Global Stability and Settlement of Segmental Retaining Walls Reinforced with Geogrid

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Abstract: Most of segmental retaining wall design procedures such as NCMA, BS8006, AASHTO and NCHRP do not take into account global stability and foundation settlement in their design calculation. A system to solve the problem and to predict the stability of the wall quickly and accurately by using simple input was planned to be developed. This study used a residual soil that was classified as SC-SM according to the Unified Soil Classification System (USCS). Geogrid used in this study had a characteristic strength of 40 kN/m while concrete blocks had a minimum strength of 35 MPa. Simulations were performed using two-dimensional FEM to calculate maximum deflection, maximum foundation settlement and maximum surface settlement. In addition, global stability was calculated by using phi/chi reduction method for each design. Prediction was done by using Response Surface Methodology. Mathematical models used for the RSM were MLR (Multiple Linear Regression), Pure Quadratic, Interactions and Full Quadratic. Among all the mathematical models in RSM, output of Full Quadratic was the closest to the target value.

Key words: Prediction, Segmental retaining wall, Geogrid, FEM, RSM

Introduction

In Malaysia, the first reinforced retaining structure was built in 1982 and since then has expanded its use (Chiu 1987). Geogrid reinforced segmental retaining walls are used extensively throughout the world because of its low cost, simple construction and its ability to accommodate the deformation (Yoo and Kim 2008; Zhang et al. 2008). However, studies of this type of walls, especially on the mode of failure and the bonding mechanism of reinforcement are still at the level of exploration (Skinner and Rowe 2005; Al and Muhunthan 2006).

Reinforced retaining walls offer competitive solutions to the problems associated with lack of space caused by the phenomenal growth in the infrastructure at present. Research on the retaining wall is reported in many papers since its introduction e.g. Edgar et al. (1989), Faisal (1993), Wong et al. (1994), Ho and Rowe (1996), Kasa (1997), Bathurst et al. (2005) and Skinner and Rowe (2005). In the design of reinforced concrete, bond between the bar and the concrete provides sufficient tensile stress to the concrete. While the principles of reinforced soil, the tensile stress is caused by friction between the soil and buried layers of reinforcement (Ingold 1982).

Normally, backfill material used in the construction of the wall is granular soil such as river sand and mining sand. However, the price of sand is high at present. Another alternative is to use quarry dust or residual soil. Economically, residual soil has many advantages because it is easy to find in Malaysia at relatively low cost. By using residual soil, contractors can reduce construction costs and overall time since no transportation of backfill is needed (Kasa 1998).

Reinforced retaining walls can be constructed using various types of reinforcement and wall systems. Reinforcement may consist of metal strips or polymer products such as geotextiles, geogrid and geomembrane. Wall system may consist of a wall wrap (wrap facing), fully rigid wall, segmented block and modular block (Holtz 2001). Most widely used reinforcement in Malaysia is steel strip. Although it is well-received, there is still uncertainty about its durability, especially under wet soil conditions such as residual soil. A practical reinforcement for the work under the residual soil is geogrid which is durable and suitable for the environment. In addition, the geogrid is easier to handle, carry and install than steel strip (Kasa 1998).

The main objective of this study is (i) to predict the stability of geogrid reinforced segmental retaining wall in terms of global factor of safety, surface and foundation settlement and wall deflection, (ii) to compare the accuracy of statistical methods of MLR (Multiple Linear Regression), Pure Quadratic, Interactions and Full Quadratic to predict the stability of the wall, (iii) to observe the actual performance of segmental retaining walls by comparing results of field monitoring with the results of FEM calculations, and (iv) to produce a computer system that can predict the stability of walls quickly and accurately by using simple input such as slope angle, surcharge and height of wall.

Among the motivations for this study has to do with the problems faced by some local engineers who refused to recommend the construction of segmental retaining walls as an alternative to customers on the grounds that the design calculations received from the supplier do not take into account the global stability and foundation settlement. This is clearly stated in the design calculations. In other words, the supplier shall not be liable for if the occurrence of failure caused by the global stability or foundation settlement.

Methodology

Backfill material used in this study was classified as SC-SM (a mixture of sand and clay and inorganic clay) according to USCS (Unified Soil Classification System). Plasticity index value of this soil was between four and seven ($4 \leq PI \leq 7$). According to the Design Manual Naval Facilities Engineering Command, 7.01 version published in September 1986, a typical value for the wet unit weight was 20.4 kN/m^3 and internal friction angle 33 degrees. These values were used in all the segmental retaining wall designs. The geogrid had characteristic tensile strength of 40 kN/m and long-term design strength of 21 kN/m. The concrete block had a dimension of 305 mm x 200 mm x 150 mm with minimum strength about 35 MPa.

For predictions, RSM (Response Surface Methodology) was used. Four mathematical models of MLR, Pure Quadratic, Interactions and Full Quadratic were used to predict the stability of the wall. RSM was a technique used to model and analyze problems in which a response was influenced by several independent variables and the main objective was to optimize the response (Montgomery 2005). RSM was useful to develop, improve and optimize the response or responses. Most of the problems in the RSM, the response function, f was not known. The first order model was known as linear regression model. When there were more than two independent variables such as x_1, x_2 and x_3, the model was called MLR. In general, the equation was as follows

Multiple Linear Regression

$$y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon \qquad (2.1)$$

The second order model was used when there was a curve in the first order model. The second order model was more flexible and had several functions such as Pure Quadratic, Interactions and Full Quadratic. The general equations were as follows

Pure Quadratic

$$y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1^2 + \beta_5 x_2^2 + \beta_6 x_3^2 + \varepsilon \qquad (2.2)$$

Interactions

$$y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1 x_2 + \beta_5 x_1 x_3 + \beta_6 x_2 x_3 + \varepsilon \qquad (2.3)$$

Full Quadratic

$$y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1 x_2 + \beta_5 x_1 x_3 + \beta_6 x_2 x_3 + \beta_7 x_1^2 + \beta_8 x_2^2 + \beta_9 x_3^2 + \varepsilon \qquad (2.4)$$

where y_i was the predicted value, x_1 was slope angle (degree), x_2 was surcharge (kN/m^2), x_3 was height of slope (m) and ε was error. y_i and x_1, x_2, x_3 were input values while β_0 until β_9 were output values obtained from analysis using the equations.

For the purpose of obtaining data, analysis of deflection, surface and foundation settlement and global FOS (factor of safety) were performed by using Plaxis ver. 8 while MATLAB ver. 2009 was used to make the statistical analysis. All software was working under Microsoft Windows XP system with Intel® Core™ 2 Duo, 2.80 GHz and 1.99 GB of RAM. FEM simulation of the retaining walls was carried out by using two dimensional analysis. A triangular-shaped element with 15 nodes was used since the weakness of using the element of six nodes was over prediction of bearing capacity and some calculations using phi/chi reduction method (Plaxis 2008).

Model of the retaining wall is shown in Figure 2.1. The height of wall was 5.5 m, the length of geogrid was 3.5 m and the depth of soil below foundation level was 6.0 m. Dimension of modular block was 30 cm long, 15 cm high and 20 cm wide. The width of drainage using granular materials was 30 cm. Interface elements were used to model the interaction between the geogrid and soil.

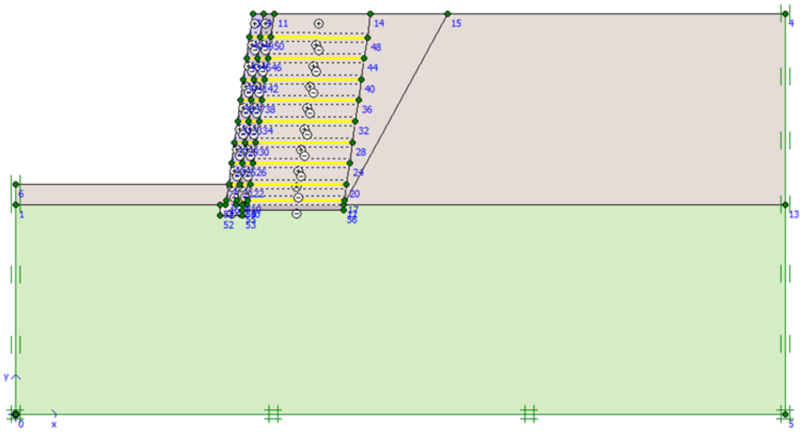

Figure 2.1 Geometry of retaining wall used in FE analysis

The input values for FEM simulation such as unit weight, cohesion and friction angle of the foundation, concrete blocks, drainage and residual soil were similar to the input values used in the NCMA design while other input values such as Young's modulus, Poisson's ratio and hydraulic conductivity which were not considered in the NCMA design were obtained from literature. To avoid any failure on the concrete blocks and drainage, a high value of strength ($c = 200$ kN/m^2) was used. High value of elasticity (EA = 1,200 kN/m) was also used for geogrid since the strength of geogrid did not affect the failure because soil would fail sooner in the event of excessive strain (Guler and Hamderi 2002). The output obtained from FEM analysis used for prediction using RSM was the value of (i) max. deflection, (ii) max. foundation settlement, (iii) max. surface settlement and (iv) global FOS.

To observe the actual performance of the wall and accuracy of FEM calculations, a full-scale wall was built. This five-meter high wall was installed with various instruments such as strain gauges, horizontal and vertical pressure cells, inclinometer, stand pipe and pneumatic piezometer and surface settlement markers at specified location as shown in Figure 2.2.

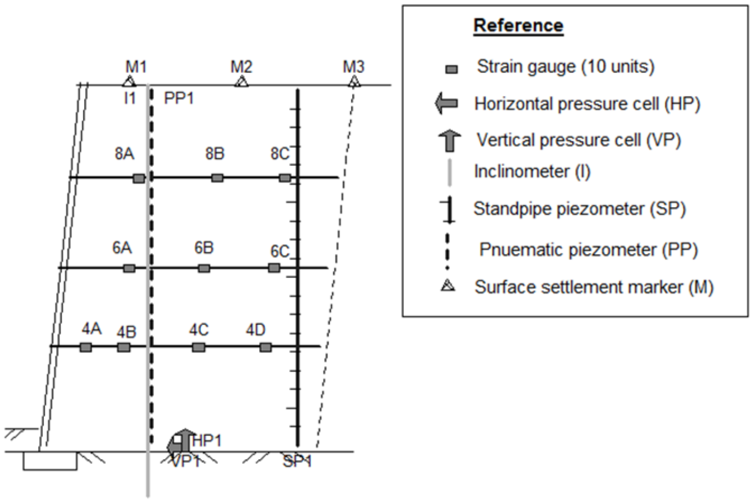

Figure 2.2 Location of various type of instrument

The purpose of strain gauges installed on the geogrid was to determine the tensile force distribution along the geogrid layers. Strain gauge type 5 YFLA applied in this study uses the principle of electrical resistance of a conductor. The conductivity changes when the material was strained. So, strain and tension can be calculated from the change in electrical resistance. Strain changes were measured by using a digital strain meter, TC-1K model.

Horizontal deflection of the whole wall was measured by using inclinometer. An inclinometer casing was installed behind the wall and readings were taken at every 0.5 m depth by means of inserting a sensor into the casing. Vertical and horizontal earth pressures including effective stress and pore water pressure were measured by using a pair of total pressure cell. Effectiveness of drainage system and water pressure in soil was measured by using a pneumatic piezometer installed at the base of the wall. In addition, a standpipe piezometer was used to measure water level by inserting a sensor up to the water level. To measure settlement, three surface settlement markers were installed after end of construction.

Results and Discussion

Actual performance of the segmental retaining walls could be observed by comparing the results of field monitoring with the results of FEM calculation. According to the original design, this wall was with a surcharge of 5.0 kN/m^2, but during the monitoring, no load was applied in the field. FEM calculation results discussed here was based on the original design as the effect of the surcharge on the results of FEM calculations was too small. For example, the max. deflection of the wall without surcharge and with surcharge was 12.67 mm and 12.77 mm respectively, as well as the value of the max. foundation settlement, 15.86 mm and 15.87 mm respectively. Based on FEM calculations for the instrumented wall, it was found that the max. deformation was 27.82 mm. The max. effective stress was 167.48 kN/m^2 and based on the analysis of phi/chi reduction method, the global FOS was 2.29.

Changes in the measurement of inclinometer over 203 days showed that the max. deflection of the wall was 13.0 mm at the height of 4.0 m from the base of the wall (See Figure 3.1). FEM results showed clear similarities with the value of 12.77 mm, a difference of only 0.33 mm. Location of the max. deflection was also similar, i.e. 4.0 m high. However, there were significant differences in shape of the distribution because the value of the measured deflection at the base of the wall was only 1.0 mm. This happened because the base of inclinometer casing was fixed to the concrete mix. In FEM simulation, there was no fixity considered. Based on the results, it could be concluded that the FEM simulation of the retaining wall could estimate the value of max. deflection accurately.

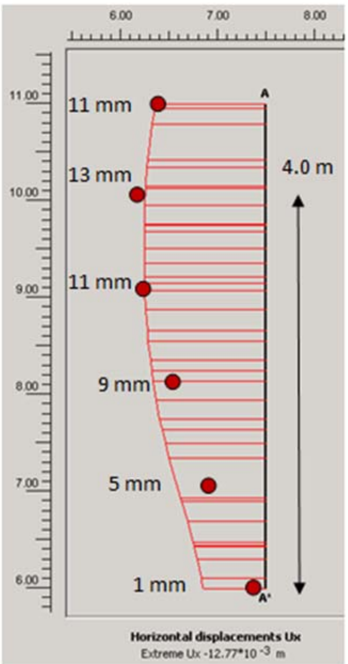

Figure 3.1 Horizontal deflection of the wall

The value of the max. surface settlement measured in the field was 17 mm. This value was different from the values obtained by FEM (24.55 mm) with a difference of 7.5 mm. In engineering practice, this difference could be considered small for a five meter high wall because the wall of this type could accommodate large deformation (BS8006 1995). Besides, if we looked at the distribution of the surface settlement, the location of the max. settlement for both cases was similar, i.e. at the center of the reinforced zone. No measurements were taken for foundation settlement in the field for comparison. The max. value calculated by FEM was 15.87 mm. The distribution of foundation settlement was shown in Figure 3.3.

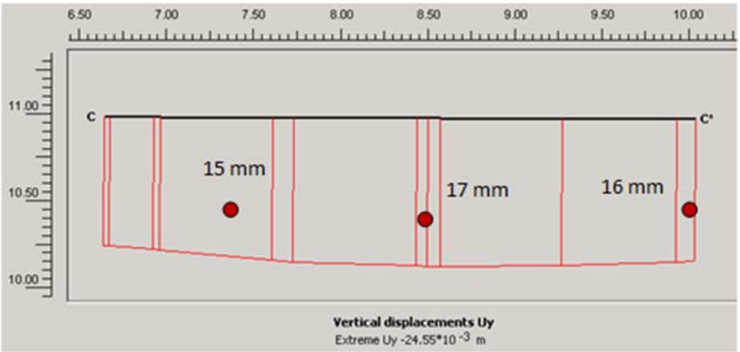

Figure 3.2 Surface settlement of the wall

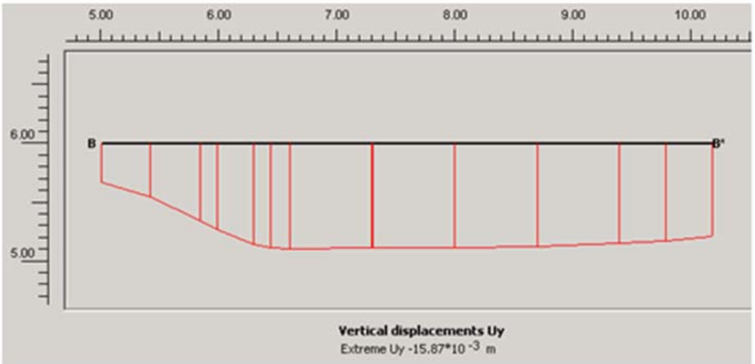

Figure 3.3 Foundation settlement of the wall

Value of RMSE (Root Mean Square Error) based on 232 data for each mathematical model was shown in Figure 3.4 while value of R^2 was shown in Figure 3.5. From Figure 3.4, it was obvious that Full Quadratic was the best model for RSM since the value of RMSE for each output parameter, i.e. global FOS, surface settlement, foundation settlement, location of max. deflection and deflection was the lowest or closest to zero. Similarly, from Figure 3.5, it was obvious that Full Quadratic was the best model because the value of R^2 for each output parameter was the highest or closest to one. Thus, equation of Full Quadratic was selected to be used in developing a computer system to predict the stability of the segmental retaining wall.

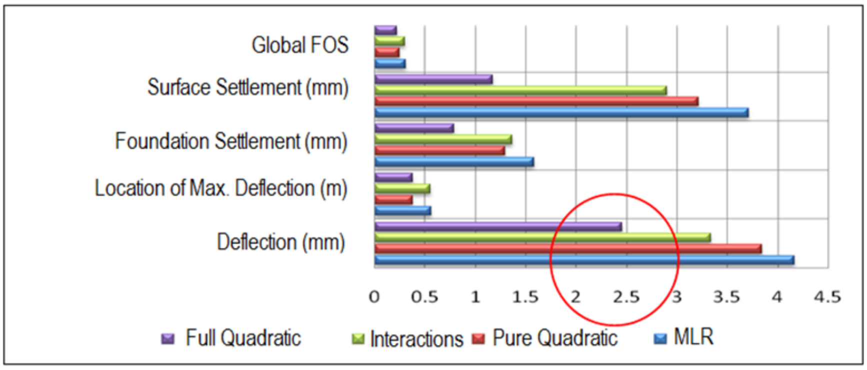

Figure 3.4 Value of RMSE for each mathematical model

Conclusion

In conclusion, this study has successfully predicted the stability of geogrid reinforced segmental retaining wall in terms of global FOS, surface and foundation settlement and wall deflection, compared the accuracy of statistical methods of MLR, Quadratic Pure, Interaction and Quadratic Full, observed the actual performance of the retaining wall by comparing the results of field monitoring with the results of FEM calculations and produced a system that can predict the stability of walls quickly and accurately. Since Full Quadratic is the best mathematical model to predict global FOS, surface settlement, foundation settlement, location of max. deflection and deflection, it has been used to develop a computer system.

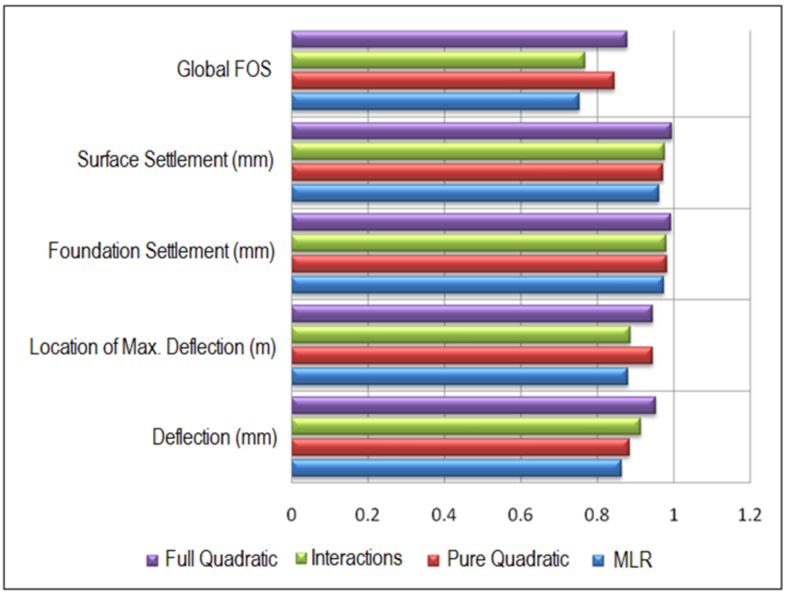

Figure 3.5 Value of R^2 for each mathematical model

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