

### **UNIVERSITI PUTRA MALAYSIA**

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

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### 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

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### 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<th:Professor Bujang Bin Kim Huat, PhD</th>Faculty: Engineering

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, 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

#### NORLIANA SULAIMAN

#### Oktober 2017

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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.

 $\bigcirc$ 

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.



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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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### 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
$V_{\rm w}$	Weighted velocity
DOE	Department of Environmental
RMS	root mean square
VC	Vibration curve
VDV	Vibration dose value
W <sub>b</sub>	Vertical motion
W <sub>d</sub>	Horizontal motion
SASW	Spectral analysis surface wave
ATC	Automatic traffic counter
TMS	Time mean speed

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### **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.



#### REFERENCES

- Ab Mughni, A. G., Adnan, M. A., Zamalik, S. Z., Jamali, F., Mohammad, M., Karim, Z. A., dan Sulaiman, N. (2016). Evaluation of Operating Speed at Multilane Highway along Jalan Meru: Case Study of Reliability of Posted Speed Limit. In *InCIEC 2015* (pp. 995-1006). Springer Singapore.
- Adnan, M. A., Adnan, N., and Sulaiman, N. (2012). Visual Field Monitoring of Road Defect and Modeling of Road Pavement Vibration From Moving Truck Traffic. IEEE Colloquium on Humanities, Science and Engineering Research, CHUSER2012. Sabah, Malaysia.
- Adnan, M. A., Sulaiman, N., Zainuddin, N. I. and Besar, T. B. H. T. (2013). Vehicle speed measurement technique using various speed detection instrumentation. In Business Engineering and Industrial Applications Colloquium (BEIAC), IEEE (pp. 668-672). IEEE.
- Agostinacchio, M., Ciampa, G. & Olita, S. (2014). The Vibration Induced by Surface Irregularities in Road Pavements- a Mathlab<sup>@</sup> approach. European Transportation Research Review, 6, 267-275.
- Amick, H., Gendreau, M., Busch, T. and Gordon, C. (2005) Evolving criteria for research facilities: I Vibration. Proceedings of SPIE Conference 5933: Buildings for Nano scale Research and Beyond San Diego, CA, 31 Jul. to 1 Aug.
- Arahan Teknik Jalan (2013). Manual for the structural Design of the Flexible Pavement. Cawangan Kejuruteraan Jalan dan Geoteknik. Public Work Department of Malaysia.
- ATJ (Arahan Teknik Jalan) (2014). (A Guide on Geometric Design of Roads) (Pindaan 2014). Cawangan Kejuruteraan Jalan dan Geoteknik. Public Work Department of Malaysia.
- ARRB (Australian Road Research Board) Group (2009). User Manual Roughnometer III. Vermont South, Australia. . Part No: UM-RM3-USR. Issue Date 2/7/2009.
- ASCE (American Society of Civil Engineers) (2006). Seismic Rehabilitation of Existing Buildings. ASCE/SEI 41-06, Reston, VA.
- ASCE (American Society of Civil Engineers) (2010). Minimum Design Loads for Buildings and Other Structures. ASCE/SEI 7-10, Reston, VA.
- Bahrekazemi M. (2004). Train-induced ground vibration and its prediction. PhD Thesis, Royal Institute of Technology, Sweeden.
- Bay, J.A. (2000). Site characterization using the spectral analysis of surface waves method. Seminar at the University of Alabama at Birmingham.

- Besar, T. B. H. T., and Adnan, M. A. (2015). Modelling Malaysian operating speed prediction model at two-lanes rural highway while exiting curve. International Journal of Advanced and Applied Sciences, 2(12), 67-72.
- Berezan, J.J. (2006). Human Vibration Monitoring System. M.Sc. Thesis, University of Alberta, Canada.
- Bencat, J. (1993). Investigation of traffic induced ground vibration by random process theory. International conference on Case History in Geotechnical Engineering. June 1-4. No 4.11.
- BS 1377 (1990). Methods of test for soils for civil engineering purposes. General requirements and sample preparation. Part 1.
- BS 6472-1(2008). Guide to evaluation of human exposure to vibration in buildings Part 1: Vibration sources other than blasting.
- British Standard. (1990). (BS 7385-1).Evaluation and measurement for vibration in buildings. *Part 1.Guide for Measurement of Vibrations and Evaluation of Their Effects on Buildings*. Retrieved from http://vibration.shef.ac.uk/doc/0441.pdf
- Building Seismic Safety Council (2003). NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures and Accompanying Commentary and Maps, FEMA 450, Chapter 3, pp. 17–49.
- Braile, L. (2010). Seismic Wave Demonstrations and Animations. Purdue University. (http://web.ics.purdue.edu/~braile/edumod/waves/WaveDemo.htm)
- California Building Standards Commission (2010). California Building Code, California Code of Regulations Title 24, Part 2, Volume 2 of 2.
- Cao, Y. M., Xia, H., & Lombaert, G. (2010). Solution of moving-load-induced soil vibrations based on the Betti-Rayleigh Dynamic Reciprocal Theorem. Soil Dynamics and Earthquake Engineering, 30(6), 470–480. https://doi.org/10.1016/j.soildyn.2010.01.003
- Cenek, P.D., Sutherland, A.J. and McIver, I.R. (2012) Ground vibration from road construction. NZ Transport Agency research report 485. 80pp.
- CDOT (2013). Transportation and Construction Vibration Guidance Manual. September 2009 California: California Department of Transportation.
- CDOT (2006). Seismic Design Criteria. (California Department of Transportation) Version 1.4, June.
- Chan, C. M. (2010). Bender Element Test in Soil Specimens: Identifying the Shear Wave Arrival Time. EJGE 15, 1263–1276.
- Chua, K. H. Lo, K. W., and Balendra. T, (1995). Building Response Due To Subway Train Traffic. Journal of Geotechnical Engineering, Vol. 121, No. 11.

- COTO, Committee of Transport Officials (2007).Guidelines for Network Level Measurement of Road Roughness. Version 1.0. April. South Africa.
- Crispino, M. and D'Apuzzo, M. (2001). Measurement and Prediction of Traffic-Induced Vibrations in a Heritage Building. Journal of Sound and Vibration, 246(2), 319-335.
- Das, B.M. and Luo, Z. (2015). Principles of Soil Dynamics. 3<sup>rd</sup> Edition. Cengage Learning, USA.
- Das, B.M. and Ramana, G.V. (2011). Priciples of Soil Dynamics. 2<sup>nd</sup> Edition. Cengage Learning, USA.
- DOE (2007). The Planning Guidelines for Vibration Limits and Control in the Environment. Department of Environment, Ministry of Natural Resources & Environment, Malaysia.
- DIN-3. (1999).Deutsches Institut f<sup>\*</sup>ur Normung. Structural vibrations Part 3: Effects of vibration on structures.
- Du, Y., Liu, C., Wu, D. and Jiang, S.C. (2014) Measurement of International Roughness Index by Using Axis Accelerometers and GPS. Mathematical Problems in Engineering Volume. (http://dx.doi.org/10.1155/2014/928980)
- Gámez, H. V., Rodríguez, A. R. and Valencia. D. R. (2011). Measurement and interpretation of vibrations produced by the traffic in Bogota D.C. Rev. ing. constr. vol.26 no.1 Santiago. Revista Ingeniería de Construcción Vol. 26 No 1, 61-80.
- Geophysical Survey Fact File. Retrieved on 13 March 2017. http://www.geophysical.biz/seisrf1.htm
- George and Mallery (2010). SPSS for windows step by step: A simple Guide and reference (17.0 ed.) Boston: Pearson.
- Gillespie, T.R., Sayers, M.W., and Segel, L. (1980). Calibration and Correlation of Response-Type Road Roughness Measuring Systems. Final Report. Highway Safety Research Institute, University of Michigan, Ann Arbor, Michigan.
- Guan Tan, C., Majid, T.A., Ariffin, K.S. and Bunnori, N.M. (2012). Site-Specific Empirical Correlation between Shear Wave Velocity and Standard Penetration Resistance using MASW Method. IEEE Colloquium on Humanities, Science & Engineering Research (CHUSER 2012), December 3-4, Kota Kinabalu, Sabah, Malaysia
- Gupta, S., Liu, W.F., Degrande, G., Lombaert, G., and Liu. W.N. (2008). Prediction of vibrations induced by underground railway traffic in Beijing. Journal of Sound and Vibration 310, 608-630
- Gutowski T. G. and Dym C. L. (1976). Propagation of Ground Vibration: A Review. Journal of Sound and Vibration 49(2), 179-193.
- Hajek, J.J., Blaney C. T. and Hein, D. K. (2006). Mitigation of Highway Traffic-Induced Vibration. Session on Quiet Pavements: Reducing Noise and Vibration

Annual Conference of the Transportation Association of Canada Charlottetown, Prince Edward Island.

- Hao, H. and Hang, T. C. (1998) Measurement and analysis of impact pile driving induced surface ground motions", Journal of Civil and Structural Engineering, the Institution of Engineers, Singapore, Vol. 38(2), pp19-26.
- Henwood, J.T. and Haramy, K.Y. (2002). Vibrations Induced by Construction Traffic: A Historic Case Study. (Retrieved on 29 July 2015-(http://www.dot.ca.gov/hq/esc/geotech/geo\_support/geophysics\_geology/pdf/ge ophysics\_2002/043henwood\_construction\_vibrations.pdf)
- Hons, M., Stewart, R., Lawton, D., Bertram, M. and Hauer. G. (2008). Accelerometer vs. Geophone Response: A Field Case History. CSPG/CSEG/CWLS GeoConvention 2008, Calgary, Alberta, Canada, May 12-15.
- http://www.environmental-geophysics.co.uk/documentation/info/seismics.pdf (retrieved on 13 March 2017)
- Hunaidi, O. (2000). Traffic Vibration in Buildings. Construction Technology Update No 39. Institute for Research in Construction, Canada.
- Hunaidi O, Guan W, Nicks J. (2000). Building vibrations and dynamic pavement loads induced by transit buses. Journal of Soil Dynamics and Earthquake Engineering; 19(6):435–53.
- Hunaidi, O. and Tremblay, M. (1997). Traffic-induced Building Vibration in Montreal. Canadian Journal of Civil Engineering, 24(5), 736-753.
- Hunaidi, O., Rainer, J, H. and Pernica, G. (1994). Measurement and Analysis of Traffic-Induced Vibration. Second International Symposium- Transport Noise and Vibration, St Petersburg, Russia. 103-108.
- Hunt H. E. M. and Hussein M. F. M. (2007). Ground-Borne Vibration Transmission from Road and Rail Systems: Prediction and Control. Handbook of Noise and Vibration Control. John Wiley & Sons, Inc.
- Hunt, H.E.M. (1991) 'Stochastic modelling of traffic-induced ground vibrations", Journal of Sound and Vibration 144, 53-70.
- Ismail N.N. (2012). Refinement of Beam Forming Technique for Practical and Reliable Stiffness Profiling. Master Thesis. Chung-Ang University.
- ISO 2631-1.International Organization for Standardization. (1997). Mechanical vibration and shock Evaluation of human exposure to whole-body vibration Part 1: General requirements.
- ISO 2631-2. International Organization for Standardization. (2003). Mechanical vibration and shock Evaluation of human exposure to whole-body vibration Part 2: Vibration in buildings (1 Hz to 80 Hz)
- Javier Fernando Camacho-Tauta, Juan David Jiménez Álvarez and Oscar Javer Reyes-Ortiz.(2012) A Procedure to Calibrate and Perform the Bender Element

Test. Print version ISSN 0012-7353. Dyna rev.fac.nac.minas vol.79 no.176 Medellín Nov. /Dec.

- Ju, S.H. (2009). Finite Element Investigation of Traffic Induced Vibrations. Journal of Sound and Vibration, 321, 837-853
- Kliukas, R., Kačianauskas, R. and Jaras, A. (2008). Investigation of Traffic-Induced Vibration in Vilnius Arch-Cathedral Belfry, Transport 23(4): 323–329. doi:10.3846/1648-4142.2008.23.323-329

Klæboed, R., Turunen-Rise, I.H., Harvik, L., Madshus, C. (2003). Vibration in Dwellings from Road and Rail Traffic-Part II: A New Norwegian Measurement Standard and Classification System. *Applied Acoustics*, 64, 89–109.

- Kouroussisa, G., Conti, C. and Verlinden, O. (2013). A numerical analysis of the influence of tram characteristics and rail profile on railway traffic ground-borne noise and vibration in the Brussels Region. STOTEN-14840; No of Pages 9.
- Kouroussisa, G., Conti, C. and Verlinden, O. (2014). Building vibrations induced by human activities: a benchmark of existing standards. Mechanics & Industry 15, 345–353.
- Kutz, M. (2011). Handbook of Transportation Engineering. McGraw-Hill Education.
- Kuznetsov, S.V. and Nafasov, A.E. (2011). Horizontal Acoustic Barriers for Protection from Seismic Waves. Advances in Acoustics and VibratioN. Volume 2011, Article ID 150310.
- Kyong-Soo, Y. (1987). An empirical analysis of the behavior of weaving traffic in a freeway weaving section. PhD, Dissertation. Ohio State University.
- Lak, M.A., Degrande, G. and Lombaert, G. (2011). The Effect of Road Uneveness on The Dynamic Vehicle Response and Ground-Borne Vibration due to Road Traffic. Soil Dynamics and Earthquake Engineering, 31, 1357-1377.
- Leslie, D. and Sarah, S. (2000). University of the West of England, Bristol in association with Swiss Federal Technical Institute, Zurich. May. Based on part of the GeotechniCAL reference package by Prof. John Atkinson, City University, London. (Retrieved on 13 November 2017 http://environment.uwe.ac.uk/geocal/SoilMech/basic/soilbasi.htm)
- Liu, X., Yang, J., Wang, G. and Chen, L. (2016). Small-strain shear modulus of volcanic granular soil: An experimental investigation. Soil Dynamics and Earthquake Engineering 86, 15–24.
- Lombaert G, and Degrande G. (2001). Experimental validation of a numerical prediction model for free field traffic induced vibrations by in situ experiments. Soil Dynamic Earthquake Engineering; 21:485–97.
- Lombaert G, and Degrande G. (2003). The experimental validation of a numerical model for the prediction of the vibrations in the free field produced by road traffic. Journal of Sound and Vibration 262, 309–331

- Lombaert, G. and Degrande, G. (2009). Ground-borne vibration due to static and dynamic axle loads of InterCity and high-speed trains. Journal of Sound and Vibration 319, 1036–1066.
- Lai, C. G. (2000). Spectral Analysis of Surface Waves Active Methods Technical Recommendations.
- Long, L.T. (1993). Measurements of Seismic Road Vibrations. In Proceeding of the Third International Conference on Case Histories in Geotechnical Engineering, Paper # 4. 10 p. 677-680.
- Madshus, C., Bessason, C., and Harvik, L. (1996) "Prediction model for low frequency vibration from high speed railways on soft ground," J. Sound Vib., vol. 193, no. 1, pp. 195–203.
- Marcotte P, Beaugrand S, Boutin J, Larue C. (2010). Design and evaluation of a suspension seat to reduce vibration exposure of subway operators: a case study. Ind Health; 48 (5):715-24.
- Mathew Tom V. (2010). Traffic stream models. Lecture notes in Transportation Systems Engineering. Retrieved on 20 February 2017. (https://www.civil.iitb.ac.in/tvm/1100\_LnTse/503\_lnTse/plain/plain.html)
- MOA (Ministry of Agricultural), (1966). Selangor Schematic Reconnaissance Soil Map. Director of Agricultural Malaysia.
- MDOT (Minnesota Department of transportation) (2007). Bituminous Smoothness Training Workshop. (http://www.dot.state.mn.us/materials/smoothnessdocs/IRIIntroduction.pdf)
- Meyer, K. (2011). Handbook of Transportation Engineering. Volume II: Application and Technology. McGraw Hill Companies, Inc.
- Mhanna, M., Sadek, M., & Shahrour, I. (2012). Numerical modelling of trafficinduced ground vibration. Computers and Geotechnics, *39*, 116–123. https://doi.org/10.1016/j.compgeo.2011.07.005
- MHCM (Malaysian Highway Capacity Manual) (2011). Highway Planning Unit. Ministry of Works Malaysia.
- Mohamed, N., Sulaiman, N., Adnan, M. A., & Diah, J. M. (2016). Validation of Operating Speed Prediction Model for Horizontal Curve with Established Models. InCIEC 2015 (pp. 921-934). Springer Singapore.
- Paneiro, G., Durao, F.O., Costa e Silva, M., Falcao Neves, P. (2015). Prediction of Ground Vibration Amplitudes Due to Urban Railway Traffic Using Quatitative and Qualitative Field Data. Transportation Research Part D 40, 1-13.
- Paolucci, R., Maffeis, A., Scandella, L., Stupazzini, M., and Vanini, M. (2003). Numerical prediction of low-frequency ground vibrations induced by high-speed trains at Ledsgaard, Sweden. Soil Dynamics and Earthquake Engineering 23, 425–433.

- Park H. M., (2002). Univariate Analysis and Normality Test Using SAS, STATA, and SPSS-Univariate Analysis and Normality Test. The Trustees of Indiana University. http://www.indiana.edu/~statmath.
- Picouxa, B. Rotinat, R. Regoin, J.P. Houedec, D. L. (2003). Prediction and measurements of vibrations from a railway track lying on a peaty ground. Journal of Sound and Vibration 267,575-589.
- Quaternary Geological Map of Peninsular Malaysia (1989). First Edition. Published by The Director General of Geological Survey Malaysia.
- Rosenblad, B., Rathje, E.M. and Stokoe, K.H. (2006). Shear Wave Velocity Profiling by the SASW Method at Selected Strong-Motion Stations in Turkey. (Retrieved on 13 March 2017) (http://peer.berkeley.edu/lifelines/lifelines\_pre\_2006/final\_reports/2A02a-FR.pdf)
- Salvador, P., Real, J., Zamorano, C. and Villanueva. A. (2011). A procedure for the evaluation of vibrations induced by the passing of a train and its application to real railway traffic. Mathematical and Computer Modelling 53, 42–54.
- Sayers, M. W., Gillespie, T.R., Paterson, P.O. (1986). Guideline for Conducting and Calibrating Road Roughness Measurements. World Bank Technical Paper Number 46. The World Bank Washington D.C. USA.
- Shun, L. J., Dong Z. X. and Wei, Z.H. (2014). Experimental Study on the Dynamic Characteristic of Soft Soil under Cyclic Loads. Journal of Highway and Transportation Research and Development. Vol 8, No. 4, 018.
- Stein, S. and Wysession, M., 2003. An Introduction to Seismology, Earthquakes, and Earth Structure, Blackwell Publishing, Malden, Massachusetts, USA.
- Stokoe, K.H., II and Santamarina, J.C. (2000), Seismic-wave-based testing in geotechnical engineering, GeoEng 2000, Proceeding International Conference on Geotechnical and Geological Engineering., Melbourne, Australia, 1490-1530.
- Tuan Chik, T. N., Asiew, R.A., Ibrahim, M.H.W. and Yusoff, N.A. (2013). Dynamic Performance on Multi Storey Due to Ground Borne Vibrations Input From Passing Vehicles. International Journal of Integrated Engineering, 5(2), 51-58.
- Tuan, B.T.B.H., Adnan, M. A., Sulaiman, N., Zainuddin, N. I. and (2013). Vehicle speed measurement technique using various speed detection instrumentation. In Business Engineering and Industrial Applications Colloquium (BEIAC), IEEE (pp. 668-672). IEEE.
- Turunen-Rise IH (2001).Assessment of Vibrations from Landbased Transport- A Norwegian Standards. Journal of Low Frequency Noise, Vibration and Active Control. Vol. 2 No 3. Page 21-28
- Turunen-Rise IH, Brekke A, Hårvik L, Madshus C, Klaeboe R, (2003). Vibration in dwellings from road and rail traffic Part I: A new Norwegian measurement

standard and classification system. Applied Acoustics, 64(1), 71–87. http://dx.doi.org/10.1016/S0003#-682X(02)00052-X.

- Wair, B.R., De Jong, J.T. and Shantz, T. (2012). Guidelines for Estimation of Shear Wave Velocity Profile. PEER Report 2012/08. Pacific Earthquake Engineering Research Center, Headquarters at the University of California, California.
- Wan Yaacob, W.Z, Samsudin, A.R., Ramziemran, M. & Loon, C.Y. (2004). Natural absorption capability of heavy metals: Granitic residual soil from Broga and marine clay from Sg. Besar Selangor. Geological Society of Malaysia, Bulletin 48. June, p. 13 -16
- Watts, G.R. (1990). Traffic Induced Vibrations in Buildings. Research report 246. Transport and Road Research Laboratory, Crowthorne, Berkshire.
- Watts, G.R. and Krylov, V.V. (2000). Ground-borne vibration generated by vehicles crossing road humps and speed control cushions. Applied Acoustic, 59, 221-236
- Watts, G. R., & Stait, R. E. (2008.). Characteristics of vehicles producing excessive noise and ground- borne vibration Phase 1.
- White Industrial Seismology Inc. (2009). Mini-Seis Digital Seismograph. Operating Manual.
- WinSASW version 3.2.6 software. Data Interpretation and Analysis for SASW Measurements. Universiti of Texas.
- With, C., Bahrekazemi, M. and Bodare, A. (2006). Validation of an empirical model for prediction of train-induced ground vibrations. Soil Dynamics and Earthquake Engineering 26, 983-990.
- Wong, I.F.T. (1970). Reconnaissance Soil Survey of Selangor. Ministry of Agriculture and Lands, Malaysia. Buletin 122.
- Xu, Y.L., & Hong, X.J. (2008). Stochastic Modelling of Traffic-Induced Building Vibration. Journal of Sound and Vibration. 313 (1–2), 149-170.
- Yin, C.L. (2007).Characterizing Shear Wave Velocity Profiles by the SASW Method and Comparison with other Seismic Methods. PhD Thesis. The University of Texas at Austin, US.
- Zainuddin, N. I., Adnan, M. A. & Md Diah, J. (2013). Optimization of Speed Hump Geometric Design: Case Study on Residential Streets in Malaysia. Journal of Transportation Engineering, 140(3), 05013002
- Zomorodian S.M.A., Hunaidi, O., (2006). Inversion analysis of SASW dispersion curve based on maximum flexibility coefficients in the wave number domain. Soil Dynamics and Earthquake Engineering 26, 735–752.

#### LIST OF PUBLICATIONS

- Sulaiman, N., Azureen, F., Adnan, M.A. & Huat, B.K., (2013). Investigation of Ground-borne Vibration Due to road Traffic Parameter: A Case Study at Lenggong, Perak. IEEE Symposium on Business, Engineering and Industrial Application. Sarawak, Malaysia.
- Sulaiman, N., Idayu, M., Adnan, M.A. & Huat, B.K. (2013). Relationship of Ground Borne Vibration with Moving Vehicles Traffic Parameter: A Case Study in Marang, Terengganu. IEEE Symposium on Business, Engineering and Industrial Applications. Sarawak, Malaysia.
- Sulaiman, N (2016). Critical Review of Ground-Borne Vibration and Impact Assessment: Principle, Measurement and Modelling. *Pertanika Journal of Scholarly Research Reviews*. PJSRR (2016) 2(1): 22-23. Universiti Putra Malaysia Press.
- Sulaiman, N, Asadi, A. & Huat, B.K. (2017) Empirical Statistical Model for Prediction of Ground Borne Vibration Incorporating Shear Wave Velocity. Journal of Soil Dynamics and Earthquake Engineering. (Under review)
- Sulaiman, N, Adnan, M.A., Huat, B.K. & Nahazanan, H. (2017) Empirical Modelling Of Ground Borne Vibration Imposed By Road Traffic on Soft Ground. *Journal* of Transportation Part D: Transport and Environment. (Under Review)



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