EXPANDED POLYSTYRENE SMALL-SCALE MODEL FOR SIMILITUDE STUDIES OF ELEVATED WATER TANK

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DEDICATION

This thesis is wholeheartedly dedicated to my parents, who have been my source of inspiration and gave us strength when I thought of giving up, who continually provide my moral, spiritual, emotional and financial support.

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ABSTRACT

In June 2015, Malaysia was shocked by a strong earthquake in Sabah. Three years later, another earthquake of 5.2 magnitude occurred in the same area. These incidents have triggered structural engineers in Malaysia to consider seismic analysis during load calculation process during the analysis phase. A full-scale seismic test is often expensive and time-consuming to construct, while a small-scale test is found rather limited and the activities are still rare among local engineers. Most of the existing small-scale tests use the same material of reinforced concrete, which has nearly 10 times model in mass due to dynamic effect and dangerous to implement. In this study, the probability to replace the material used in full-scale testing with more suitable material with equivalent properties to concrete in small-scale testing is investigated. This is achieved by conducting a seismic performance study of an elevated water tank scale model using expanded polystyrene (EPS) material. EPS was selected as the material for this study since it has high compression and low tensile value. The main objective of this study is to obtain the dynamic characteristic and ultimate behaviour of a small-scale model made with EPS. To conduct this study, 10 experimental models with different heights, types of coated layers and reinforcements were considered to vary their stiffness. The material was tested using compression test and hysteresis test to acquire the E-value for the material. Then, the model was tested using the shaking table test and the response acceleration was recorded using accelerometers. The value of natural frequency and deformed shape of the experimental model were compared and verified against Finite Element Method (FEM) modal analysis by Autodesk Simulation Mechanical software. The results show that, among the 10 experimental models, the model with mortar and paint coated layers reinforced with 6 rods of 2 mm steel rods and 0.55 mm steel mesh demonstrated a good agreement in terms of natural frequency value compared to the FEM analysis. This study has proven that a proper setting of reinforcement of the small-scale model can lead to a better prediction of real seismic behaviour, thus offering an alternative material replacement for concrete that would aid time and cost savings.

ABSTRAK

Pada Jun 2015, Malaysia telah dikejutkan dengan satu gempa bumi yang kuat di Sabah. Tiga tahun kemudian, satu lagi gempa bumi berukuran 5.2 berlaku di kawasan yang sama. Kejadian tersebut telah mencetuskan kesedaran kepada jurutera struktur di Malaysia bagi mengambil kira analisis seismik semasa proses pengiraan beban ketika fasa analisis. Ujian seismik berskala penuh adalah mahal dan mengambil masa yang lama untuk dibina, manakala ujian berskala kecil pula sukar untuk dijumpai dan dianggap bukan kebiasaan dalam kalangan jurutera di Malaysia. Sebilangan besar ujian skala kecil menggunakan bahan konkrit bertetulang yang sama, mempunyai model hampir 10 kali ganda kerana kesan dinamik dan berbahaya untuk dilaksanakan. Dalam kajian ini, kebarangkalian untuk menukar bahan yang digunakan dalam ujian berskala penuh dengan bahan yang lebih sesuai yang mempunyai ciri seakan dengan konkrit disiasat. Ini boleh dicapai dengan menjalankan kajian terhadap prestasi seismik tangki air yang diperbuat daripada bahan polistirena. Polistirena dipilih sebagai bahan kajian kerana mempunyai nilai daya mampatan yang tinggi dan nilai ketegangan yang rendah. Objektif utama kajian ini ialah untuk mendapatkan ciri dinamik dan kelakuan muktamad model berskala kecil yang diperbuat dari polistirena. Untuk menjalankan kajian ini, 10 model eksperimen yang terdiri daripada pelbagai ketinggian dan dilapisi pelbagai lapisan dan pengukuhan digunakan untuk mengubah kekuatan mereka. Bahan tersebut diuji dengan ujian mampatan dan ujian histerisis bagi mendapatkan nilai E bagi bahan tersebut. Selepas itu, model struktur diuji di atas meja gegaran dan pecutan tindak balas direkodkan menggunakan "accelerometer". Nilai frekuensi semula jadi dan kerosakan bentuk model eksperimen dibandingkan dan disahkan melalui kaedah unsur terhingga (FEM) dengan menggunakan perisian "Autodesk Simulation Mechanical". Hasil kajian mendapati bahawa daripada 10 model eksperimen, model yang menggunakan mortar dan cat sebagai lapisan luar dan dikukuhkan dengan 6 batang keluli berukuran 2 mm dan 0.55 mm keluli fabrik menunjukkan tanda positif dalam terma nilai frekuensi semula jadi apabila dibandingkan dengan perisian FEA. Kajian ini menunjukkan, penetapan yang betul dalam pengukuhan model berskala kecil boleh membawa kepada ramalan yang lebih baik dalam tingkah laku seismik yang sebenar, seterusnya dapat menawarkan bahan alternatif lain untuk menggantikan konkrit yang mampu menjimatkan masa dan kos.

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LIST OF ABBREVIATIONS

A.M	-	Ante Meridiem
FRF	-	Frequency Response Function
EMA	-	Experimental Modal Analysis
EPS	-	Expanded Polystyrene
DOF	-	Degree of Freedom
RC	-	Reinforced Concrete
OPC	-	Ordinary Portland Cement
UTM	-	Universiti Teknologi Malaysia
M1	-	Model 1
M2	-	Model 2
M3	-	Model 3
M4	-	Model 4
M5	-	Model 5
M6	-	Model 6
M7	-	Model 7
M8	-	Model 8
M9	-	Model 9
M10	-	Model 10
FEA	-	Finite Element Analysis
PGA	-	Peak Ground Acceleration
ULS	-	Ultimate Limit State

LIST OF SYMBOLS

L	-	Length
M	-	Mass
F	-	Force
v	-	Velocity
T	-	Time
I	-	Moment of Inertia
r	-	Radius
a	-	Acceleration
L_p	-	Length of Prototype
L_m	-	Length of Model

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CHAPTER 1

INTRODUCTION

On 5 June 2015, an earthquake with 6.0 magnitude struck Ranau district in Sabah, Malaysia at 7.15 AM for 30 seconds which had killed 18 people due to rock falls on Mount Kinabalu. On 8 March 2018, another earthquake measuring 5.2 magnitude occurred again near the same place. These incidents had triggered a warning to structural engineers in Malaysia to consider seismic analysis during the process of structural analysis. Since Malaysia is located outside from the ring of fire, earthquake phenomenon rarely occurs in Malaysia. Thus, there are not many studies regarding earthquakes in Malaysia since engineers do not consider lateral force action on the building. A structure designed without seismic consideration can cause a huge catastrophic and killed thousands of people.

This study was aimed at developing a composite material for civil structure products in scaled-down seismic analysis of elevated water tank. By comparing the location of weak points of the scaled model with weak points of the building using software analysis, determination of suitable prototype in the scaled-down seismic analysis can be performed.

1.1 Background of the Study

Structural model is defined as any physical representation of structural elements built to a reduced scale (in comparison with full size structures) to be tested. Since their early days, scale models have been used in many disciplines such as hydraulics, structural engineering, naval architecture, automotive, aeronautical engineering as well as meteorology and geophysics. Hydraulic engineering models have been studied as early as the late 1800s with considerable success. Studies regarding fluid motion in pipes, pumps and open channels and wave action beach erosion have all been successfully carried out by means of physical models. Naval architects have for a long time relied on the use of physical models in designing ships. All important features of ship design such as ship manoeuvrability in smooth and rough seas, ship bending; and vibrations have been examined using scale models in model testing tanks or water basins.

However, scaling often poses problems because although the models are reduced geometrically (e.g. $1/8^{th}$ scale), they retain the same behavioural characteristics of the full-scale materials even if the material properties have been re-engineered. Thus, the failure in scaled modelling experiment can result in representative models. It is also well known that structures under dynamic loads do not usually follow the scaling laws due to effects such as material strain rate sensitivity. In that case, appropriate model materials must be substituted, and reduced-size structure must be properly designated as a model.

1.2 Problem Statement

In civil engineering, small scale models have been commonly used using reinforced concrete and steel to experimentally study the seismic performance of the structures since the capacities of testing facilities are limited; and are more economically viable. For example, Xu, Yang, Zhang and Yu conducted an experiment using 1:5 scale for multi-story reinforced concrete frame structure using C35 concrete grade. Usually, concrete using similar grade of full scale are widely used in small scaled model lab tests, causing a difficulty in achieving dynamic similarity. The procedure for small scaled concrete modelling requires long duration, high cost, high skilled personnel and can cause a problem if one does not have enough manpower. Cost for even a concrete modelling is more expensive due to more tools and material needed. Concrete material consisting of cements, small aggregate(sand), large aggregate(pebbles) and plasticizer (to increase workability) can form any structural shapes as long as the formwork is allowed. Constructing formwork for small scaled concrete members is complicated and need excellent and detailed workmanship. Meanwhile, assembling and disassembling of the formwork requires multiple tries and errors.

In many cases, a proposed small-scale structure does not effectively represent the real structure problem since the stiffness of structural materials used are relatively stiffer than the full scale. Particularly in dynamic analysis, a reinforced concrete structural model was often used to construct the small-scale model, and this may result in an addition of nearly ten times the mass of the model due to dynamic effect, which has been proven dangerous during the test. In this situation, a replacement of concrete materials for the scaled structure is vital.

Since the 1950s, expanded polystyrene (EPS) is one of the building materials capable of enhancing the design and structural integrity of the building. It is utilized in many building structures owing to its sustainability benefit and improvement in terms of energy efficiency, durability and indoor environmental quality. (Ramli Sulong, Mustapa, & Abdul Rashid, 2018). In general, the use of EPS can effectively reduce the risk of earthquake damage since the earthquake acceleration and its magnitude is mainly depending on the weight of the structure (Sayadi, Tapia, Neitzert, & Clifton, 2016). Since there are limited studies on the considerations of EPS material in the development of small-scale models, a research question on whether the EPS is feasible to be used as a replacement to concrete materials in a scaled structure should be addressed. For this purpose, a study on the dynamic characteristics and ultimate behaviour of a scaled structural model using EPS shape layered with mortar are worth of study.

1.3 The Objective of the Study

The overall aims of the study are to determine the feasibility of using EPS as a concrete replacement for a small-scale model in predicting the real behaviour of the prototype structure. The objectives that need to be achieved are:

1) To obtain the dynamic characteristics through modal analysis of several proposed small-scale model with new forming material of EPS
2) To determine the dynamic ultimate behaviour of small-scale model made with polystyrene using time history table.
3) To determine the relationship between the small-scale model and the prototype structure using finite element analysis.

1.4 Scope of Study

In this study, several scaled down models of elevated conical water tanks, possibly of a ratio 1:15, with different considerations of column height and coating layers were studied and tested in a laboratory using modal test and time-history shaking table. Here, the water tank structure was selected due to its simplicity as it is known as a single degree-of-freedom structure, and since the main concern of this study is on the effect of EPS as concrete-replacement material. Various seismic intensities for the dynamic test are considered including the scaled magnitude of Ranau (Sabah) earthquake in 2015. Meanwhile, the layered polystyrene material properties were tested for compressive strength, elasticity modulus and hysteresis value. Finite element software analysis of Autodesk Simulation Mechanical is used to validate the results from experimental works and also to extend the study on the prediction of the real behaviour of prototype structure. In this study, the stress and strain of the materials reinforcements are not included and observation is made at the global behaviour level of water tank at the ultimate limit state, in particular, the modal properties and ultimate failure of the models.

1.5 Significance of Research

This study produces a new composite material with a reasonable methodology in structural engineering testing of a scaled model considering dynamic and seismic loads. Rapid prototyping methodology can be used to prove the accuracy of the small-scale model against the real dynamic structural analysis. Moreover, rapid prototyping can also be used to assess the capability of existing building structures to immediately determine whether the structure is capable of resisting seismic events or not, up to the level of reliability analysis of the building. Such a contribution is very significant for the situation in Malaysia, where preparation and retrofitting can quickly be made to strengthen the existing building to restrain the seismic force during unpredictable seismic events.

1.6 Flow of the thesis

Chapter 1 describes the background of research, problem statements and its aim and objectives. It also discussed the scope of study, significance of the research and ended with brief summary of the flow of thesis.

Chapter 2 presents the findings of the literature review. It focuses on the small scaled model testing of the structure on the shaking table test. Besides that, the behaviour of the elevated water tank from Finite Element Analysis (FEA) are summarized in this chapter. Then, the review for analytical, experimental and numerical studies of Expanded Polystyrene (EPS) material in geotechnical area.

Chapter 3 introduces the operational framework of the research. In this chapter, the small scaled structures dimensions, research instruments and experimental testing procedures were described in more detail. Lastly, the modelling of the small scaled structure was illustrated in this chapter.

All recorded experimental laboratory results are placed in Chapter 4. Material properties, hysteresis curve, chirp burst test results and free vibration test results were placed in chapter 4. Furthermore, the shaking table test result for 10 small scaled models were discussed in detailed in this chapter. Then, this chapter describes the procedures and results for Finite Element Analysis. FEA results were then compared with validation test and experimental results in term of failure mode. Then, natural frequencies values obtained from experimental results during shaking table test were compared with the natural frequency obtain from FEA.

Chapter 5 concludes the results of the research. The recommendation for future study were presented in this chapter.

REFERENCES

Balawi, S., Shahid, O., & Al Mulla, M. (2015). Similitude and Scaling Laws - Static and dynamic behaviour beams and plates. 1st International Conference on Structural Integrity.

Barret, A. R., Setareh, M., & Avci, O. (2006). Observation from Vibration Testing of In-Situ Structures. Structures Congress 2006, (pp. 1-10). Missouri.

Bathurst, R., Keshavarz, A., Zarnani, S., & Take, W. (2006). A simple displacement model for response analysis of EPS geofoam seismic buffers. Soil Dynamics and Earthquake Engineering.

Bayraktar, A., Sevim, B., Altunisik, A., & Turker, T. (2009). Effect of the model updating on the earthquake behaviour of steel storage tanks. Journal of Constructional Steel Research.

Beju, Y., & Mandal, J. (2017). Expanded polystyrene(EPS) geofoam: preliminary characteristic evaluation. Procedia Engineering.

Chen, W., Hao, H., Hughes, D., Shi, Y., Cui, J., & Li, Z.-X. (2015). Static and dynamic mechanical properties of expanded polystyrene. Materials and Design.

Coutinho, C., Baptista, A., & Rodrigues, J. (2016). Reduced scale models based on similitude theory : A review up to 2015. Engineering Structures.

Durgesh, R. C. (2001). Performance of elevated tanks in Mw 7.7 Bhuj earthquake of January 26th,2001 . Kanpur.

Ghateh, R., Kianoush, M., & Pogorzelski, W. (2015). Seismic response factors ofreinforced concrete pedestal in elevated water tanks. Engineering Structures.

Gurkalo, F., Du, Y., Poutos, K., & Jiminez-Bescos, J. (2016). The nonlinear analysis of an innovative slit reinforced concrete water tower in seismic regions. Engineering Structures.

Harris, H. G., & Sabnis, G. G. (1999). Structural Modeling and Experimental Techniques. CRC Press.

Ilki, A., & Kumbasar, N. (2000). Hysteresis Model for Reinforced Concrete Members. ASCE 14th Engineering Mechanics Conference.

Jabar, A., & Patel, H. (2012). Seismic Behaviour of RC Elevated Water Tank Under Different Staging Pattern And Earthquake Characteristic. International Journal of Advanced Engineering Research and Studies.

Jabar, A., & Patel, H. (2012). Seismic Behaviour of RC Elevated Water Tank Under Different Staging Pattern and Earthquake Characteristics. International Journal of Advanced Engineering Research and Studies.

Kim, N.-S., Lee, J.-H., & Chang, S.-P. (2007). Equivalent multi-phase similitude law for pseudodynamic test on small scale reinforced concrete models. Engineering Structures.

Lu, X., Zhou, Y., & Lu, W. (2007). Shaking table Model Test and Numerical Analysis of Complex High-Rise Building. The Structural Design of Tall and Special Buildings.

Malai, A., Youwai, S., & Jaturabandit, N. (2017). Stress-Strain Mechanism of Expanded Polystrene Foam under Cyclic Loading Conditions within and Beyond Yield States. 2017 International Conference on Transportation Infrastructure and Materials.

Mazzariol, L., Oshiro, R., & Alves, M. (2015). A method to represent impacted structures using scaled models made of different materials. International Journal of Impact Engineering.

Miha, T., Klemene, I., & Weiss, P. (2008). Seismic upgrading of old masonry buildings by seismic isolation and CFRP laminates: a shaking-table study of reduced scale models. Bull Earthquake Eng.

Momtazi, A., Langrudi, M., Haggi, A., & Atigh, H. (2010). Durability of Lightweight Concrete Containing EPS in Salty Exposure Conditions. Second International Conference on Sustainable Construction Materials and Technologies.

Moslemi, M., Kianoush, M., & Pogorzelski, W. (2011). Seismic response of liquid-filled elevated tanks. Engineering Structures.

Musa, A., & El Damatty, A. (2016). Capacity of liquid steel conical tanks under hydrodynamic pressure due to horizontal ground excitations. Thin-Walled Structures.

Omidinasab, F., & Shakib, H. (2012). Seismic Response Evaluation of the RC Elevated Water Tank with Fluid-Structure Interaction and Earthquake Ensemble. Journal of Civil Engineering.

Ossa, A., & Romo, M. (2010). Dynamic characterization of EPS geofoam. Geotextiles and Geomembranes.

Ozturk, U. E., & Anlas, G. (2010). Finite element analysis of expanded polystyrene foam under multiple compressive loading and unloading. Materials and Design.

Parmar, A., Patel, U., Parmar, A., Joshi, C., Vaghasiya, A., & Joshi, A. (2015). Light Weight Concrete Using EPS beads and Aluminium Powder. Asian International Confererence on Science,Engineering & Technology.

Ramli Sulong, N., Mustapa, S., & Abdul Rashid, M. (2018). Application of expanded polystyrene(EPS) in buildings and constructions: A review. Journal of Applied Polymer.

Sayadi, A. A., Tapia, J. V., Neitzert, T. R., & Clifton, G. C. (2016). Effect of expanded polystyrene(EPS) particles on fire resistance, thermal conductivity and compressive strength of foamed concrete. Construction and Building Materials, 716-724.

Schawrz, B., & Richardson, M. (1999). Experimental Modal Analysis. CSI Reliabilty Week.

Shah, Q. H., & Topa, A. (2014). Modeling Large Deformation and failure of Expanded Polystyrene Crushable Foam using LS-DYNA. Hindawi.

Shakib, H., & Alemzadeh, H. (2017). The effect of earthquake site-source distance on dynamic response of concrete elevated water tanks. X International Conference on Structural Dynamics, EURODYN 2017.

Shehadeh, M., Shennawy, Y., & El-Gamal, H. (2015). Similitude and Scaling of large structure elements: Case study. Alexandria Engineering Journal.

Sol, H. (2004). Identification of the material properties of slender composite structures.

Sol, H. (2014). Idenfication of the material properties of slender composite structures.

Soroushnia, S., Tafreshi, S., Omidinasab, F., Beheshtian, N., & Soroushnia, S. (2011). Seismic Performance of RC Elevated Water Tanks with Frame Staging and Exhibition Damage Pattern. Procedia Engineering.

Suhad, M., Dhamya, G., Maan, H., & Dunya, K. (2016). Effective Replacement of Fine Aggregates by Expanded Polystyrene Beads in Concrete. International Journal of Engineering Research and Science & Technology.

Sweedan, A., & El Damatty, A. (2001). Experimental and analytical evaluation of the dynamic characteristics of conical shells. Thin-Walled Structures.

Tagel-Din, H., & Meguro, K. (2000). Analysis of a Small Scale RC Building Subjected to Shaking Table Test Using Applied Element Method. 12th World Conference on Earthquake Enginnering.

Tongkul, F. (2016). The 2015 Ranau Earthquake : Cause and Impact. Sabah Society Journal Vol. 32.

Trandafir, A., Bartlett, S., & Lingwall, B. (2010). Behaviour of EPS geofoam in stress-controlled cyclic uniaxial tests. Geotextiles and Geomembranes.

Tsai, M.-h., Wu, S.-Y., Chang, K.-C., & Lee, G. (2006). Shaking table test of a scaled bridge model with rolling type seismic isolation bearings. Engineering Structures.

Zarnani, S., & Bathurst, R. (2008). Numerical modeling of EPS seismic buffer shaking table test. Geotextiles and Geomembranes.

Zarnic, R., Gostic, S., Crewe, A., & Taylor, C. (2000). Shaking table tests of 1:4 reduced-scale models of masonry infilled reinforced concrete frame building. EARTHQUAKE ENGINEERING AND STRUCTURAL DYNAMIC.

Zohuri, B. (2015). Dimensional Analysis and Self-Similarity Methods. Springer Publishing Company.

LIST OF PUBLICATIONS

Roslan, M. H. and Marsono, A. K. (2019). Dam break test for scaled down slab beam and flat slab Dom-ino house structural system. *GEOTROPIKA – ICHITRA 2019*