Jurnal
Teknologi

Full Paper

NUMERICAL AND PHYSICAL MODELLING OF KAOLIN AS BACKFILL MATERIAL FOR POLYMER CONCRETE RETAINING WALL

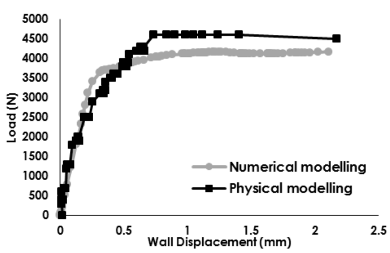
Ali Arefnia*, Khairul Anuar Kassim, Houman Sohaei, Kamarudin Ahmad, Ahmad Safuan A Rashid

Department of Geotechnics and Transportation, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

Article history
Received
6 July 2015
Received in revised form
26 July 2015
Accepted
30 July 2015

*Corresponding author
ali1979arefnia@yahoo.com

Graphical abstract



Abstract

The failure mechanism of backfill material for retaining wall was studied by performing a numerical analysis using the finite element method. Kaolin is used as backfill material and retaining wall is constructed by Polymer Concrete. The laboratory data of an instrumented cantilever retaining wall are reexamined to confirm an experimental working hypothesis. The obtained laboratory data are the backfill settlement and horizontal displacement of the wall. The observed response demonstrates the backfill settlement and displacement of the retaining wall from the start to completion of loading. In conclusion, numerical modelling results based on computer programming by ABAQUS confirms the experimental results of the physical modelling.

Keywords: Retaining wall; backfill material; ABAQUS; failure mechanism; kaolin

Abstrak

Mekanisme kegagalan bahan kambus balik untuk tembok penahan telah dikaji dengan melakukan analisis berangka menggunakan kaedah unsur terhingga. Kaolin digunakan sebagai bahan kambus balik dan tembok penahan dibina menggunakan Polimer Konkrit. Data makmal daripada tembok penahan julur teralat telah instrumen diteliti kembali untuk mengesahkan hipotesis kerja ujikaji. Data kajian makmal adalah enapan bahan kambus balik dan anjakan mengufuk tembok penahan. Tindakbalas pemerhatian mempamerkan enapan kambus balik dan anjakan tembuk penahan dari mula sehingga pembebanan tamat. Kesimpulannya, keputusan pemodelan berangka berdasarkan dari peraturacaraan program computer ABAQUS mengesahkan keputusan ujikaji permodelan fizikal.

Kata kunci: Tembok penahan; bahan kambus semula; ABAQUS; mekanisma kegagalan; kaolin

1.0 INTRODUCTION

The first usage of retaining walls and backfill applied was Coulomb's theory in 1776, which came from total force equilibrium calculate lateral earth pressure in terms of wedge between plain sliding and frictional retaining wall. The theory of active earth pressure [1] assumes that the condition of the backfill is an incipient failure. The theory represents smooth vertical backfill; however, practical retaining walls are harsh with friction. The satisfactory of the analysis is with the equilibrium force with the limitation of realistic work. Thus, the popularity of these analyses grew amongst engineers due to its nature of simplicity. A general wedge theory has been proposed by Terzaghi [2], assumes the arc of logarithmic spiral as a failure surface.

Soil backfills are supported by retaining walls such as traditional gravity, semigravity, counterfort and cantilever retaining walls made of plain and reinforced concrete. Retaining wall can retain the backfill in order to widen a roadway or support a structure and also constructed from other materials, such as steel, gabions, timber and reinforced earth. Retaining walls must be designed to resist the external forces applied such as earthquake loads, lateral earth pressure, hydrostatic pressure and surcharge load.

Although soil-retaining structures have been constructed for many years, their failure mechanisms are not fully understood [3]. Understanding failure mechanisms is possible with laboratory and field tests as well as with finite element analysis, but the conventional design of retaining wall structures is commonly performed by using limit equilibrium analysis. The failure planes used in current design codes reflect the findings of failure planes determined for conventional retaining structures. Failure can be occurred due to displacement of the wall or settlement of the backfill more than permissible limit. A verification of physical and numerical modelling using ABAQUS was conducted by Guang-yun [4] which the simulated results by software were matched with the physical modelling results reasonably well showing that the numerical model was reasonable for this purpose. The objective of the current study is to investigate the load-settlement of backfill and load-displacement of polymer concrete retaining wall. While, the results of laboratory tests were used by performing a numerical analysis of failure mechanisms and physical modelling of Kaolin as a backfill material for polymer concrete retaining wall to verify the physical modelling results of load-settlement and load displacement.

2.0 MATERIAL AND TEST PROCEDURE

The backfill material used in this research was Kaolin. Laboratory tests such as specific gravity, compaction and direct shear have been conducted according to British Standard and Arefnia *et al*. [5,6,7]. Coefficient at rest K_0, Poisson's Ratio and Void Ratio obtained by Equations 1, 2 and 3 respectively [8]:

$$K_0=1-\sin\Phi \quad (1)$$

$$\upsilon= K_0/(1+ K_0) \quad (2)$$

$$e=((G_s*\gamma_w)/ \gamma_d)-1 \quad (3)$$

2.1 Kaolin

The Kaolin used in this study was purchased from Kaolin (Malaysia) Sdn. Bhd. Kaolin properties are presented in Figure 1 and Table 1.

Kaolin should mix with water in optimum moisture content. In order to prevent material flocculation, the mixing procedure was done sufficiently and properly in accordance with British Standard. The mixtures were mellowed 24 hours prior to compaction. Sample mellowing was conducted by adding water during mixture preparing. Compaction was done in box layer by layer.

Figure 1 Kaolin

2.2 Retaining wall

The Polymer Concrete Retaining Wall properties were considered in order to use in the model. According to the study of Gorninski *et al*. [9], Modulus Elasticity (E) was obtained 27.28 GPa, Poisson's ratio (v) was assumed 0.2 and unit weight (γ) was calculated 27 kN/m³. The dimension of physical model retaining wall was scaled by 20 times from the actual. As shown in Figure 2, the wall dimension was selected with 15 mm on the top of the wall followed by 20 mm in the bottom. The wall toe has been constructed horizontal 145 mm followed by 17.5 mm vertically [10].

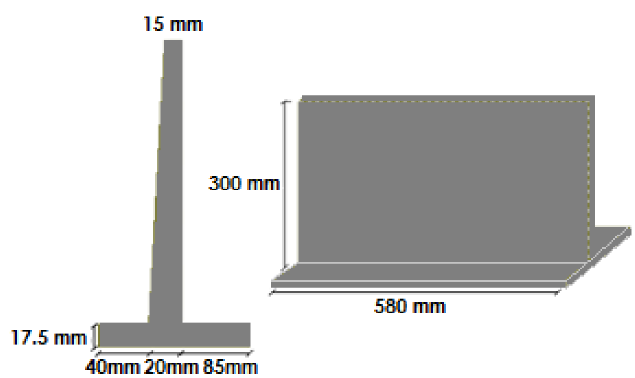


Figure 2 Retaining wall dimension in this study

Table 1 Physical properties and chemical composition of Kaolin (Kaolin Malaysia Sdn. Bhd.)

Physical Properties	
In-house Test Method	
Moisture Content	Below 5.0 %
60 Mesh per inch (24 Mesh per cm) Residue	Below 20.0 %
Chemical Composition	
XRF Test Method	
Aluminum (Al_2O_3)	15.0 – 25.0%
Silica (SiO_2)	60.0 – 75.0 %
Iron (Fe_2O_3)	Below 5.0 %
Potassium (K_2O)	Below 2.5 %
Magnesium (MgO)	Below 1.0 %
Loss on Ignition 1025 °C	5.0 – 10.0 %

3.0 MODELLING ANALYSIS

3.1 Physical Modelling

The physical model was conducted in a model box with the inner dimensions of 0.6 m × 0.9 m in plan × 0.6 m in height. Friction between the sidewalls of the box and the backfill was minimized by lubricating the area in order to insulate the soil from the frictional effects. The box was sufficiently rigid to maintain plane strain conditions in the polymer concrete retaining wall model. The selection of model materials was conducted taking account of scaling laws according to a report by Gibson [11].

The length of the backfill was 500 mm and the height was 300 mm. A load cell was positioned on the strip foundation to control the loading with an amount of 4.5 kN to the backfill. Strip foundation was made of steel with a dimension of 0.58 m × 0.075 m × 0.025 m. There were two vertical displacement gauges on the top and two horizontal displacement gauges on the wall face, in order to measure the backfill settlement and wall movement, respectively, as shown in Figure 3.

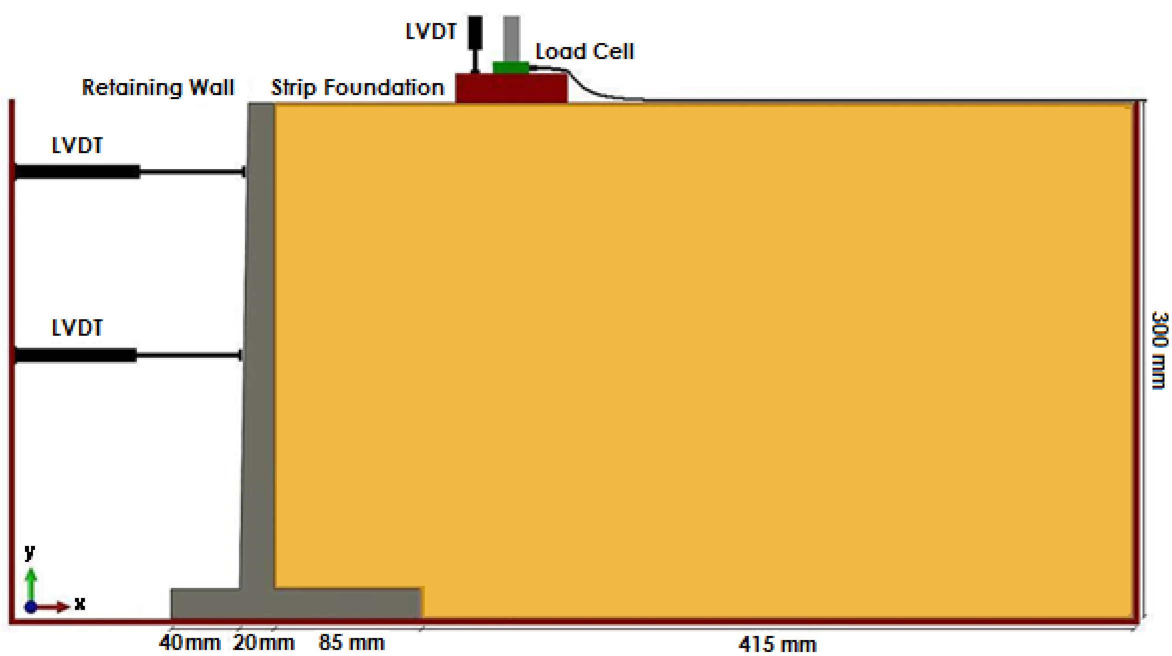


Figure 3 Schematic of physical modelling

3.1.1 Elasticity Modulus

Young's modulus (E) is related to stress-strain which is the basic stiffness modulus in Mohr-Coulomb model and the elastic model. A non-linear behavior is represented by geomaterial from the initial loading. Thus, special attention is required for the stiffness parameters adopted in a calculation.

The initial slope (tangent modulus) is usually indicated as E_0 in soil mechanics and the secant modulus at 50 % strength is denoted as E_{50}. According to the manual, E_0 is used for materials with a large linear elastic range while as for loading of soils generally E_{50} is used. In this study, E_{50} was obtained from the stress-strain curve as shown in Figure 4.

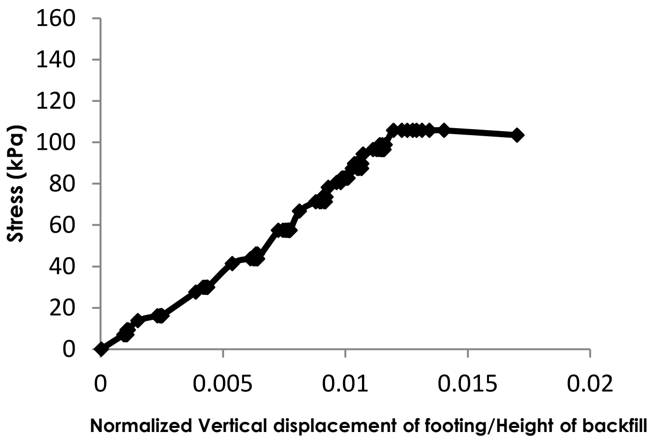


Figure 4 Modulus Elasticity from the stress-strain curve

3.2 Numerical Modelling

The soil behavior has to be defined realistically and properly to perform successful numerical analysis. Therefore, properties of the material were obtained from the results of laboratory tests. To define soil behavior in ABAQUS software, constitutive model of Mohr-Coulomb failure criterion was considered in this study. Hence, Poisson's ratio (v), elasticity modulus (E), internal friction angle (φ), cohesion (c), dilation angle (Ψ), the mass density of the soil (ρ) and lateral earth pressure coefficient at rest (K_0) were considered in the software.

3.2.1 Finite Element Analysis of the Retaining Wall

The proposed retaining wall was modelled in the plane strain analysis of numerical which was performed due to shorten the computation time and simplify the model. Whereas, two-dimensional of ABAQUS software, as shown in Figure 5, were established as same as a physical construction model in terms of backfill, retaining wall dimensions and properties. The simulated soil boundary was conducted with height and a length of 30 cm and 50 cm, respectively.

The strip foundation was considered to be rigid, so that, in order to model a rigid condition, a downward displacement boundary condition was applied on the soil stratum. Since the maximum settlement measured in the laboratory was 5.1 mm, the amount of 5.1 mm in 10 subsequent steps was applied to the soil body. While, 0.5 mm prescribed downward displacement in each step, was applied for the interface area of soil-foundation.

The boundary condition on the free side of the soil body was closed in the x direction of the displacement / rotation in order to allow settlement on the soil boundary based on loading. The soil layer in bottom of model was fixed in all directions while the bottom of the wall was fixed only for the vertical movement.

In the model, a 3-node linear plane strain triangle elements (CPE3) were considered in the FEM Analysis. The mesh used in the analysis consists of 494 nodes and 848 elements. The generated FEM mesh is shown in Figure 5.

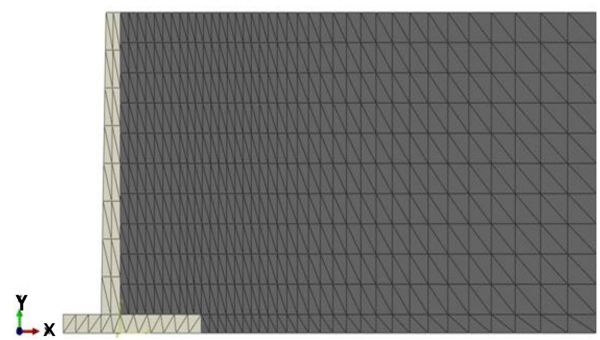


Figure 5 Two dimensional ABAQUS and general FEM mesh

Automatic technique was used for the meshing of the soil body. Nevertheless, finer mesh was considered in the vicinity of the strip foundation and wall, because of the significant displacement changes in this area. It is also important that the stress concentration was around this zone. Although the wall was applied automatic meshing, the size of the meshing should be greater than the soil. It is because of the rigidity of the wall or higher elasticity value than the soil allows the wall, penetrate into the soil body. According to a research by Helwany [12], a friction coefficient of 0.3 as a surface to surface contact (standard) was defined for the frictional interaction between the soil and the concrete wall.

In order to analysis the load imposed on the top of the strip foundation based on certain displacement, the prescribed displacement method was used in numerical model. The uniform boundary condition was applied in the strip foundation interface area which caused the settlement of foundation uniformly. In the analysis result, sum of the forces over the area produced the bearing capacity while based on researches of Merifield and Nguyen [13] and Zhu [14] the history output defined the downward displacement boundary condition. The consideration of maximum settlement of the model was 5.1 mm which was obtained from physical modelling results.

Static analysis was performed for retaining wall. The load was applied and geostatic command was defined for soil elements to determine the initial stresses in soil. The running process was completed and the soil equilibrium was ensured in order to get desirable result of minimum displacement from analysis.

4.0 RESULTS AND DISCUSSION

The results of the aforementioned laboratory tests and FE analysis are discussed in this section.

Kaolin properties were tabulated in Table 2 based on Arefnia *et al* [6],[7]. The results were used as input data for modelling in order to consider the displacement of walls due to the loading on the backfill.

Table 2: Test results of Kaolin

Engineering and physical properties	Unit	Value
Specific Gravity Gs	-	2.67
Maximum Dry Density (ρ_d)	kg/m^3	1750
Optimum Moisture Content (ω)	%	16
Cohesion (*c*)	kN/m^2	4.42
Friction Angle (Φ)	-	27.45
Coefficient at rest (K_0)	-	0.539
Elasticity Modulus (*E*)	kN/m^2	7600
Poisson's Ratio (υ)	-	0.35
Void Ratio (*e*)	-	0.529
Dilation angle Ψ	-	0

Figure 6 represents the load-settlement curve of strip foundation for a settlement of 5.1 mm in numerical modelling (ABAQUS) and physical modelling. Consequently, bearing capacity of the settlement was 4.5 kN and 4.17 kN, respectively in physical modelling and numerical modelling (ABAQUS). The difference between two diagrams was because of the location of displacement gauges and strip foundation on the soil surface in physical modelling. The soil compaction on the surface could not be same as the deeper layers. In addition, the air effect on the moisture of the soil surface before loading is important, however, ABAQUS could not consider it.

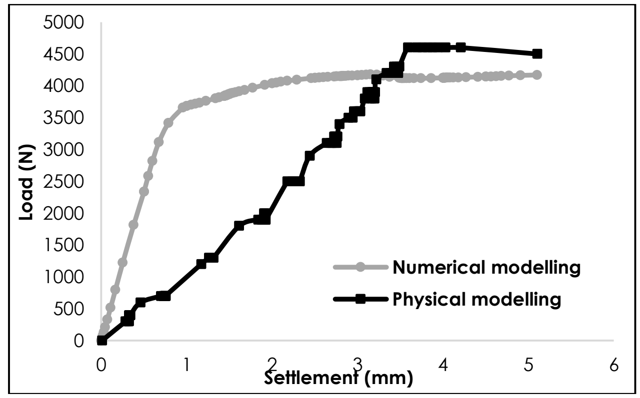


Figure 6 Comparison of Load-Settlement in numerical modelling (ABAQUS) and Physical modelling

As can be seen in Figure 7, the Load-Wall displacement diagram in Physical modelling is coincident with the ABAQUS result while the failure points are almost same in both models.

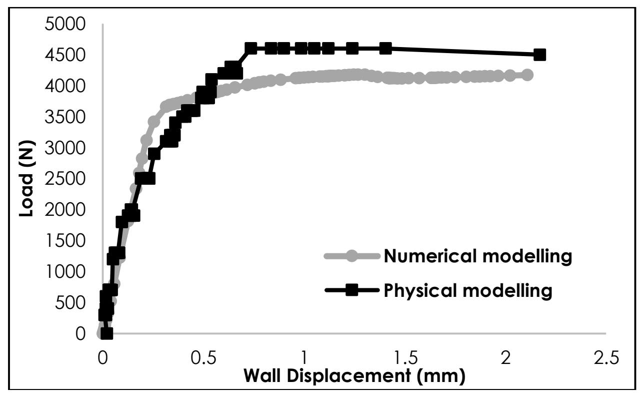


Figure 7 Comparison of Load-Wall displacement in numerical modelling (ABAQUS) and Physical modelling

The deformed mesh and wall movement due to vertical displacement is shown in Figure 8. Deformations were occurred in the zone below the strip foundation and close to retaining wall while as, the changes were not important in the end of backfill as shown in Figures 8 and 9.

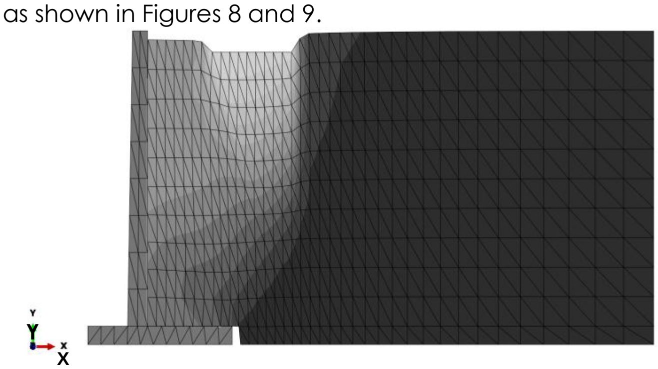


Figure 8 The deformed mesh and wall movement due to vertical displacement

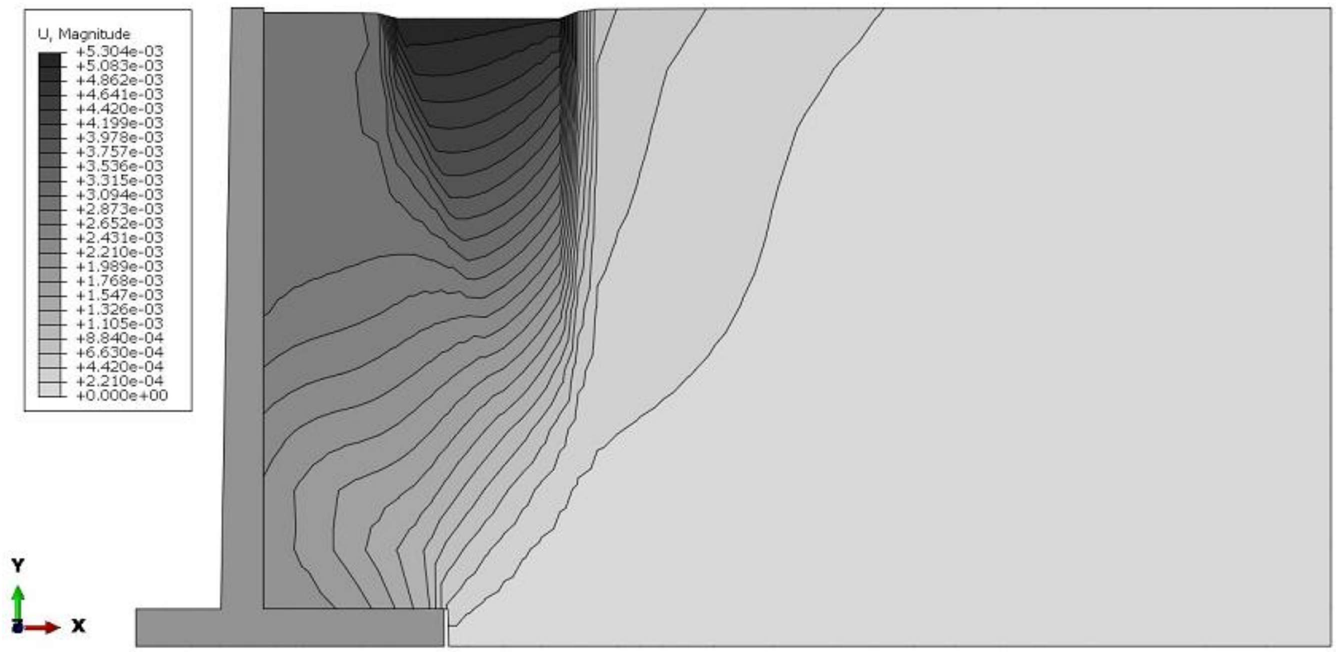


Figure 9 The influenced zone of the soil in terms of loading

Figure 9 shows the influenced zone of the soil in terms of loading while the dark parts show the high magnitude of loading on soil and the lighter parts indicate the low effects of the loading on the soil.

5.0 CONCLUSION

A parametric study was conducted to examine predicted failure mechanisms of Kaolin retained by Polymer Concrete wall using finite element analysis. A verification study of the physical model was conducted by using the results of geotechnical laboratory tests to compare the results obtained from well-instrumented small-scale test in laboratory and numerical model which were validated with the results of geotechnical laboratory tests. In conclusion, results of the verification study show that horizontal displacement of the wall and strip foundation settlements are in a reasonable agreement with numerical predictions by ABAQUS.

Acknowledgement

The authors would like to thank the Faculty of Civil Engineering, Universiti Teknologi Malaysia for providing the laboratory equipment needed in this research.

References

[1] Rankine, W. J. M. 1857. On the Mathematical Theory of the Stability of Earthwork and Masonry. *Proceedings of the Royal Society of London*. 2011. 8: 60–61.

[2] Terzaghi, K. 1943. *Theoretical Soil Mechanics*. Wiley, New York.

[3] Leshchinsky, D. and Vulova, C. 2001. Numerical Investigation of the Effects of Geosynthetic Spacing on Failure Mechanisms in Mechanically Stabilized Earth Block Walls. *Geosynthetics International*. 8(4): 343–365.

[4] Guang-yun, Y., Yong-sheng, B., Ping, S. and Rui-ping, G. 2009. Mechanical Performance of a Double-Face Reinforced Retaining wall in an Area Disturbed by Mining. *Mining Science and Technology (China)*. 19(1): 36–39.

[5] British Standard Institution. 1990. *Methods of test for Soils for Civil Engineering Purpose*, Part 4: Compaction related test.:London. British Standard Institution. BS 1377-4:1990.

[6] Arefnia, A., Jahed Armaghani, D., and Momeni, E. 2013. Comparative Study on the Effect of Tire- Derived Aggregate on Specific Gravity of Kaolin. *Electronic Journal of Geotechnical Engineering*. 18(B): 335–344.

[7] Arefnia, A., Momeni, E., Armaghni, D. J., Kassim, K. A. and Ahmad, K. 2013. Effect of Tire Derived Aggregate on Maximum Dry Density of Kaolin. *Jurnal Teknologi*. 66(1):19-23.

[8] Head, K. H. 1998. *Manual of Soil Laboratory Testing*. Volume 2: Permeability, Shear Strength and Compressibility Tests (2th Edition). Pentech Press, London.

[9] Gorninski, J. P., Dal Molin, D. C. and Kazmierczak, C.S. 2004. Study of the modulus of elasticity of polymer concrete compounds and comparative assessment of polymer concrete and portland cement concrete. *Cement and Concrete Research*. 34(11): 2091–2095.

[10] Huang, Y., Chen, C., Huang, C., Kuo, Y. and Chen, K. 1998. Database for retaining wall design. *Advances in Engineering Software*. 29(7): 619–626.

[11] Gibson, A. D. 1997. Physical scale modelling of geotechnical structures at one-G. Report no. SML 97-01. Pasadena, CA: California Institute of Technology.

[12] Helwany, S. 2007. *Applied Soil Mechanics with ABAQUS Applications* (Vol. 2). New York: John Wiley & Sons.

[13] Merifield, R. S. and Nguyen, V. Q. 2006. Two- and three dimensional bearing capacity solutions for footings two layered clays. *Geomechanics and Geoengineering*: An International Journal. 1(2):151-162.

[14] Zhu, M. 2004. Bearing Capacity of Strip Footings on Two-layer Clay Soil by Finite Element Method" *Proceedings of ABAQUS Users' Conference*. 777–787.