridge structural drawing for finite element modelling and the soil data for site specific analysis and soil-pile interaction analysis.

The modelling parameter of bridge study involved the collection and testing of material properties of bridge structure from factories in Malaysia. The materials collected were tested in laboratory to produce mechanical material properties and nonlinear stress- strain relationship. The mechanical material properties of prestressed concrete box-girder bridge are discussed in detail in Chapter 4.

The structural drawing of integral prestressed concrete box-girder bridges is required to model the finite element bridge. The structural drawings are collected from Public Works Department of Malaysia (JKR) and C&S consultancy (a private Malaysian company). The soil data or N_{SPT} data is required for producing soil dynamic parameter and soil-pile interaction parameter using empirical correlations.

In this research, the following activities were performed in order to obtain the required data for finite element modelling:

1. Collecting structural drawings for integral prestressed concrete box-girder bridge.
2. Collecting soil data or N_{SPT} value at abutments and piers at the bridge location.

The data were used to model the elements of bridge using a computer program. This study is described in detail in Chapters 5 and 6.

For result validation purposes, the experimental work is carried out to verify the accuracy of finite element modelling under seismic loading. The information required to implement this study is as follows:

1. Material properties of bridge model
2. Shaking table setting and capability information.

1.7.2 Analysis and Experimental Work

Generally, there are seven main processes performed in this experimental work as shown in Figure 1.9. Mechanical material properties laboratory test, Soil-pile interaction analysis, bridge finite element modelling, nonlinear seismic study, capacity of bridge component, shaking table experimental work and numerical study.

1.7.2.1 Mechanical Material Properties Laboratory Test

In this study, bridge materials are obtained from a Malaysian precast concrete factory. The laboratory tests conducted are compressive strength, flexural strength, modulus of elasticity, Poisson's ratio and stress-strain curve relationship.

The laboratory work was carried out in Structural and Material Laboratory of Universiti Teknologi Malaysia. In the investigation, all testing of the specimens was performed in accordance to the relevant British Standards, namely BS1881part 102, 116, 118 and 121.

For dynamic soil properties, the correlations of N_{SPT} soil data were used in this study since no laboratory work was carried out for soil parameters.

1.7.2.2 Soil – Pile Interaction

The soil-pile interaction analysis requires soil data such as soil stratigraphy, ground water level and soil dynamic properties. In this study, empirical relationships were used to determine the soil dynamic properties. In the seismic analysis of the bridge structures, the foundation stiffness is a major element. Given the interplay between superstructure and substructure responses of the bridge, realistic evaluation of total bridge response dictates the need for a practical and realistic model for assessing the stiffness of the bridge foundations. The foundation stiffness can be modelled by a set of springs that represents the stiffness of the foundations.

In this research, the following activities were performed in order to obtain soil stiffness inputs for soil-pile interaction study:

1. Collecting the standard soil penetration investigations and seismic tests at the bridge location.
2. Conducting the analysis by using existing soil data to obtain soil stiffness (p-y curves at every certain pile depth).

The correlated N_{spt} soil properties were used in order to determine dynamic soil properties in bridge location. The procedure for soil structure interaction is described in detail in Chapter 6.

1.7.2.3 Bridge Modelling

The non-linear seismic analysis of bridges was done using finite element software for its three dimensional modelling.

1. Pier, abutment, and pile using 3D beam element.
2. Box-girder deck using Shell element.
3. Bearing using Link element.
4. Pilecap is represented by a stiff constraint with lumped mass in the centroid.
5. Soil-pile interaction using lumped springs along the pile.

1.7.2.4 Non-linear Seismic Analysis

Non-linear seismic analysis is performed in order to obtain the performance of bridge component under damaging level of earthquake. Nonlinear seismic analyses implemented are non-linear push-over analysis and non-linear time history analysis.

1.7.2.5 Shaking Table Experimental Work

This experimental study is performed in order to validate the result of numerical approach. Four steps involved in experimental work are as follows:

1. Scaling integral concrete box-girder bridge by implementing Buckingham PI theorem.
2. Setting the shaking table, shaker controller, strain gauge, Load Varied Displacement Transducer (LVDT) and accelerometer.
3. Analysing finite element modelling of scaled integral concrete box-girder bridge
4. Validating the results by comparing the acceleration, displacement of structure response from instrument and finite element modelling.

1.7.2.6 Numerical Study of Cast Bridge Model

This study is performed to obtain a good prediction and verify the result of the experimental work by using SAP 2000 computer program.

1.8 Organisation of Theses

The connection between the methodology and each chapter is shown in Figure 1.10. The body of this document begins with Chapter 1; Introduction. Following this introductory chapter is Chapter 2 which representing a Literature Review of the past and present body of knowledge pertaining to integral prestressed concrete Box-Girder bridges. Chapter 3 presents the theoretical background of linear and nonlinear seismic analysis. Chapter 4 presents the laboratory results and discussion of materials used in the experimental test. Chapter 5 presents the parametric study for continuous deck and monolithic pier deck system. Chapter 6 presents the case study for selected bridge in Malaysia. Chapter 7 presents the validation result by conducting experimental method by using shaking table. The Conclusions and Recommendations are presented in Chapter 8.

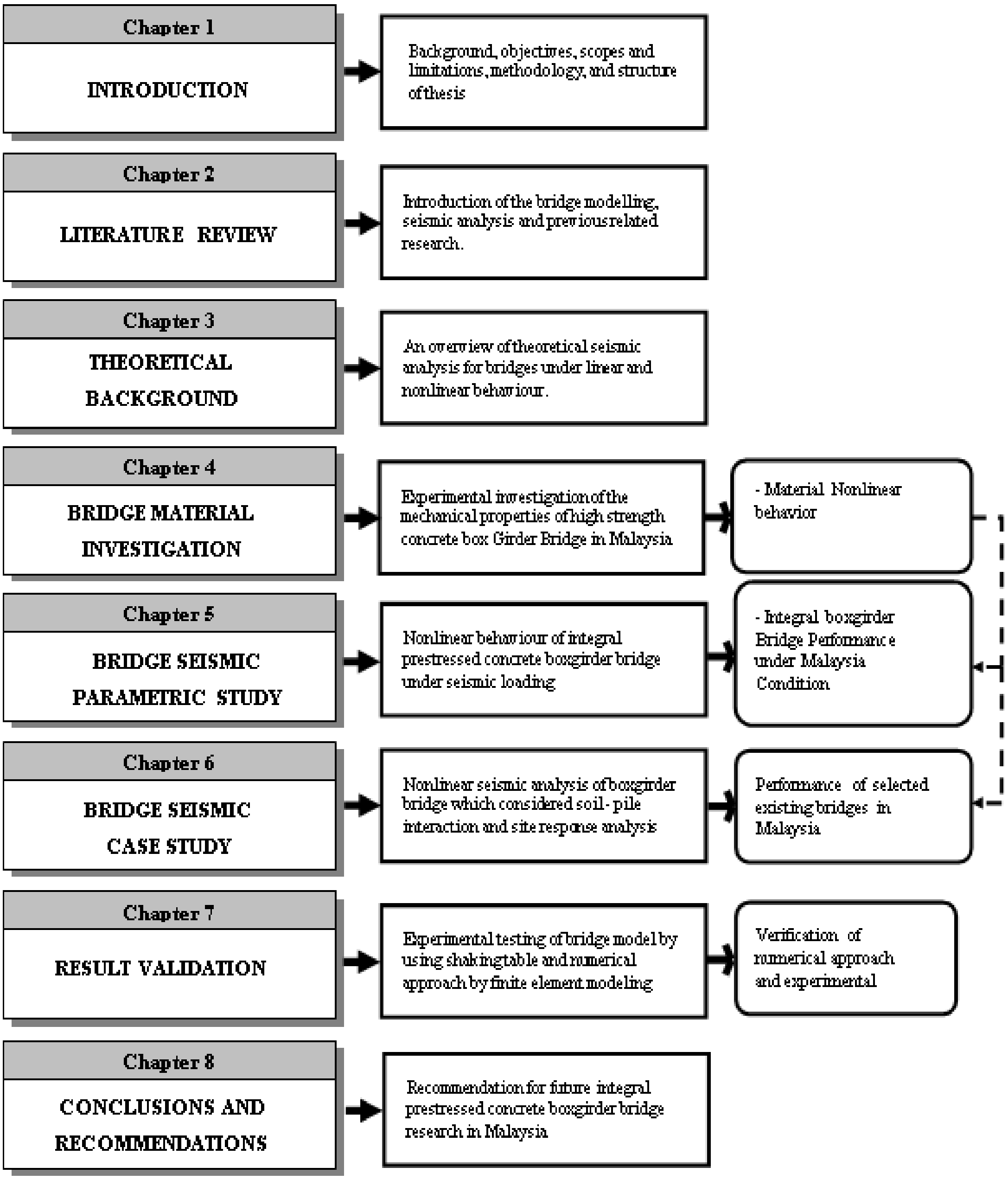

Figure 1.10 The organisation of thesis

The content of each chapter can be described briefly as follows:

- ***Chapter 1: Introduction.*** This chapter describes the background of the research, the objectives to be achieved, the research scopes, the methodology, and the structure of the thesis.
- ***Chapter 2: Literature Review***. This chapter reviews and evaluates the topics which are related to earthquake engineering. This chapter presents how the integral prestressed concrete box-girder bridge components are modelled using finite element software including the effect of boundary condition and soil pile interaction. Literature study regarding nonlinear seismic bridge analysis and the bridge response under seismic loading are also discussed in this chapter.
- ***Chapter 3: Theoretical Background***. This chapter describes the theory of seismic analysis for bridge under linear and nonlinear behaviour.
- ***Chapter 4: Bridge Material Investigation.*** In this chapter, the concrete, rebar, and tendon material for box-girder deck are collected from the precast concrete factory in Malaysia and tested in the laboratory so as to obtain reliable mechanical material properties data for the bridge modelling in Chapter 5 and 6
- ***Chapter 5: Bridge Seismic Parametric Study***. The two types of integral prestressed concrete box-girder bridge modelling is the most critical point in seismic risk assessment. Hence, the bridge nonlinear behaviour is implemented in this chapter and requires the detailed understanding to model and analysis the bridge.
- ***Chapter 6: Bridge Seismic Case Study***. This chapter analyses the selected existing integral prestressed concrete box-girder bridge in Malaysia under seismic loading. The soil-pile interaction are analysed to obtain the soil stiffness which requires for modelling purposes. The seismic loadings at bridge location are defined using local site effect analyses. The material mechanical properties from the laboratory testing in chapter 3 are applied in this seismic risk analyses.
- ***Chapter 7: Result Validation.*** This chapter describes the application of dimensional analysis to model and simplify the bridge. The performance of bridge under shaking table test in term of acceleration, displacement

and strain is compared with the numerical approach which verifies the accuracy of seismic analysis using finite element software.

- ***Chapter 8: Conclusions and Recommendations***. This chapter concludes and summarises the results on the previous chapters and give recommendations for further study.