Slope Stability of Landfill with Waste Degradation

Salhana Ismail, Aizat Mohd Taib, Norinah Abd. Rahman, Dayang Zulaika Abang Hasbollah, Ahmad Bukhari Ramli

Abstract*: *Nowadays, a large amount of municipal solid waste (MSW) is generated due to the rapid urbanisation in developing countries leads to the demand for larger and higher capacity landfills. Bioreactor landfill technology has been introduced to accelerate the stability of landfill and to solve the issue of limited landfill area. However, the accelerated degradation of the refuse in bioreactor landfills also considerably changes the geotechnical characteristics of the waste in the landfill and thereby increases the concern for waste stability. Hence, this study aims to analyse the stability of both conventional and bioreactor landfill slope with the effects of waste degradation. Finite element method has been used in the slope stability analysis and the stability is presented by the factor of safety. The objectives of this study are i) to determine and assess the main parameter which influences the stability of the waste slope, ii) to determine the effects of waste degradation to the waste properties and iii) to obtain the factor of safety of the landfill slope using numerical analysis by finite element method. From the literature review, it is found that slope stability of a landfill mainly depends on the geotechnical properties of waste, such as moisture content, unit weight, shear strength parameters and hydraulic conductivity of waste. After the degradation process, engineering properties of field refuse are affected which includes the increased pore-water pressure and unit weight, decreased strength and lower hydraulic conductivity. Based on the analysis of conventional landfill slope stability by using Plaxis software, slope ratio of 1:3, 1:4 and 1:5 calculated safe with 1.69, 2.3 and 2.8 whereas the analysis of bioreactor landfill slope stability calculated safe only for slope ratio of 1:4 and 1:5 with 1.60 and 1.97. Moreover, the factor of safety for steeper slopes is lower and vice versa. From the parametric analysis, it is found that the full height of slope and unit weight of waste input affect the result analysis. This study is significant to evaluate the landfill slope stability with the effects of waste degradation and to ensure both conventional and bioreactor landfill slope stability for long periods.

Keywords* : *Landfill, bioreactor, waste degradation, finite element analysis, factor of safety.

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Salhana Ismail, Public Works Department, Ministry of Works, Kuala Lumpur, Malaysia. Email: salhana@jkr.gov.my

Aizat Mohd Taib*, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi, Selangor, Malaysia. Email: amohdtaib@ukm.edu.my

Norinah Abd Rahman, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi, Selangor, Malaysia. Email: norinah@ukm.edu.my

Dayang Zulaika Abang Hasbollah, Faculty of Civil Engineering, Universiti Teknologi Malaysia, Skudai, Johor, Malaysia. Email: dzulaika@utm.my

Ahmad Bukhari Ramli, Kulliyyah of Engineering, International Islamic University Malaysia, Kuala Lumpur, Malaysia. Email: bukhari@iium.edu.my

I. INTRODUCTION

In waste disposal process, landfill is the main method and preferred choice as the final receptors of ultimate residue for urban solid waste, industrial waste, recycled waste and sewerage sludge [1]. According to Huang et al. [2], the rapid development of the world township resulted in extensive waste production especially in developing countries, thereby increasing demand for high-capacity disposal sites. However, the opening of the new landfill location usually takes a long period and is subject to various stringent rules causing the maximum capacity to be sent to the existing waste disposal site and sometimes exceed the original design capacity. According to Babu et al. [3], more and more of the disposal sites are built with higher and steep slopes. Hence, the method of disposal using bioreactor technology is gaining popularity as an option in overcoming the problem of the increasing space demand for landfills.

Unlike conventional landfills that minimise the response between water and waste during operation, the bioreactor operation uses a liquid enhancement approach to encourage the degradation process. The injection of collected leachate into the waste mass increases the water content of the bioreactor landfill and accelerates waste degradation, changing the waste geotechnical characteristics. According to Warith [1], the stability of the bioreactor disposal site can be achieved earlier due to the faster degradation of waste enabling life expectancy reduced by (i) reduction in leachate treatment period, (ii) increase in methane gas production and (iii) the recovery of a faster site air space. However, rapid waste degradation at bioreactor disposal site can cause changes in waste geotechnical properties faster and have raised issues on the slope stability of the landfill.

II. FACTORS AFFECTING LANDFILL SLOPE STABILITY

Jahanfar et al. [4] stated that factors affecting the slope stability of the landfill are pore-water pressure, slope geometry, waste shear strength and disposal methods used during disposal operations. The landfill slope geometry changes when the wastes settle from time to time had a significant impact on the waste geotechnical properties and slope stability [5]. The high rainfall capacity which permeated into the waste layer can result in reduced waste strength and weakens the underlying soil structure and thus creating a less stable slope condition [6].

Based on the study, Babu et al. [3] also agreed with Xu et al. [7] that the injection of fluid bioreactor landfill operation has increased the water pressure and unit weight which leads to the reduction in waste shear strength that may interfere with the stability of the dumping site.

According to Babu et al. [3], the landfill slope stability depends on the geotechnical properties of the waste, such as unit weight and shear strength. Type and waste density are the two parameters that mostly influence waste shear strength. When the waste compaction is not made during the disposal process, the capacity of high rainfall water seeps into the waste layer can increase the water pressure of the pores and thus reduce the strength of waste shear. Zekkos et al. [8] studied the unit weight of waste based on waste compaction and soil contents and introduced three field-fitted hyperbolic curves as illustrated in Fig. 1.

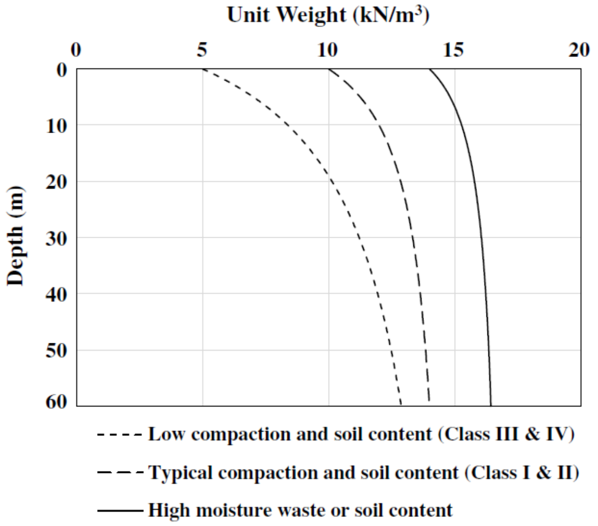

Fig. 1.Unit weight field-fitted hyperbolic curves for different classes of waste [8]

Blight [9] explained that an inappropriate compaction rate can lead to a failure of the slope of dumping sites as a result of the low shear strength and low waste mass intensity rate, as occurring in the case of the slope failure of the dumping site in Istanbul and Sarajevo (no waste compaction made) as well as in Bogota and Durban (compaction wastes made inconsistent).

III. EFFECTS OF WASTE DEGRADATION ON THE LANDFILL SLOPE STABILITY

Reddy et al. [10] defined waste degradation as the process of changing organic material to biogas involving changes in physical, chemical, and waste mass. Degradation rate of wastes is influenced by several factors such as waste composition, waste nutrient content, moisture content, pH, temperature and operational methods used on disposal sites. The closed landfill site has various degradation rates depending on the location and duration of disposal of the waste is made [11]. According to Reddy et al. [10], the degradation phase can be divided into five levels, i.e. (i) the aerobic phase which occurs within the short period, as soon as the wastes are disposed of, (ii) the anaerobic phase known as the change phase, when all oxygen gases were used by bacteria and the production of carbon dioxide gases began to occur, (iii) phase of the conversion of debris from bacteria to acid, alcohol, carbon dioxide gases and hydrogen causing reduced pH, (iv) increase in production rate of methane gas and (v) decline in the production rate of methane gas.

Degradation process also affects the waste geotechnical characteristics; such as moisture content, shear strength, weight unit and hydraulic conductivity rate. Hossain et al. [12] studied the impact of the degradation to bioreactor landfill reported the value of moisture content increased from 149.1% to 198.4% due to the reduction of waste particle size after the degradation has reduced the space between the wastes thereby increasing the residual capacity to accommodate moisture. Hossain et al. [13] examined the impact of degradation on the shear strength of bioreactor landfill and found that there is a large reduction in the friction angle and cohesion at 28% and 47% respectively after the degradation of wastes occurred.

Hossain et al. [13] also mentioned that when a waste degradation occurs, the size of the waste particle that is fragmented into smaller mass decrease the empty space between wastes and therefore increase the unit weight of the wastes. The increase in waste unit weight with the degradation was shown in their study, i.e. the waste unit weight is 8.5 - 9.1 kN/m^3 for the newly disposed wastes compared to 10.7 - 11.2 kN/m^3 for wastes that experienced degradation. The degradation process will as well change the waste structure which shrinks the space between wastes and thus decreases the hydraulic conductivity rate of the waste. Reddy et al. [14] reported that the waste hydraulic conductivity rate before and after the degradation is within 10-3 to 10-8 cm/s and Hossain et al. [13] states that the waste rate of the bioreactor disposal site is reduced by the degradation of 10-2 cm/s up to 10-4 cm/s.

IV. FACTOR OF SAFETY

The purpose of slope stability analysis is to obtain a quantitative measure of slope stability in whole or in parts. Generally, it is expressed by the estimation of factor of safety (FOS), defined as the ratio of the available strength to the strength at failure. There is much research that studied the changes in factor of safety influenced by rainfall, extreme drying, vegetation or earthquake such as Mohd Taib et al. [15], Mukhlisin et al. [16], Altalhea et al. [17], Mukhlisin et al. [18], Mukhlisin et al. [19], Harianto et al. [20], Kristo et al. [21] and Fan et al. [22] work. In this paper, the stability of slopes is affected by the waste degradation where Babu et al. [3] suggested that the value of safe safety factors to guarantee long-term slope stability of the landfill is 1.5-3.0. Datta [23] also suggested that the safety factor of long term slope stability is 1.5.

V. SLOPE GEOMETRY

In this study, models with slope angles of 1: 1, 1: 2, 1: 3, 1: 4 and 1: 5 are built to analyse the stability of landfill slope of both conventional and bioreactor types. The slope geometry is constructed at an overall height of 50 m and is divided into five layers with a height of 10 m on each layer.

The five layers also represent the five stages of degradation at the landfill. The geometry was designed based on on-site project of landfill area in Sg. Udang, Melaka as shown in Fig 2. In addition, Fig. 3 shows the geometry of the slope constructed at the ratio of 1: 3.

Fig. 2.Slope reconstruction in Sg. Udang, Melaka

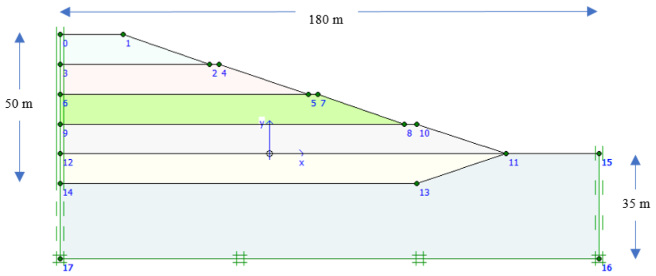

Fig. 3.Geometry of the slope model

VI. MATERIAL MODEL AND CALCULATIONS

The model represents the heterogeneous nature of waste at landfill that has undergone waste degradation. In this study, the first layer is assumed to be constructed as soon as the waste is disposed, which is in the early stages of degradation. At the same time, the second, third, fourth and fifth layers each represent four stages of degradation. Unit weights and different hydraulic conductivity rates are used to account for overburden stress. Different shear strengths are used for each layer to take into account the effect of degradation on the geotechnical properties of the waste.

In the Mohr-Coulomb modelling analysis, six parameters were used as inputs: friction angle (Ø '), cohesion (c'), dilation angle, Young's modulus (M'), Poisson’s ratio (ν') and unit weight (γ'). According to Matsui et al. [24], the Young's Modulus parameter and Poisson's ratio did not have significant effects on slope stability analysis when using soil strength reduction methods. In this study, the Young Modulus values and Poison’s ratio used as inputs in the study were 2.5×10^4 kN/m^2 and 0.4 respectively. The dilatancy angle was set to zero as it approaches zero for clay and sand with a friction angle of less than 30°. The unit weight used varies according to the height of the waste to take into account overburden stress. According to Zekkos et al. [8], the unit weight calculation can be done based on Equation 1.

$$\gamma = \gamma_i + z/(\alpha + \beta z) \quad (1)$$

γ = Unit weight at z height (kN/m3)
γi = Unit weight near the surface (kN/m3)
z = height of waste (m)
α (m4/kN) dan β (m3/kN) are model parameters

In this study, different shear strengths (shear values and friction angles) were used according to the height of the waste to take into account the effect of degradation on the geotechnical properties of the waste. The shear values and friction angles used are from the Giri et al. [25] study. The hydraulic conductivity rates for conventional landfills are taken from the study of Norsyahariati et al. [26] while for bioreactor disposal sites are taken from the Giri et al. [19] study. Tables 1 and 2 show the input parameters of conventional and bioreactor landfill models used in this study. It can be seen that the different of both types of landfill are in the unit weight and hydraulic conductivity. The cohesion and friction angles are assigned with same values for all models at 35 kPa and 15˚ respectively.

Table- I: Soil input parameters for conventional landfill

Height, z (m)	Unit weight, ϒ (kN/m^3)	Hydraulic conductivity (m/day)
0 – 10	10.41	4.32×10^{-5}
10 – 20	12.50	4.50×10^{-5}
20 – 30	13.75	1.47×10^{-5}
30 – 40	14.59	1.90×10^{-5}
40 – 50	15.18	1.90×10^{-5}

Table- II: Soil input parameters for bioreactor landfill

Height, z (m)	Unit weight, ϒ (kN/m^3)	Hydraulic conductivity (m/day)
0 – 10	17.2	1.12×10^{-3}
10 – 20	18.4	4.49×10^{-4}
20 – 30	19.0	5.70×10^{-6}
30 – 40	19.4	1.30×10^{-7}
40 – 50	19.7	3.8×10^{-7}

VII. RESULTS AND DISCUSSION

Slope stability analysis was performed on five different slope models with the gradient ratio of 1: 1, 1: 2, 1: 3, 1: 4 and 1: 5. Based on the analysis, it is found that the factor of safety for conventional landfill slope with a slope angle of 1: 1 and 1: 2 are less than 1.5 and do not exceed the recommended factor of safety over the long term. The factor of safety is low when the slope is built with steep angle and vice versa. Fig. 4 shows the factor of safety for both conventional and bioreactor slope obtained from the analysis. Based on the analysis, it is found that the 1: 1 slope for conventional landfill produced a very low factor of safety of 0.93.

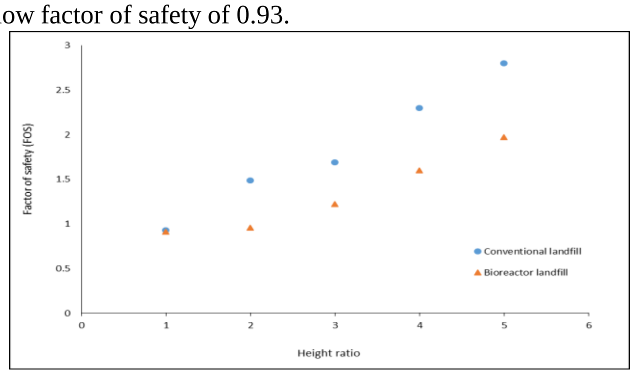

Fig. 4.Factor of safety obtained from the analysis of slope height ratio

Comparisons of the results are made with the studies by Omari [27]. Similar results are obtained where the factor of safety decreases proportionally to increasing slope angles. The factor of safety obtained by Omari [27] is slightly lower than this study due to: i) the difference of composition of industrial waste and municipal waste, ii) the geotechnical input values (unit weight and friction angle) of industrial waste are different from those of municipal waste. The shear strength of the industrial waste is lower compared to the municipal waste which has higher shear strength and larger friction angle, and iii) the previous model of slope geometry are uniform and did not take into account the waste degradation effects.

As for bioreactor landfill, it is found that the factor of safety for slopes of 1: 1, 1: 2 and 1: 3 did not exceed the recommended long-term safety factor. The factor of safety for slopes with angle of 1: 4 and 1: 5 are beyond the recommended safe level. The results are similar to the results of Hossain et al. [28] study which only slope of 1: 4 and above exceed recommended safety level. Both studies found that the safety factors for slope 1: 2 and 1: 3 did not exceed the recommended safety level. For slope 1: 4, the value obtained in this study is 1.6 and it is very similar to the value obtained in Hossain et al. [28] work. The minimum difference in the mean value of the obtained safety factor is due to the different stages of degradation used in both cases. In this study, the waste disposal stage is assumed to occur in five phases at 20%, 40%, 60%, 80% and 100%. While the study by Hossain et al. [28] suggested the stage of degradation of waste in four phases. Although there are minimal differences in the value of the safety factors obtained, both studies agree that only slopes of 1: 4 and beyond exceed the recommended safety level.

A. Result Analysis at Different Stages in Factor of Safety and Total Displacement

Based on the analysis performed on all five slope models, only landfills with slopes of 1: 4 and 1: 5 exceed the safety level based on the safety factors obtained. For the 1: 3 slope, conventional landfills are beyond the safe level while bioreactor landfills are not above the safe level. Fig. 5 shows analysis of the slope model 1: 3 for the conventional landfill to look at the impact of total displacement and safety factors on the waste degradation stage, from the first phase to the fifth phase of waste degradation. Based on the analysis, it is found that degradation process has a significant impact on safety factors. The factor of safety decreased with the degradation period of 3.41, 2.61, 2.17 and 1.74 from the second phase to the fifth phase of the degradation. As the waste degradation time increases, the shear strength rate of each layer of sediment decreases, causing the slope stability to decrease. Although the reduction in safety factors can be seen as the residual degradation period increases, overall the 1: 3 conventional landfill slope is still at the recommended safe level.

In comparison, the factor of safety for bioreactor decreased with the degradation period of 3.41, 2.61, 2.17 and 1.74 from the second phase to the fifth phase of the degradation. As the waste degradation time increases, the shear strength rate of each layer of sediment decreases, causing the slope stability to decrease. In the fifth stage, the residual degradation was found to result in a safety factor of 1.23 which did not exceed the proposed safe level and a significant change in the landfill with a high overall displacement rate of 7.01 m as shown in Fig. 6. The maximum displacement occurred at the middle of the fifth layer of the landfill due to the lower unit weight of the top layer compared to the lower layers which had increased in density after the longer degradation.

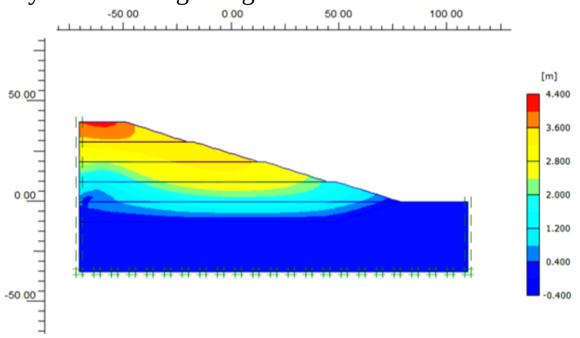

Fig. 5.Total displacement for conventional landfill at the final stage

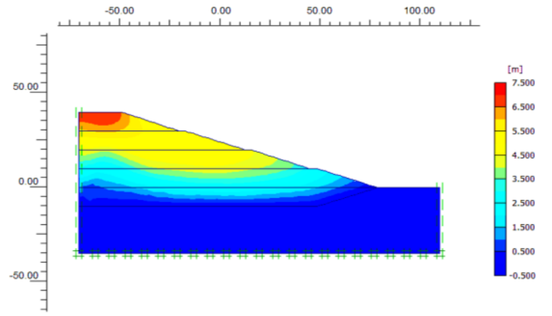

Fig. 6. Total displacement for bioreactor landfill at the final stage

B. Parametric Analysis on Height of Slopes and Waste Compaction Degree

Parametric analysis was performed to determine the effect of input parameters on slope modelling of landfills. In this study, the analysis was performed on the effect of slope height and compaction degree on the slope stability. Based on the safety factors obtained, the stability of the landfill slope site is different when the same slope angle is constructed at different heights. When the higher slope is built, the safety factor obtained decreases as shown in Fig. 7.

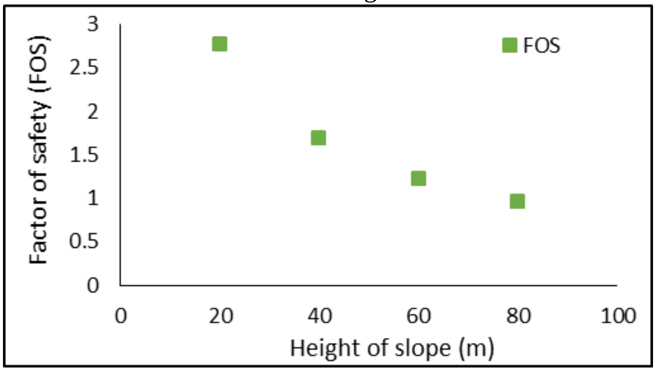

Fig. 7.Graph of factor of safety against slope height

For slopes with a 1: 3 angle, slopes with a height greater than 40 m, 60 m and 80 m, the value of the obtained safety factor does not exceed the level of the proposed safety factor.

As the height of the slope increases, changes in the geotechnical properties of the residuals such as unit weight and shear strength also change, resulting in changes in slope stability. Accordingly, the height of the slope should be taken into account not only during the design but during the disposal and construction of the slope to ensure the stability of the slope of the landfill is in safe condition. Accurate elevation input during modelling is crucial to ensure that the results obtained show the true stability of the slope on the site.

The study of the impact of unit weight of waste on landfill slope stability was performed on slope 1: 3 using input based on capacity and waste compaction rate as suggested by Zekkos et al. [8]. The results obtained are as shown in Table III. Based on the analysis, it is found that waste that has high compaction method produce low safety factor. When the waste is compacted, the spaces between the residues become smaller causing the density of the waste to increase. The high unit weight causes the safety factor to decrease and the overall slope displacement increases.

Table- III: Factor of safety for landfill slope with different unit weight

Unit Weight	Factor of Safety (FOS)
Low Capacity and Compaction Effort	1.94
Moderate Capacity and Compaction Effort	1.57
High Capacity and Compaction Effort	1.29

VIII. CONCLUSION

This study was conducted to analyse the stability of conventional and bioreactor slopes by taking into account of the residual degradation factors. Based on the objectives of the study, the conclusions can be drawn as follows: (i) the main parameters of the waste that affect the stability of the slope of the landfill are the unit weight and shear strength indicated by the cohesion and friction angle, (ii) the effect of degradation on the geotechnical characteristics of the waste is the increase in unit weight and waste stiffness, as well as the reduction of friction angle and hydraulic conductivity rate, (iii) the factor of safety of both conventional and bioreactor disposal sites obtained using PLAXIS 2D, were found to be directly proportional to the increased slope of landfill. For conventional landfills, the slopes with height ratio of 1: 3, 1: 4 and 1: 5 exceed the recommended safe level with 1.69, 2.3 and 2.8 respectively, while for bioreactor disposal sites, only 1: 4 and 1: 5 slope ratio exceeds the recommended safe level with 1.60 and 1.97. This is because the slope geometry plays an important role in affecting the stability of slope sites and (iv) the slope height inputs and unit weight of waste have significant effects on slope stability analysis. It is also can be said that lower safety factors will be generated when higher slope height and higher unit weight of waste are used.

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AUTHORS PROFILE

Salhana Ismail is a senior civil engineer at Public Work Department (PWD) and currently attached with the Division of Geotechnical Engineering. She is registered a graduated member of Board of Engineers Malaysia with 15 years of working experiences in structural design, waterworks, health facility projects and solid waste management. Her knowledge and experiences in project management best practice have qualified her as registered project manager of PWD Malaysia and CIDB Malaysia in 2017. She graduated as a civil engineer from Universiti Teknologi Malaysia and has recently completed master degree in Universiti Kebangsaan Malaysia in 2019 with research in landfill slope stability analysis.

Aizat Mohd Taib is currently a lecturer at the Faculty of Engineering and Built Environment of Universiti Kebangsaan Malaysia (UKM). Having graduated as a civil engineer from Universiti Malaysia Pahang, he continued his MEng in Universiti Teknologi Malaysia and received his doctoral degree from Newcastle University, UK. His research interest is primarily in geotechnical engineering cases particularly slope stability and the effects of climate change, utilising field investigation, laboratory tests, numerical modelling and programming. He has been conducting research and works as an engineer professionally since 2011. Aizat actively engages in civil engineering undergraduate and postgraduate teaching, research, consultation as well as industrial works.

Norinah Abd Rahman received the B.Eng. degree in civil engineering from Universiti Kebangsaan Malaysia (UKM), in 2007, and the M.Eng. and Ph.D. degrees in civil engineering from the Chung Ang University (CAU), Seoul, South Korea, in 2011 and 2015, respectively. In 2007, she joined the Department of Civil and Structural Engineering, UKM, where she was a tutor, became a lecturer in 2011, and a senior lecturer in 2016. Her current research interests include non-destructive testing by stress wave primarily for civil engineering materials characterization such as soil, pavement and concrete, in-situ and laboratory geotechnical testing, finite element modelling and artificial neural network. She received research grant from the industry to improve the current practice and analysis of spectral-analysis-of-surface wave (SASW) test. Dr Norinah is a member of Board of Engineers Malaysia (BEM) and Institutional of Engineers Malaysia (IEM). She was the recipient of Chung-Ang University Young Scientist Scholarship (CAYSS) program for her M. Eng and Ph.D. degrees.

Dayang Zulaika Abang Hasbollah has obtained her doctorate degree in Petroleum Engineering from University of Technology Malaysia in 2017. Before that, she obtained her degree in civil engineering and pursued her masters in Geotechnical engineering. Her main area of research is in geological engineering and rock mechanics especially in clastic sedimentary rocks. However her expertise is on geological sequestration of carbon dioxide and climate change effects.. In 2018, she started her career as a senior lecturer at school of civil engineering, University of Technology Malaysia, teaching geotechnics, engineering geology and rock mechanics subject to undergraduates and postgraduates. She is registered as graduate member of Board of Engineers Malaysia and recently she has been appointed as an associate fellow in Centre of Geotropical Engineering (GEOTROPIK). She is also a principal investigator and members of a few active research grants.

Ahmad Bukhari Ramli is a Doctorate holder in Geotechnical Engineering from Universiti Kebangsaan Malaysia got enrolled in 2014 session and previously completed Master degree in Chung-Ang University, Seoul South Korea. During his master study, he had been actively involved in soil dynamics research particularly Spectral Analysis of Surface wave method and co-authored some journal papers and conferences related with two major materials which are concrete and soils including contribution of knowledge in the journal of Soil Dynamics and Earthquake Engineering, Journal of the Korean Society of Civil Engineers and KSCE Journal of Civil Engineering. In 2012 to 2015, he became a lecturer in German Malaysian Institute (GMI). His PhD research is related the Soil Bearing Capacity Based on Shear Wave Velocity using Spectral Analysis of Surface Wave. He has contributed another 2 journals Web of Science indexed or formerly known as ISI index. He is also registered as graduate member of Board of Engineers Malaysia. In the industry, he has implemented his research and participated in various project across Malaysia.