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Parametric Study of Applied Stresses on Infiltration Modular Cells installed under Roads

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Abstract

Modular geocellular units are applicable for the prevention and minimisation of stormwater runoff and flooding as a sustainable and cost-effective solution of road applications for drainage. The integrated units buried are exposed to the dead loads and live loads emerging from the surrounding soil pressure, pore water pressure and surcharge. Thus, a computer program using MATLAB is developed for the assessment of the total vertical and lateral earth pressure exerting on the modules complying with the Australian Standards AS 4678 (2002) and AS 5100.2(2004). Lateral earth pressure concept based on Rankine's theory is adopted in this model as the analytical approach. Closed-form solutions based on the fundamental soil mechanics are applied in the analytical calculation steps made. The model also considers different guidelines such as AASHTO LRFD Bridge Design Specifications (2010) for the stress distribution of vehicular loads according to the selected axle type. In consideration of the interaction of the moving vehicle and the bridge, the dynamic load allowance is also applied in terms of the static equivalent of the dynamic and vibratory effect as prescribed in AS 5100.2 (2004). Based on the results obtained, the numerical and theoretical results generated by the program provide considerable and influential factors in regarding to the parametric study and sensitivity analysis presented in this paper.

Keywords: Infiltration modules, Stormwater tank, Geocellular, Sustainable, Traffic Load, Surcharge

1 Introduction

Modular geocellular units are applicable for the prevention and minimisation of stormwater runoff and flooding as a sustainable solution of road applications for drainage and/or infiltration purpose. Detention and retention systems are considered as the major types of stormwater control systems in urban areas (ASCE, 1992). Such units buried under the ground may be considered as geotechnical structures from a design point of view because they act as retaining structures and support earthwork materials (CIRIA, 2008).

In developed areas where land cost is a major concern, sub-surface stormwater management systems have the potential to be used (AL-Hamati, Ghazali, & Mohammed, 2010). The common

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industrial practice uses polymers as the major raw material source. According to Koerner (1997), utilisation of geosynthetics generally prevents depletion of natural resources, replaces different designs using soil or other construction materials, and allows rapid installation. In addition to the fact, no geosynthetic product is made of 100% polymer resin (CUR Committee, 2012). Employment of recycled polymers further promotes sustainability and brings cost-competitiveness factor into consideration.

In this paper, the overall structural performance of the geocellular modules is investigated. The integrated units buried are exposed to the dead loads and live loads emerging from the surrounding soil pressure, pore water pressure and surcharge. For this reason, a model is developed using MATLAB software to highlight the structural performance of the system by estimating the total vertical and lateral stresses exerted due to permanent and imposed loads abiding Australian Standards AS 4678 (2002) and AS 5100.2 (2004). Case study is beyond the scope of this paper and field performance is necessary to follow up the outcomes discussed in this paper for practical significance.

2 Methodology

2.1 Computational Assumptions

In the calculation process, the effective stress analysis method is considered due to using drained material around the cell. In each execution of the program, it is optional to select the vehicular load or the uniformly distributed load on pavement slab, as the external loading. Boussinesq (1885) developed mathematic relationships for the distribution of stresses in a half-space resulting from loads acting on surface which are commonly applied in the areas of geotechnical and road engineering. The influence of soil non-homogeneity on stress distribution in elastic soil was examined by Vrettos (1998) and he demonstrated that the variation of the soil stiffness with depth did not significantly affect the distribution of the vertical stress. Thus, the outcomes indicate the Boussinesq's solution is adaptable to depth-dependent soil stress distribution. Despite the accuracy and applicability of Bousinessq's solutions, the vertical stress distribution method used in the program follow the approach as described by the AS 5100.2 which is found to give close results to the Bousinessq's solution.

Throughout all the modules aligned and stacked, the point of interest to estimate the critical vertical stress is the highest surface panels of the tank underlying in contact with the top cover soil/backfill. The imposed loading has the potential to subject its maximum impact to the closest modules rather than the lower units since the stress intensity tends to reduce with depth. Closed-form solutions based on the fundamental soil mechanics are applied. Wheel load, Q is simply accounted as half of the axle load independent of the number of tyres in wheel group. In consideration of the interaction of the moving vehicle and the bridge, the dynamic load allowance is also applied in terms of the static equivalent of the dynamic and vibratory effect.

2.2 Program Layout

A computer program using MATLAB is developed for the assessment of the effective vertical and lateral earth pressure exerting on the modules complying with the Australian Standards AS 4678 (2002) and AS 5100.2 (2004). Two individual programs are developed as the interactive program. The live loads can be sub-divided into traffic loads subjected onto the pavement layer and the surcharge. The stresses exerting on the modular geocellular units are estimated by the program developed in particular for the cross-sectional profile in Figure 1.

The output given by the analysis of vertical stress program is conveyed to the subsequent program, lateral stress analysis, as a complete package of computations. From Figure 2, it can be seen some of the input parameters provided to calculate the vertical stress are disabled to change in calculation of the lateral stress, simply to avoid inconsistent inputs. However, some unimportant variables, for instance tyre width and length, axle spacing and number of modules in vertical and horizontal, are ignored and not presented in the parametric study for the reasons they are much unlikely to vary in

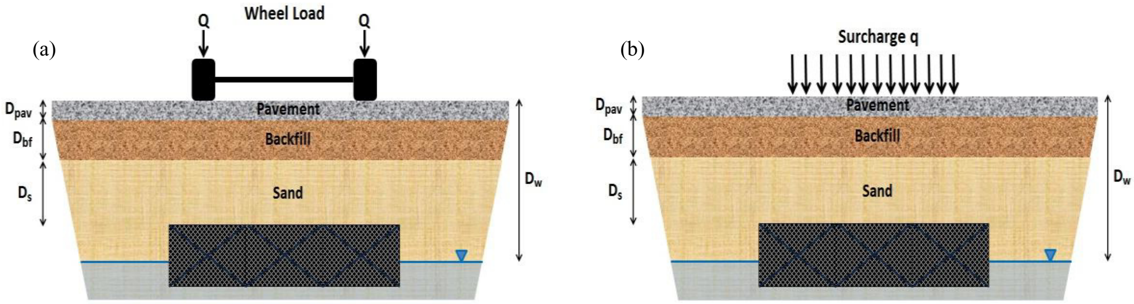


Figure 2 Illustration of cross-sectional profiles of modular tank under (a) traffic load (b) surcharge

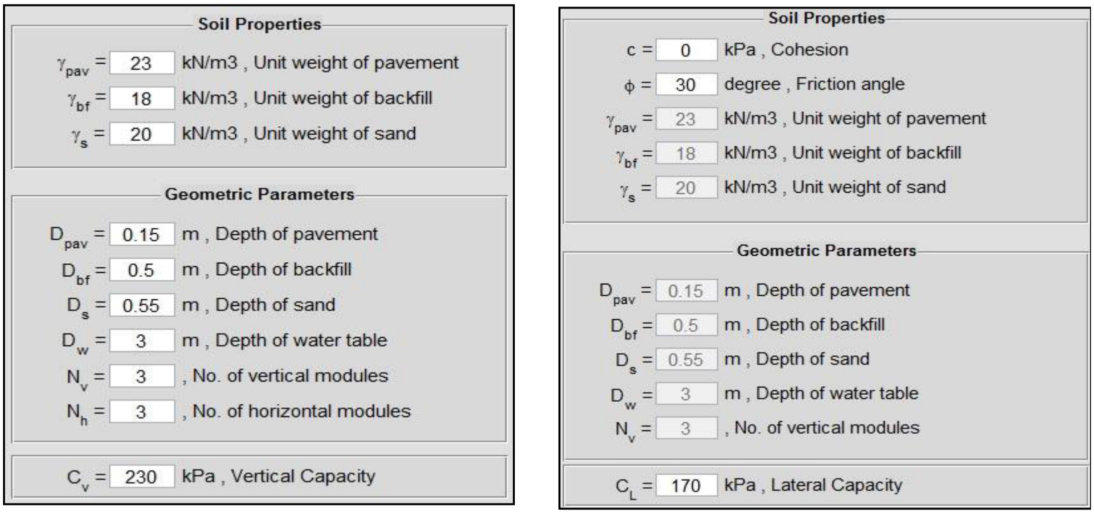


Figure 1 Snapshots of input parameters of the interactive program

value or they can be easily interpreted from general understanding, or due to their minor influence on the system.

3 Parametric Study

3.1 Overview

Parametric study is conducted to highlight and visualise the influence of parameters on the principal stresses acting on the modular tank, upon which service life of the system can vary. Normal operating point (NOP) is set as depicted in Table 1, including sets of values kept constant during analysis whilst single parameter is exclusively allowed to vary within reasonable range. The results published in this paper are complied with the Australian Standards, and are differed 7-18% from the AASHTO (2012) guideline due to the difference in partial factors applied and stress distribution method.

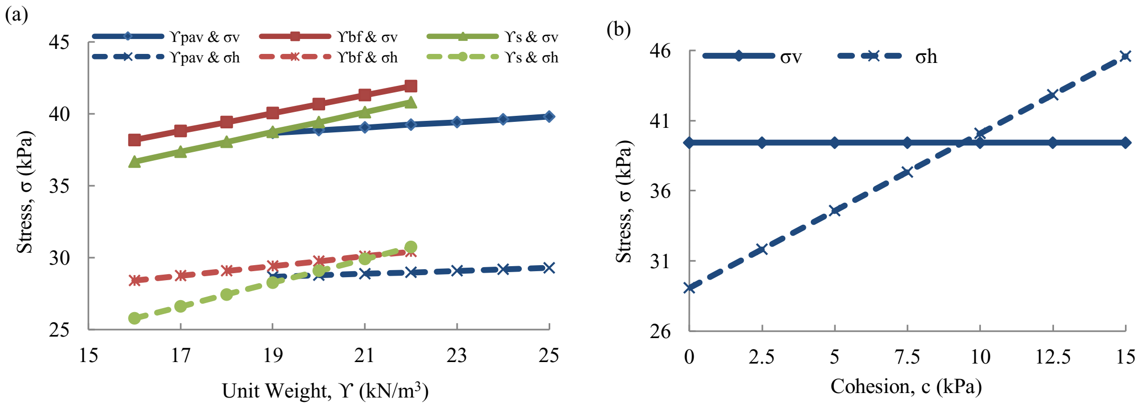
Parameters		Value at NOP	Nominal Range
Soil Properties	Υ_{pav} (kN/m^3)	23	{19, 20, 21, 22, 23, 24, 25}
	Υ_{bf} (kN/m^3)	18	{16, 17, 18, 19, 20, 21, 22}
	Υ_s (kN/m^3)	20	{16, 17, 18, 19, 20, 21, 22}
	c (kPa)	0	{0, 2.5, 5, 7.5, 10, 12.5, 15}
	φ (°)	30	{0, 7.5, 15, 22.5, 30, 37.5, 45}
Geometric Parameters	D_{pav} (m)	0.15	{0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3}
	D_{bf} (m)	0.5	{0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6}
	D_s (m)	0.55	{0, 0.15, 0.25, 0.35, 0.45, 0.55, 0.65}
	D_w (m)	3	{0, 0.5, 1, 1.5, 2, 2.5, 3}
Loading Parameters	B (m)	2	{1, 1.5, 2, 2.5, 3, 3.5, 4}
	L (m)	5	{1, 2, 3, 4, 5, 6, 7}
	q (kPa) Q (kN)	10 40	{5, 10, 15, 20, 25, 30, 35} {26.5, 40, 45, 67.5}

Table 1: Values of influencing parameters at NOP and their nominal ranges

3.2 Influence of Soil Properties

Soil properties include the unit weight of the materials for layered soil Υ, the cohesion c and the friction angle of soil φ. From Figure 3, the unit weight of pavement, backfill and sand within its nominal range simply display a linear correlation against the vertical and lateral stresses. From the following graph (a), varying the unit weight of the pavement slab which means changing the material used for the pavement unlikely causes to generate greater stress as the thickness of the slab is limited and the depth is relatively small compared to the underlying backfill and sand layers. Hence, either using asphalt pavement or concrete slab with reinforcing bars does not significantly alter the outputs of the stresses. In reality, however, rather than replacing the materials with lighter unit weight, it is more feasible to control the depth of corresponding layer along the cross-sectional profile.

Despite the cohesion and the friction angle have no effect on σ_v, the former exhibits linear correlation with σ_h while the latter decreases linearly. Thus, the backfill and soil used in conjunction with the infiltration/detention system avoid the cohesive types of soil as to compromise the lateral earth pressure. σ_h can impose 17% more by only the slight increase of cohesion from 0 to 5 kPa. On the other hand, depending on the type of backfill surrounding the geo-modules, σ_h varies approximately ±16% by the change of ±5° in φ.



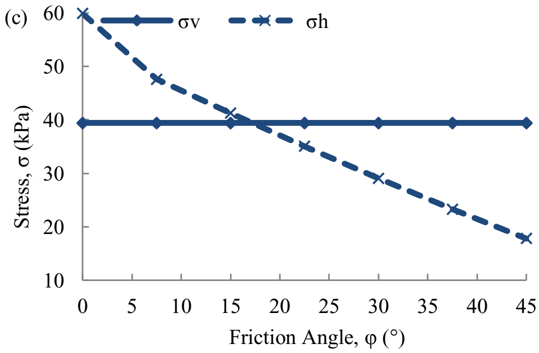


Figure 3 Effect of (a) unit weight (b) cohesion (c) friction angle on vertical and lateral stress

3.3 Influence of Cover Depth

In similar to the unit weight, the earth-fill cover for pavement, backfill and sand also exhibits linear variation with the increase in both vertical and horizontal stresses as depicted in Figure 4(a). The total depth from the ground surface including the pavement slab needs to be limited since the excess of overlying depth resting on the modules has the tendency to result huge overburden pressure which also transforms into large lateral pressure exerting on sides of the tank. It can be noted that the capacity of the module is normally weaker in the lateral direction than the vertical.

3.4 Influence of Groundwater Level

From Figure 4(b), the parameter D_w is only sensitive to a point beyond which the water-table has no effect in variation of the stresses. At NOP, the level of water-table is located at the depth of 3 m and 1.2 m for the tank from the ground, which means water-table is below the base of tank with no influence. As expected, results indicate that D_w clearly has no effect in changing σ_v beyond 1.2 m. Since the depth to water-table moves further away from the surface, σ_v increases due to the absence of pore water pressure in the soil grains. The trend is however different for the lateral stress. The earth pressure applying on the system diminishes as D_w continues to increase but only up to the vicinity of 2.5 m after which σ_h has no alteration in value. This is due to the fact that the total depth including the fill cover and the depth of the tank is equivalent to 2.55 m at NOP.

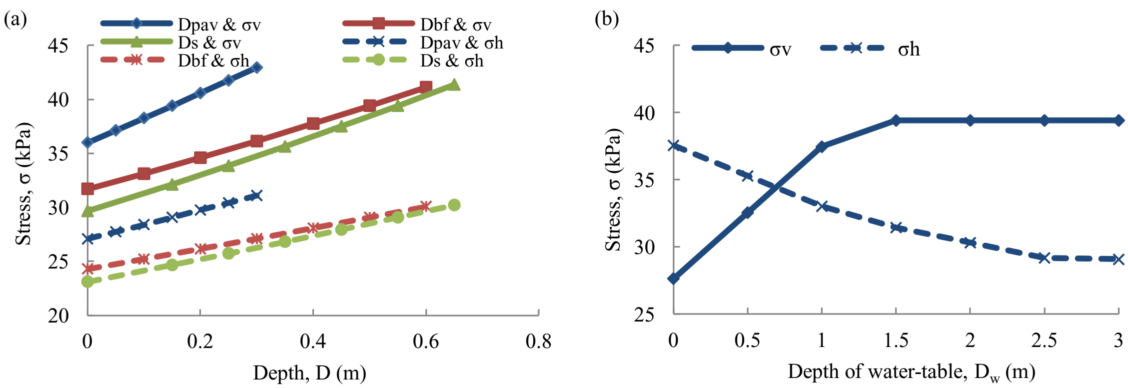


Figure 4 Effect of (a) geometric cover depth (b) depth of water-table on vertical and lateral stress

3.5 Influence of Surcharge

Clearly, both the vertical and horizontal stresses increase linearly as surcharge is incrementally increased. Since the lateral earth pressure is dependent upon the vertical, Figure 6 illustrates that σ_v increases in higher rate than σ_h. At q = 10 kPa, σ_v is 5% greater than σ_h. Whilst q is twice, σ_v is 10 times greater than σ_h. Difference between the two reaches 72% when q = 30 kPa. From the results, width and length of surcharge provide only slight contribution in variation of the stresses and can be concluded as insignificant. From 1 m to 4 m, the width parameter, B has an increase of 15% and 10% for σ_v and σ_h, respectively. Leaving the other parameters unchanged, the effectiveness of length of surcharge, L is observed within the reasonable scale of 1 m to 5 m. The trend follows in similar pattern to the width but shows σ_v has an increment of 10% and approximately 8% for σ_h.

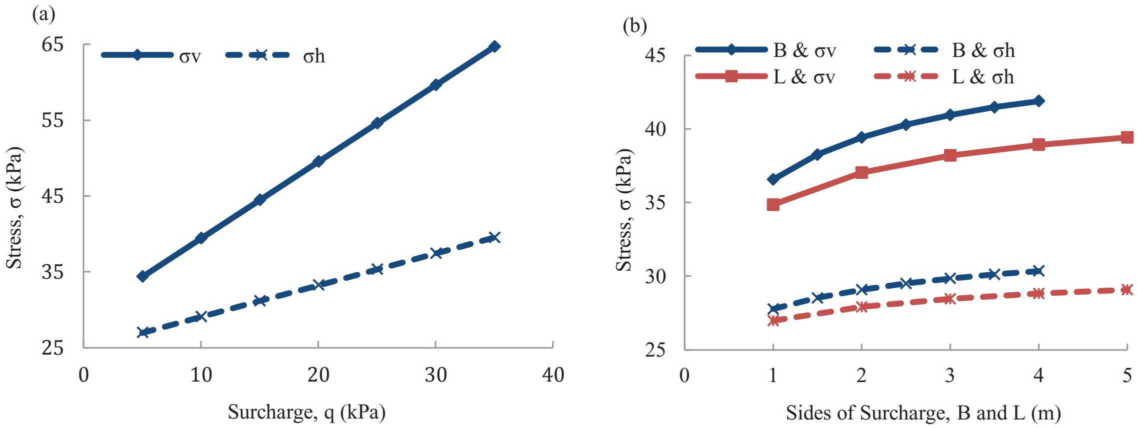


Figure 5 Effect of (a) surcharge (b) width and length of surcharge on vertical and lateral stress

3.6 Influence of Wheel Load

In order to compare with uniform surcharge loading, traffic loads are designed based on four types of axles in the model, namely single axle with single tyres (SAST), single axle with dual tyres (SADT), dual axles with single tyres (DAST), and dual axles with dual tyres (DADT), which are the four points respectively used in the Figure below. Accordingly, observations can be made that there is a sudden jump of stress values in both trends, which is mainly due to the overlapping areas of distributed stress from the axles interacting together. As can be seen similar to surcharge, the effect of wheel load is more prominent in the vertical stress than the lateral. Vehicles with DADT can impose 75% and 43% more than SAST in vertical stress and lateral stress, respectively.

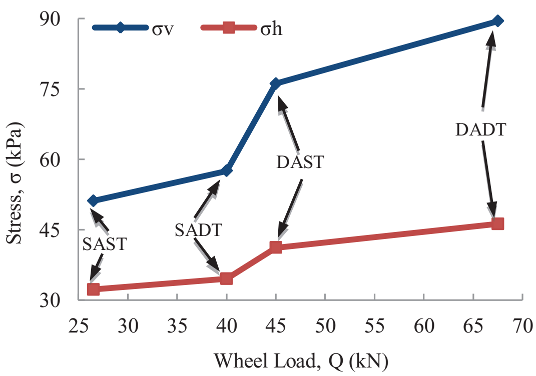


Figure 6 Effect of wheel load on vertical and lateral stress

4 Sensitivity Analysis

From the results of parametric study, sensitivity analysis can be further conducted to determine how different the independent variable can impact the dependent variable under a give set of assumptions and to compare the effectiveness of the parameters in the model. The critical part of the model amongst the parameters can be highlighted, values of critical parameters can be refined and parameters that have minor effect on the system can be ignored.

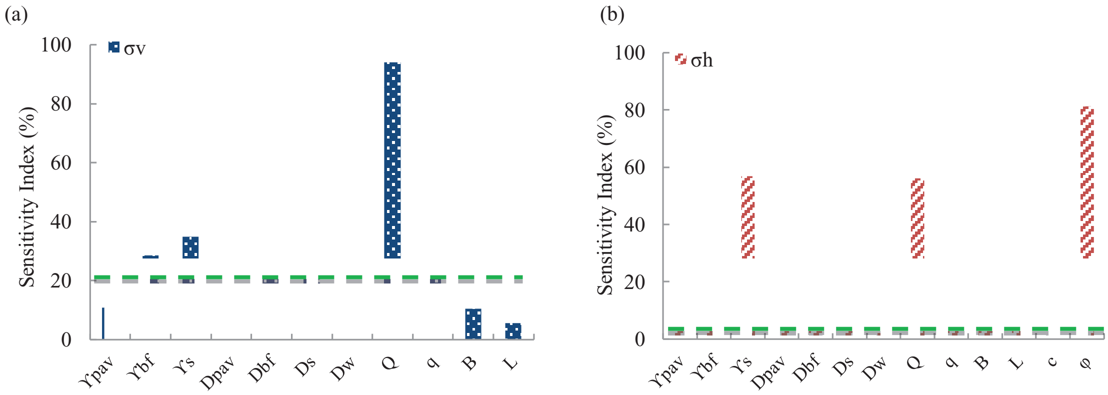


Figure 7 Sensitivities of parameters in analysis of (a) vertical stress (b) lateral stress

It should be noted that contribution of partial saturation, soil creep and cementation and its degradation can influence the stress-strain behaviour of the soils and consequently the load distribution below the ground surface. Authors are working on more comprehensive modelling techniques to capture some of the mentioned aspects (Ho, Fatahi, & Khabbaz, 2015; Nguyen, Fatahi, & Khabbaz, 2014; Le, Fatahi, & Khabbaz, 2015; Azari, Fatahi, & Khabbaz, 2016).

5 Conclusions

The numerical and theoretical results generated by the developed program provide considerable and influential factors in regarding to the parametric study and sensitivity analysis conducted in this study. The findings indicate that Q and φ are the most sensitive parameters being 93.9% and 81.2% while the medians of the sensitivity indexes are set as 21.9% and 24.1%, represented by the dashed lines in Figure 7. In design optimisation, the input parameters above the median can be refined to meet the quality and achieve the desired service life. Other insensitive parameters such as Υ_{pav}, D_{pav}, B, L and c can be ignored as they have minimum impact. Moreover, the work is in progress to superpose the effect of compaction of soil surrounding the geo-modular tank system.

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