UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF EMPIRICAL MODELS FOR GROUND-BORNE VIBRATION FROM ROAD TRAFFIC

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FK 2018 33

DEVELOPMENT OF EMPIRICAL MODELS FOR GROUND-BORNE VIBRATION FROM ROAD TRAFFIC

By

NORLIANA SULAIMAN

Thesis Submitted to the School of Graduate Studies Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

October 2017

DEDICATION

To my Mum and my late Dad, *Faridah* and *Sulaiman*, my dear Husband, *Muhammad Akram*, and my children, *Amir*, *Amin*, *Alya* and *Aisyah*.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the Degree of Doctor of Philosophy

DEVELOPMENT OF EMPIRICAL MODELS FOR GROUND-BORNE VIBRATION FROM ROAD TRAFFIC

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NORLIANA SULAIMAN

October 2017

Chairman : Professor Bujang Bin Kim Huat, PhD
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Ground-borne vibration produced from road traffic has become an area of interest in recent years due to environmental concern. Most countries have encountered the ground-borne vibration problems when the buildings and structures are near the roadway system. The ground-borne vibration may cause annoyance to the people and also can affect buildings and equipment near the roadway system. Many developed countries have designed their own approach on how to overcome the ground-borne vibration problem. In Malaysia, guidelines have been developed to describe the ground vibration threshold. However, no specific technique has been introduced on how to measure the ground vibration level. Furthermore, important parameter such as the soil dynamics factor were not considered in the current ground-borne vibration model. Therefore, the goal of this study was to develop an empirical model that can predict the ground borne-vibration from road traffic towards the surrounding area that would incorporate soil dynamics, pavement characteristics, and traffic parameters. Additionally, this study was undertaken to complement the established Malaysian guidelines using a model developed from empirical multiple regression analysis.

The research study involved at eight different sites within Selangor and with single carriageway. Several important parameters such as soil shear wave velocity, international roughness index (IRI), distance from vibration source, vehicles flow rate and speed were collected from site study. Current models were tested with field data to evaluate the reliability. The results indicated inaccurate prediction when it used with local field data. Multiple linear regression analysis with a systematic methodological procedures were used to develop the models. Three empirical models that are reliable to estimate ground vibration were developed in the study. These models are meant for estimating hard ground vibration, soft ground vibration and general ground vibration surrounding the highway area. Several significant parameters were found from the multiple regression analysis for each model. All models had been tested using new dataset and the verification results showed that there is a good agreement between the model predictions and the empirical measurement for all models. The sensitivity analysis has shown that the vehicle flow rate is highly sensitive when predicting soft ground vibration. The distance from the source of vibration is a highly sensitive

parameter for predicting hard ground vibration. Finally, the findings of this study can serve as a starting point towards developing national guidelines, for a more sustainable road development and environmental safety.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai mementuhi keperluan untuk Ijazah Doktor Falsafah

PEMBANGUNAN MODEL EMPIRIKAL GETARAN BAWAAN TANAH DARIPADA LALU LINTAS DI JALAN RAYA

Oleh

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Getaran bawaan tanah yang terhasil daripada lalu lintas di jalan raya semakin menarik perhatian dalam beberapa tahun kebelakangan ini disebabkan oleh kebimbangan terhadap alam sekitar. Kebanyakan negara mengalami masalah getaran bawaan tanah apabila bangunan dan struktur terletak berdekatan sistem jalan raya. Getaran bawaan tanah boleh mengakibatkan gangguan kepada manusia dan juga menjejas bangunan dan peralatan yang terletak berdekatan dengan sistem jalan raya. Kebanyakkan negara maju membangunkan pendekatan tersendiri untuk menyelesaikan masalah getaran bawaan tanah ini. Di Malaysia, garis panduan telah dibangunkan untuk menggambarkan ambang getaran tanah. Namun begitu, teknik khusus untuk mengukur tahap getaran tanah masih belum diperkenalkan. Tambahan pula, parameter penting seperti faktor dinamik tanah tidak dipertimbangkan di dalam model getaran bawaan tanah semasa. Oleh itu, matlamat kajian ini adalah untuk membangunkan model empirikal yang mampu meramal getaran bawaan tanah daripada lalu lintas di jalan raya, terhadap kawasan sekitarnya yang mengambilkira dinamik tanah, ciri-ciri kaki lima, dan parameter lalu lintas. Tambahan pula, kajian ini dijalankan bagi melengkapkan garis panduan yang telah terbentuk di Malaysia menggunakan model yang dibangunkan daripada analisis regresi berganda empirikal.

Kajian penyelidikan ini dilaksanakan di lapan tapak kajian berbeza sekitar Selangor dan di dalam kategori jalan selorong. Beberapa parameter penting seperti kelajuan gelombang ricih tanah, indeks kekasaran antarabangsa (IRI), jarak daripada sumber getaran, kadar aliran dan laju kenderaan dikumpulkan daripada tapak kajian. Model semasa di uji mengunakan data tapak bagi menilai kebolehpercayaannya. Keputusan mendapati ramalannya tidak tepat apabila menggunakan data tapak tempatan. Analisis regresi berganda dengan tatacara metodologi sistematik digunakan bagi membangun model. Tiga jenis model empirikal yang boleh dipercayai dibangunkan untuk menganggar getaran tanah dalam kajian ini. Model-model ini bertujuan untuk menganggar getaran tanah keras, getaran tanah lembut dan getaran tanah umum di sekitar kawasan lebuh raya. Beberapa parameter penting di jumpai daripada analisis regresi berganda untuk setiap model. Kesemua model ini diuji menggunakan set data

baru dan keputusan pengesahan menunjukkan bahawa terdapat persetujuan baik antara model-model ramalan dan pengukuran empirikal oleh kesemua model. Keputusan analisis sensitiviti menunjukkan bahawa kadar aliran kenderaan adalah sangat sensitif ketika membuat ramalan untuk getaran tanah lembut. Jarak daripada sumber getaran adalah parameter yang sangat sensitif untuk meramal getaran tanah keras. Akhir sekali, hasil kajian ini boleh menjadi titik permulaan ke arah membangunkan garis panduan kebangsaan, demi pembangunan jalan raya yang lebih mampan dan keselamatan alam sekitar.

ACKNOWLEDGEMENT

My gratitude goes to Allah SWT for all the blessings and graces that provide me health, wisdom and whole of my thesis work and study a reality and success. Firstly, I would like to express my sincere gratitude to my advisor Prof. Bujang Kim Huat for the continuous support of my Ph.D. study and related research, for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my Ph.D. study. Besides my advisor, I would like to thank the rest of my supervisory committee: Prof. Thamer Ahmad Muhammad, Dr. Afshin Asadi and Dr. Haslinda Nahazanan for their insightful comments and encouragement, but also for the hard question which incented me to widen my research from various perspectives. My sincere thanks also goes to Dr. Adnan and Ms. Aini from UTHM, Ms. Fadhilah from UPNM, Ab. Mughni and laboratory technician from UiTM, En. Khairul Annuar Mohd Nayan from UKM, who gave access to the laboratory and research facilities. Without they precious support it would not be possible to conduct this research. I would like to thank the UPM staff and friends who have supported me along the way. I am grateful to my mother, Faridah Idros, my parent in law, Noriah Abdul Majid, Adnan Abdul Rahman and my family, who have provided me through moral and emotional support in my life. Last but not the least, I would like to express my ocean of love and grateful to my beloved husband Muhammad Akram Adnan for supporting me spiritually, emotionally, physically and endless love throughout writing and completing this thesis and my life in general. Also to my sons Amir Syarif, Amin Syukri and my daughters, Alya Syafiah and Aisyah Sofia, I'm sure that, they are going to be great, *Insya-Allah.*

I certify that a Thesis Examination Committee has met on 24 October 2017 to conduct the final examination of Norliana binti Sulaiman on her thesis entitled "Development of Empirical Models for Ground- Borne Vibration from Road Traffic" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Declaration by graduate student

I hereby confirm that:

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LIST OF ABBREVIATIONS

BS	British Standard
DIN	Deutsches Institut fiir Normung
ISO	International Standard Organization
PWD	Public Work Department
GBV	Ground-borne vibration
Hz	Hertz
IRI	International roughness index
ADT	Average daily traffic
CBR	California Bearing Ratio
ATJ	Arahan Teknik Jalan
CDOT	California Department of Transportation
PPV	Peak particle velocity
V_w	Weighted velocity
DOE	Department of Environmental
RMS	root mean square
VC	Vibration curve
VDV	Vibration dose value
W_b	Vertical motion
W_d	Horizontal motion
SASW	Spectral analysis surface wave
ATC	Automatic traffic counter
TMS	Time mean speed

CHAPTER 1

INTRODUCTION

1.1 Introduction

Ground-borne vibration (GBV) produced from road traffic has become an area of interest in recent years due to environmental concern. Many countries have encountered ground borne vibration problems when the buildings and structures are near the roadway system. Normally in the dense populated area, traffic volume and vehicle speed increase. This has created the issue of ground vibration. These issues are generally responsible for the increasing disturbance to human and surrounding structures.

The GBV from road traffic is very unlikely to cause major damage to the buildings and structures. But the environmental and economic aspects of the ground vibration issue required a careful assessment of the problem especially in a congested developed area. The study attempts to develop a prediction model for GBV that can be a tool to be used in different stages of roadway design process and in planning mitigation measures assessment. Using this model, local authorities and practitioners can study this problem during the planning stage and propose the mitigation methods, if necessary.

1.2 Problem of statement

The GBV may cause annoyance to the people living near the roadway system and also can aggravate some sensitive equipment. These include disturbing the operation of equipment for research, microelectronics manufacturing and medical diagnostics. This GBV also may affect the structure or building elements such as wall and ceiling, the high technology buildings, old and historical building as shown in Figure 1.1.

Figure 1.1: Old and historical building located nearby the roadway in Negeri Sembilan and Penang, Malaysia

Most developed countries such as in United Kingdom and Germany have their own approach on how to assess and evaluate the GBV problem. The example standards and guidelines for measurement and evaluation of ground vibration on human and structures are BS 6472-1(2008), DIN 4150-3(1999), ISO 2631- 1(1997) and ISO 2631- 2(2003). In Malaysia, the planning guideline for “Vibration Limits and Control in the Environment” has been developed in 2007 to guide ground vibration acceptance criteria for quantitative assessment of vibration. In this guideline, only the vibration threshold has been stated and no tool or method to measure or predict the ground vibration level has been specified. The only way to measure the ground vibration level is by seismograph or geophone which is very costly. In Malaysia, not all local authorities can afford these expensive equipment.

A lot of research on GBV coming from train traffic. Examples are Chua et al. (1995), Madshus et al. (1996), Turunen-Rise (2001), Turunen-Rise et al. (2003), Paolucci et al. (2003), Bahrekazemi (2004), With et al., (2006), Gupta et al. (2008), Lombaert and Degrande (2009), Salvador (2011), Kouroussis et al. (2013) and Paneiro et al. (2015). Long (1993), Watts (1996), Watts and Krylov (2000), Watts and Stait (2008), Lak et al. (2011) and Tuan Chik et al. (2013) studied GBV from road traffic. However, very few researchers have conducted on empirical studies based on soil dynamics, pavement characteristics and traffic parameters from road traffic. Additionally, important parameter such as the soil dynamics factor were not considered in the current ground-borne vibration model.

Therefore this study was done to complement the established Malaysian guidelines on ‘Vibration Limits & Control in Environment’ with the focus on an empirical study that reflects Malaysian road, climatic, and soil conditions. It is therefore, necessary to develop an empirical model that can predict the GBV from road traffic affecting the surrounding area based on soil dynamics, pavement characteristics and traffic parameters. The empirical model that will be developed is expected to be able to predict GBV due to road traffic especially in the preliminary stage of the projects and in the planning of mitigation measures.

The GBV problem is seen as complex and it normally involves a number of different disciplines such as mechanical, structural, highway engineering and geotechnics (Crispino & D’apuzzo, 2001). Therefore, this research study involves multidiscipline fields such as soil dynamics, highway and traffic engineering for developing the empirical model.

1.3 Objectives of thesis

The aim of this study is to develop an empirical model of GBV that affects livability and sustainable roadway development. The specific objectives of the study are:

1. To evaluate the reliability of existing GBV model with empirical field data.
2. To determine the significant and critical parameters of GBV model.

3. To develop models of GBV which are able to relate soil dynamic parameters, pavement characteristics, and traffic parameters.
4. To validate and perform sensitivity analysis in order to evaluate sensitivity of each parameter of the developed models.

1.4 Scope and limitation of study

In this study, data collections for the empirical model were based on the road traffic in Selangor as shown in Figure 1.2. All site approved by the Public Work Department (PWD). Eight regions of study area covers northern, southern, western, and central region of Selangor in Peninsular Malaysia. The sites were selected based on various ranges of soil underneath, pavement characteristic and composition of traffic on the roadway.

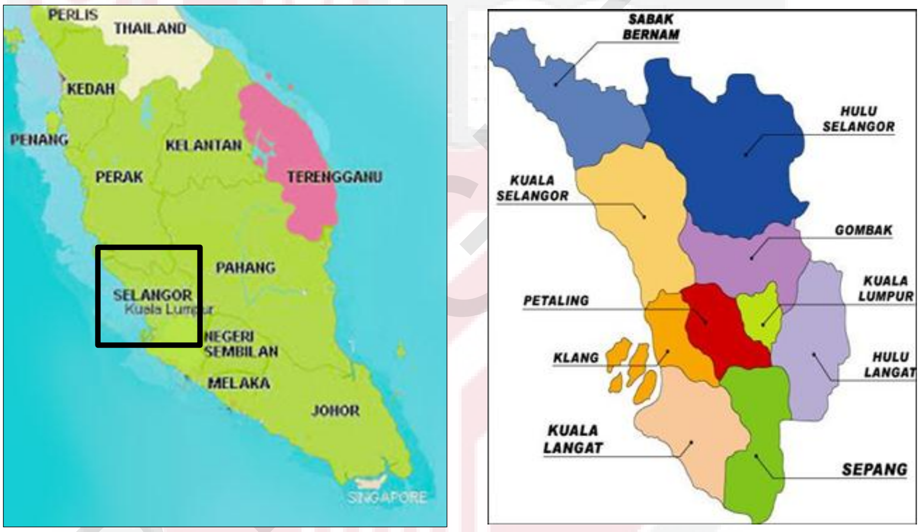

Figure 1.2: Peninsular Malaysia map (left) and Selangor map (right)

All sites are based on the PWD design standard with the specifications of U5 urban road design standards and R5 rural road design standards with single carriageway. All sites were under the jurisdiction of the PWD and proper approval was taken.

1.5 Significance of study

This research will develop an empirical model that can relate GBV to soil, pavement characteristic and traffic engineering parameters in the setting of Malaysian road condition. The GBV empirical models that are developed in this study will become a basis in a prediction tool for the future use of the developer and planner for Malaysian standard estimation in the GBV from roadway system.

1.6 Gap of research study and novelty value

This research study will successfully bridge the gap of knowledge towards understanding of GBV that involve soil dynamic parameters, pavement characteristics and traffic engineering parameters. Several parameters involved in the prediction of GBV due to vehicle movements. A crucial parameter involves in soil dynamics is shear wave velocity. The pavement parameters involved are pavement thickness, pavement width and pavement roughness index. The traffic engineering parameters are vehicle speed and flow rate.

The research study outcome will be seen as a successful reliable empirical model that uses systematic methodological procedures. The empirical models developed will become an effective tool for the practitioners and local authorities to estimate and predict the GBV generated by surrounding road traffic.

1.7 Research question and hypothesis

This study involves GBV induced by road traffic. Among research questions that need to be answered are:

- Is there any relationship between GBV and traffic parameter such as speed and flow rate of vehicles?
- Is there any relationship between GBV and pavement characteristics such as, pavement thickness and pavement roughness index?
- Is there any relationship between GBV and soil parameter such as shear wave velocity?

The hypotheses of this research based on the research question stated are:

- It is hypothesized that the higher the vehicles speed and flow rate, the more the ground vibration.
- It can be hypothesized that in thinner and rougher pavement, more GBV will be experienced.
- If the shear wave velocity of soil increases, the GBV will decrease.
- If the field data were tested with existing GBV models (Watts and Long Models), the prediction will be inaccurate.
- It can be hypothesized that combination of all parameters would be able to calculate the magnitude of GBV.

1.8 Organization of the Thesis

This thesis consists of 7 chapters. Chapter 1 discusses introduction to the subject, problem statement, scope and limitation of the study, research objectives, principle contribution, and outline of the thesis. A background review of related research in this field is summarized in Chapter 2. This chapter starts with a review of the GBV and is followed by discussion of the relevant research findings in GBV. Specifically, the reviews included some necessary background of ground vibration due to traffic, vibration effect, prediction models, guidelines and standards.

Chapter 3 describes the research methodology of this study. This chapter explains the methodology including location of the sites, flow chart of the study general plan, data collection and methodology involved in modelling the GBV. Chapter 4 discusses data analysis and outcome of the model developed. All developed models were validated through some processes in order to test its accuracy and this is discussed in Chapter 5. Sensitivity analysis and application of the models are presented in Chapter 6. The last chapter, Chapter 7 summarizes the major findings of this research, conclusions together with future research recommendations.

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