6ICEGE
6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch. New Zealand

Moment-rotation Behavior of Shallow Foundations with Fixed Vertical Load Using PLAXIS 3D

R. S. Salimath[1], M.J. Pender[2]

ABSTRACT

This paper reports on an investigation of the behavior of shallow foundations under fixed vertical load on clay subjected to moment about a centroidal axis, results for both the width axis and the length axis are given. When subjected to moment shallow foundations may uplift and lose contact with underlying soil, consequently their behavior is highly nonlinear. Analyses were carried out using the PLAXIS 3D 2011 finite element program. An interface element is used to model loss of contact between footing and soil. In this paper, rectangular foundations with *L/B* ratios of 3 and 5 are considered. The fixed vertical load moment-rotation curves obtained using PLAXIS 3D are compared with those predicted by a detachable spring bed model. The impact of factors such L/B, V/V_{uo} ratios and effective footing width B′ are discussed. The main conclusion is that, for the geometries investigated, the detachable spring bed and nonlinear finite element moment rotation curves are very similar.

Introduction

The behavior of shallow foundations subjected to moment is complex, with both geometrical and material nonlinearity being important factors. Large scale field testing to determine such behavior can be daunting and expensive. Consequently powerful numerical tools able to simulate three dimensional nonlinear soil-structure interaction are very useful. Even so in a design office context simpler approaches are important; modelling with beds of detachable springs is commonly used. Allotey and Naggar (2003) presented analytical equations to obtain static moment-rotation response for rigid foundations for the uplift-yield condition. Harden and Hutchinson (2009) used numerical modelling based on simplified beam-on-nonlinear-Winkler foundation (BNWF) to study nonlinear response of shallow foundations subjected to combined loading. Anastasopoulos and Kontoroupi (2014) presented a simple approximate method to analyze rocking behavior of SDOF systems incorporating non-linear soil behavior and foundation uplift. In this study, analysis is carried out using the finite element program PLAXIS 3D (Plaxis BV, 2012) and also using the simple spring bed model detailed by Pender (2016). Validation of the PLAXIS 3D model was carried out by comparing the results with moment-rotation response obtained from prototype field snap back experiments (Algie, 2011) as shown in Figure 1. The main objective of this paper is to analyze the behavior of rectangular shallow foundations with fixed vertical load subjected to moment about the width and length axes. This approach is drawn from the concept of integrated design of structure foundation systems (Pender, 2006). Two cases of rectangular foundations with dimensions 6mx18m and 6mx30m are

[1]Ravi Salimath, Civil and Environmental Engineering Department, University of Auckland, Auckland, New Zealand, rsal403@aucklanduni.ac.nz
[2]Michael Pender, Civil and Environmental Engineering Department, University of Auckland, Auckland, New Zealand, m.pender@auckland.ac.nz

considered. Initially the footing is subjected to vertical load at the center and then moment is applied in increments keeping the vertical load constant. For each of these footings two cases were analyzed, one with moment about the width axis and another with moment about the length axis. The moment-rotation responses obtained using PLAXIS 3D and the spring bed model were then compared and analyzed. From this it is clear that the conventional detachable spring-bed solutions are able to represent some aspects of shallow foundation behavior but not others. All numerical tools have their limitations and PLAXIS 3D is no exception. One of the challenges in PLAXIS 3D for such problems is to use the interface element correctly, to select an appropriate degree of mesh refinement close to the foundation, and to establish satisfactory distances to the outer boundaries of the mesh. All such concerns were carefully addressed by carrying out preliminary studies and examining closely the program outputs for deformed mesh, interface stresses, and plastic failure points (if any).

Model Validation

Verification and validation of numerical model is very important before progressing to the actual problem. Preferably the model should be validated using either field or laboratory experimental results. Fortunately, in this case the model was validated using results from the pull-back phase of field shallow foundation snap-back tests on Auckland residual clay (Algie, 2011). The PLAXIS 3D model consisted of 0.4mx2mx0.4m footing with vertical load of 130kN, embedded 0.4m into the clay layer (same dimensions as test footing, Algie 2011). The overall model dimensions were 15mx15mx15m, well extended beyond the footing in order to simulate site condition and ascertain that the deformations induced by the footing are not impacted by the model boundaries. Interface was used along the underside and sides of the footing. The interface was extended about 0.5m beyond the footing boundaries to avoid high stress concentrations at the corners. The undrained shear strength of the soil, s_u at the test location was around 140kPa with maximum shear modulus of 40 MPa. The Figure 1 shows the comparison of moment-rotation curve obtained using PLAXIS 3D analysis and the results from one of the snap-back experiments. It is evident that the results from PLAXIS 3D are in good agreement with pull-back results. Similar procedures were repeated for another set of snap-back test data and results from PLAXIS 3D analysis again compared very well. Hence, it was concluded that PLAXIS 3D with footing uplift and nonlinear soil behavior models the shallow foundation behavior well.

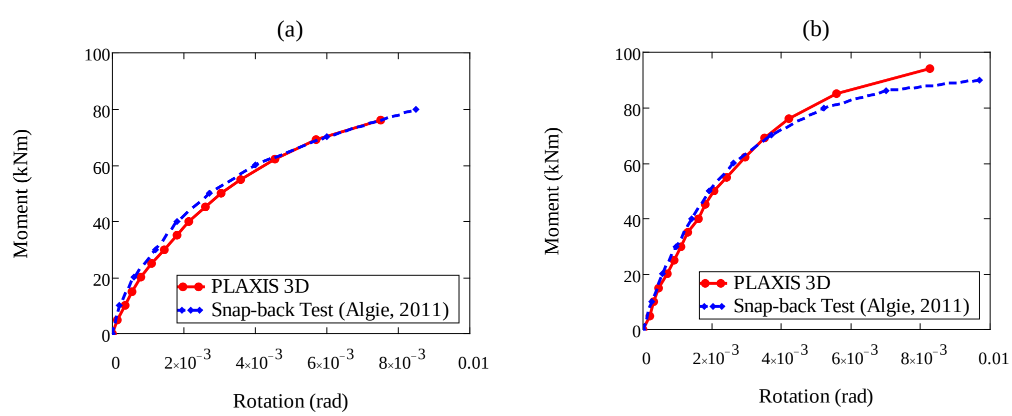

Figure 1. Comparison of static moment-rotation curves from PLAXIS 3D and snap-back tests (Algie, 2011) (a) Test 7 and (b) Test 9

Finite Element Analysis Using PLAXIS 3D 2011

Once the model was validated, further analyses were undertaken for rectangular footings. In this study emphasis is given on the footing behavior about the direction of the applied moment with fixed vertical load. Two sizes of rectangular footings with dimensions 6mx18m and 6mx30m were analyzed in PLAXIS 3D. Both footings were 1m thick and were modelled as rigid blocks. The footings were subjected to a vertical load at the center and then moment was applied in various load steps without changing the vertical load. Both footings were analyzed with moment about shorter axis and another with moment about longer axis for various V/V_{uo} load combinations as shown in Figure 2 (where V_{uo} is the bearing strength of the footing when subject to vertical load only). Interface elements were used on the underside of the footing in order to facilitate loss of contact with soil during the uplift phase. Default boundary conditions were applied assuming undrained behavior of saturated clay. Model input parameters for soil and interface are shown in Table 1. The footing was modelled as volume element consisting of nonporous material. The hardening soil model (Plaxis B V. 2012) was used for both soil and interface which is formulated using hyperbolic stress-strain curves with stress dependent stiffness inputs to simulate realistic soil behavior. In the interest of calculation time, the mesh was locally refined only around the footing and interface boundaries as shown in Figure 3.a. This mesh arrangement does not impact the results as the right mesh size is used within the footing zone of influence. Vertical load on the footing was defined in relation to the bearing strength of the foundation (V_{uo}). For each footing four loading cases, $V=0.1V_{uo}$, $0.2V_{uo}$, $0.3V_{uo}$ and $0.4V_{uo}$ were analyzed as shown in Table 2. With the same loading configuration as shown in Table 2 each footing was analyzed with moment about shorter axis and then about longer axis. Moment-rotation curves were developed for each loading case. Similarly, the analysis was also carried out with identical load cases using the detaching spring bed model. Figures 3.a and 3.b show PLAXIS 3D output of deformed mesh and vertical settlement distribution for 6mx18m footing with vertical load $V/_{Vuo}$ = 0.3 respectively. The footing uplift and loss of contact is evident in Figure 3.a and vertical settlement distribution is as expected. The behavior of the footing about the direction of the applied moment was analyzed and the effect of V/V_{uo}, L/B, B'/B ratios is demonstrated.

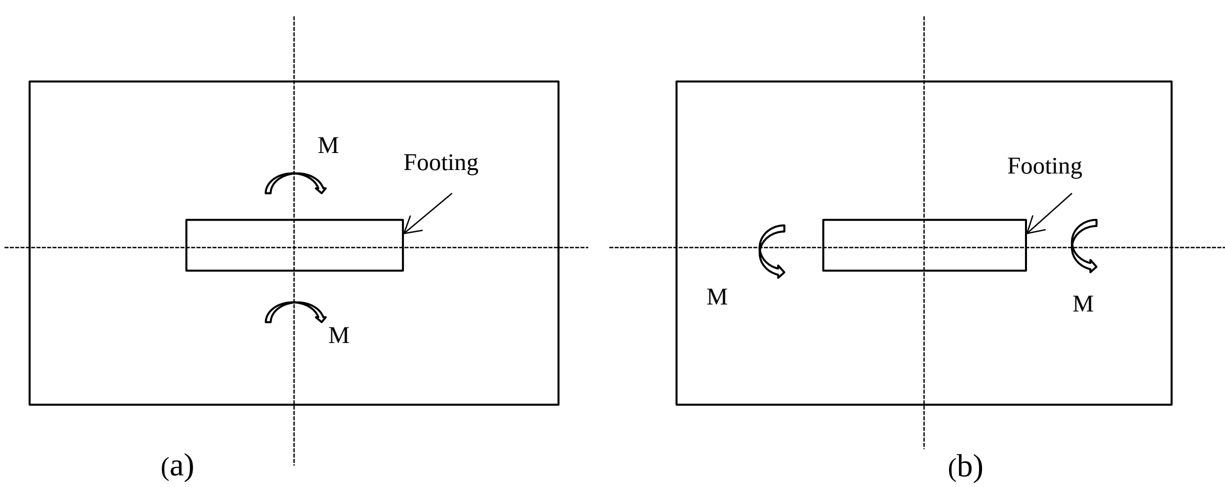

Figure 2. Two cases of analysis a) moment about shorter axis b) moment about longer axis

Table 1. Model input parameters.

Parameters	Clay	Interface
Material Model	Hardening soil	Hardening soil
Drainage	Undrained (B)	Drained
γ_{sat} / γ_{unsat} (kN/m^3)	19.5/17.5	19.5/17.5
Initial void ratio, e_{init}	0.7	0.7
Secant modulus, E_{50}^{ref} (kPa)	7900	7900
Oedometer modulus, E_{oed}^{ref} (kPa)	7900	7900
Unloading/Reloading modulus, E_{ur}^{ref} (kPa)	23800	23800
Undrained shear strength, su (kPa)	85	-
Friction angle, ϕ'(deg)	-	34
Cohesion, C' (kPa)	-	5
Over-consolidation ratio, OCR	2	2
Pre-overburden ratio	0.0	0.0

Table 2. Vertical loads on the footing.

V/V_{uo} (kN)	Vertical load, V (kN)	
	6mx18m	6mx30m
0.1	5040	8180
0.2	10080	16360
0.3	15120	24540
0.4	20160	32720

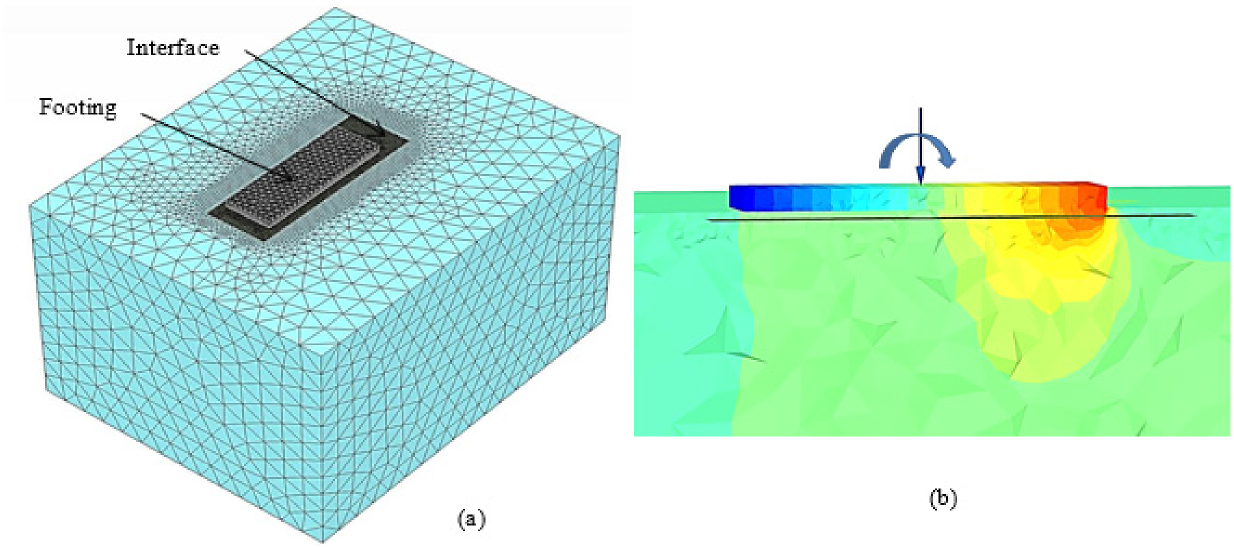

Figure 3. PLAXIS 3D outputs of 6mx18m footing: (a) generated mesh with interface; (b) vertical settlement under the footing (cross-section view) Mult = 93800kNm at V/V_{uo} = 0.3.

Moment-rotation Response of the Footing

Figures 4 to 7 show the moment-rotation response about the direction of the applied moment obtained using PLAXIS 3D and spring-bed model analysis for 6mx18m footing at V/V_{uo} = 0.1 and V/V_{uo} = 0.4 . From the plots it is clear that the results from PLAXIS 3D analyses differ from spring-bed model, in some cases variation is significant. The results indicate the effect of factors such as V/V_{uo}, L/B ratio and the direction of the applied moment. For instance in Figures 4 and 5, for the case of V/V_{uo} = 0.4 the spring-bed model shows higher rotational stiffness than PLAXIS 3D when moment is applied about the shorter axis whereas the results are vice versa when the moment is applied about the longer axis. For the case of V/V_{uo} = 0.1, there is a close match between the results from PLAXIS 3D and spring-bed model when moment is applied about shorter axis whereas the results differ when moment is applied about the longer axis. The trend is very much similar for 6mx30m footing as shown in Figures 6 and 7. This shows how critical it is to incorporate the effects of V/V_{uo} and L/B ratios when analyzing the behavior of shallow foundations subjected to moment.

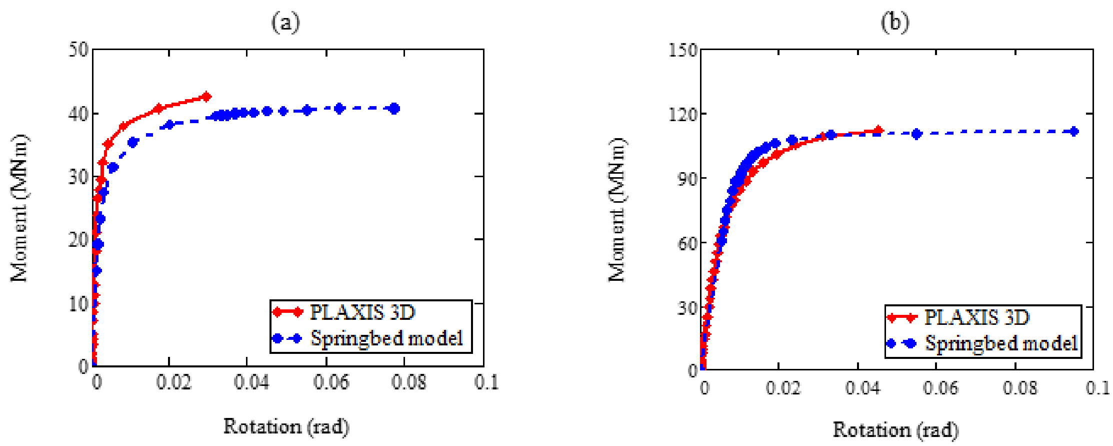

Figure 4. Moment-rotation curves for 6mx18m footing with moment about shorter axis and a fixed vertical load (a) V/V_{uo} = 0.1 and (b) V/V_{uo} = 0.4

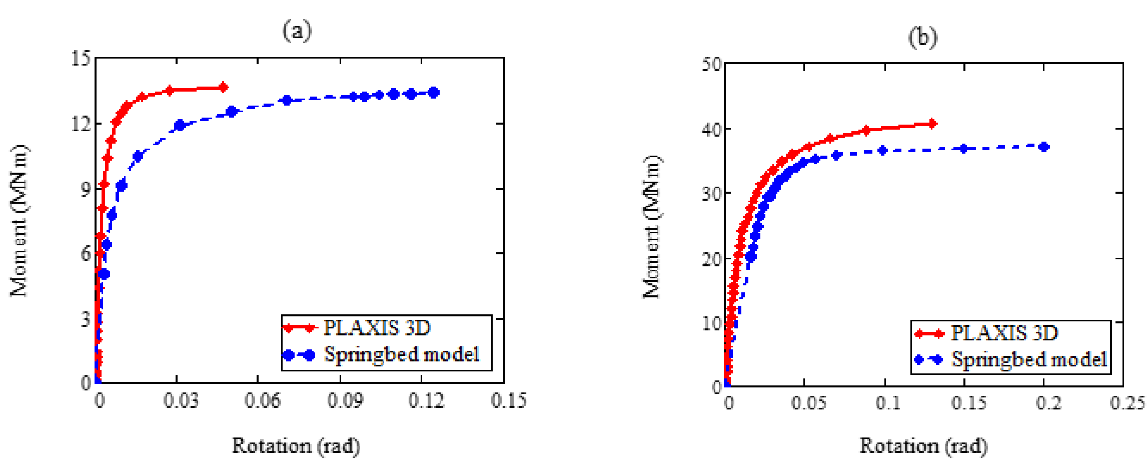

Figure 5. Moment-rotation curves for 6mx18m footing with moment about longer axis and a fixed vertical load (a) V/V_{uo} = 0.1 and (b) V/V_{uo} = 0.4

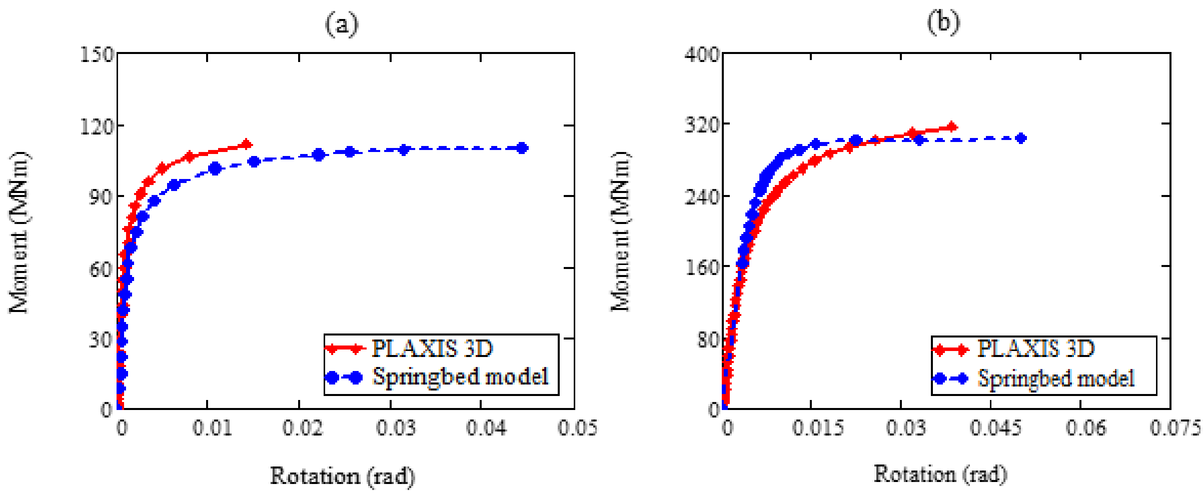

Figure 6. Moment-rotation curves for 6mx30m footing with moment about shorter axis and a fixed vertical load (a) V/V_{uo} = 0.1 and (b) V/V_{uo} = 0.4

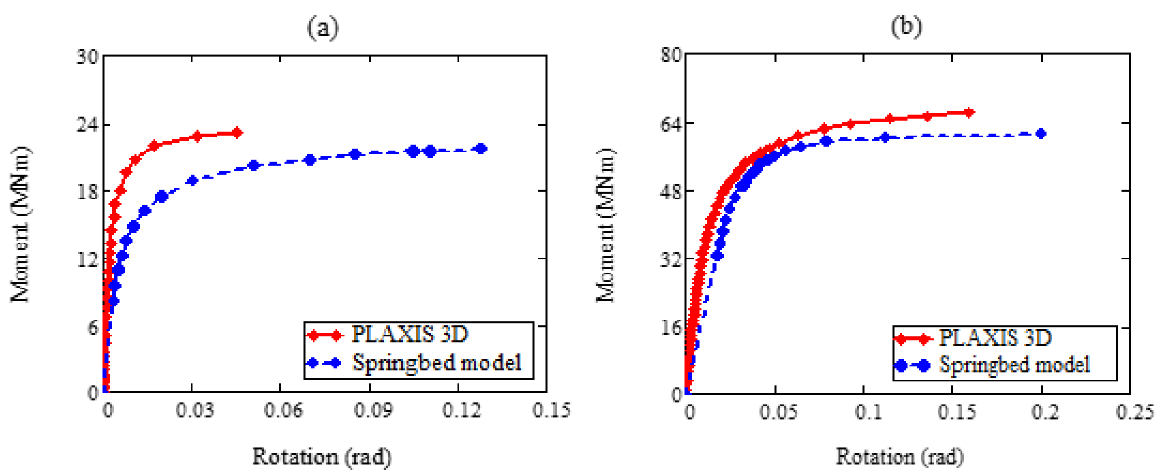

Figure 7. Moment-rotation curves for 6mx30m footing with moment about longer axis and a fixed vertical load (a) V/V_{uo} = 0.1 and (b) V/V_{uo} = 0.4

Effective Width of the Footing at Ultimate Moment

The evaluation of actual available width of the footing during the uplift phase is very critical in assessing the available bearing strength. The conventional equation for effective width ($B' = B-2M/V$) is valid only at ultimate moment and is based on a three-dimensional rectangular stress block under the footing and ignores the effects of V/V_{uo} and L/B ratios. In Figure 8 the effective width of the foundation, when the ultimate moment capacity at the fixed vertical load is mobilized, is compared for the PLAXIS 3D, spring bed model and the conventional solution. The plots indicate that the effective width obtained using PLAXIS 3D analysis is significantly greater than for the spring bed case. However, the location of the zero contact pressure boundary is not as definite in the finite element calculations as it is for the spring bed as the position of zero contact pressure varies along the footing; the values given in Figures 8, 9 and 10 are those at the centre of the footing. Figures 9 and 10 show variation of effective width of 6mx18m footing with increasing moment at a fixed vertical load of V/V_{uo} = 0.1 and 0.4 respectively, for PLAXIS 3D and spring-bed model analysis. Each of the load cases was analyzed with moment about shorter and longer axis.

Results indicate that spring-bed model underestimates the effective width especially when moment is applied about longer axis. The plots demonstrate the inability of the spring-bed model to account for the effects of V/V_{uo} and direction of the applied moment. Similar observations were made for the case of 6mx6m, 6mx12m and 6mx30m footings.

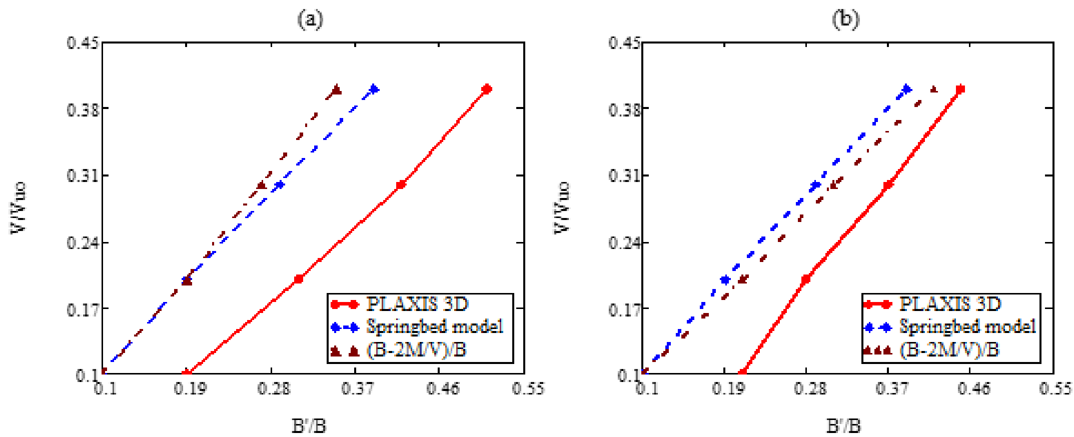

Figure 8. Variation of effective width B′/B vs V/V_{uo} at ultimate moment for 6mx18m footing with (a) moment applied about shorter axis (b) moment applied about longer axis.

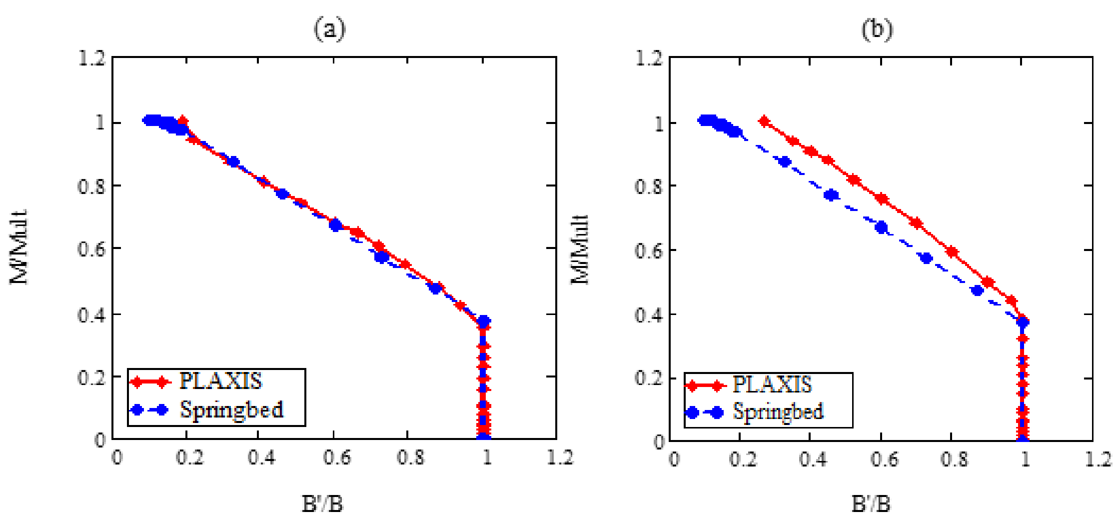

Figure 9. Variation of effective footing width, B'/B vs M/M_{ult} for 6mx18m footing at V/V_{uo} = 0.1 with (a) moment applied about shorter axis (b) moment applied about longer axis.

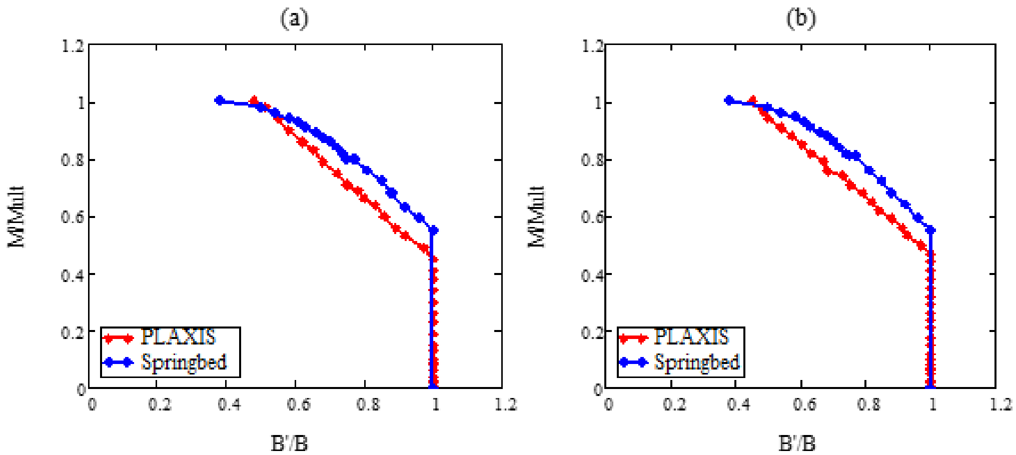

Figure 10. Variation of effective footing width, $B^{'}/B$ vs M/M_{ult} for 6mx18m footing at V/V_{uo} = 0.4 with (a) moment applied about shorter axis (b) moment applied about longer axis.

Conclusions

Figures 4, 5, 6 and 7 clearly indicate how the moment-rotation response obtained using PLAXIS 3D and spring-bed model analyses depend on the direction of the applied moment for different combination of V/V_{uo} and *L/B* ratios. The behavior of the footings subjected to moment can be better understood when the effect of moment-rotation response is analyzed in relation to V/V_{uo} and L/B. Figures 8, 9 and 10 show considerable variations in B'value depending on the direction of the applied moment for different combinations of V/V_{uo} and *L/B* and also how the values for the spring bed and finite element models are apparently different. The magnitude of this variation depends on undrained shear strength of the soil as well. This demonstrates how the effective width of the footing based on conventional triangular stress distribution can be misleading. This study exposes the shortcomings in existing solutions and emphasizes the need for carrying out detailed finite element analysis to arrive at solutions incorporating the effects of soil nonlinearity, V/V_{uo} and *L/B* ratios. Addressing these issues by undertaking extensive field or laboratory experiments can be daunting and highly uneconomical. But with availability of advanced simulation and numerical tools such as PLAXIS 3D it is possible to model and analyze complex soil-structure interaction problems with high degree of accuracy. After all addressing the existing problems and arriving at effective design solutions is the prudent goal.

Acknowledgements

The first author acknowledges the support of a University of Auckland Doctoral Scholarship.

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