DESIGNING STIFFENED RAFT FOOTING ON NON-ENGINEERED FILL

M Schult[1], A. Haque[2], and P.G. Ranjith[3]
[1]Postgraduate student, [2]Lecturer, [3]Senior Lecturer
Department of Civil Engineering, Monash University, Melbourne, Australia.

ABSTRACT

This paper presents the results of numerical analyses of a stiffened raft footing on non-engineered fill (NEF) located in the Melbourne suburb of Chelsea. Analyses have been undertaken using a simplified approach with linear elastic parameters in a commercial Finite Element (FE) program (STRAND6) followed by a more comprehensive analysis using a non linear constitutive model in a commercial Finite Difference (FD) program (FLAC3D). The results of the numerical analyses and findings of a simplified empirical design approach known as the "Soft Spot" method are compared with the field settlement behaviour. The results indicate that the "Soft Spot" method is unable to predict the field behaviour of the raft, in particular the behaviour of the raft slab panels, while the FLAC3D program predicts the raft behaviour more closely. Furthermore, the efficiencies of using additional concrete (such as the haunching, increasing slab thickness) are evaluated and it is found that an increase in slab panel thickness is a more efficient alteration which reduces differential settlement of the raft footing. The use of haunches is observed to reduce the shear stresses compared to no haunches; however the developed shear stresses in both the cases are well within the requirements of AS 2870 (1996). An aspect ratio (length/width) of unity for the raft footing is also found to be more effective in reducing the surface deflection and total settlement of raft over NEF.

1 INTRODUCTION

The greater Melbourne area consists of a delta area to the mouth of the Yarra River and low lying alluvial soils to the south east of the city centre which extend far down the perimeter of Port Phillip Bay and into the newly developing areas to the east and west. Many areas including Port Melbourne and the low lying swamp areas behind Edithvale to Carrum have been filled with non-engineered local and imported filling to form residential and commercial areas. At the mouth of the Yarra River and along its river banks which extend into the Melbourne business area and also within the lower areas of the Maribyrnong River, there are deep deposits of highly compressible clays (e.g. Coode Island Silt (CIS)) where both commercial and residential development has occurred and continues. The properties of Yarra Delta soils including CIS are reported by Ervin (1992).

For larger developments on the Non-Engineered Fill (NEF) and CIS, footing systems are extended through these soils and into underlying gravel, rock or stiff clays. Where the CIS or NEF is very deep, the cost of constructing smaller commercial structures and residential buildings generally prohibits the use of deeper piled foundations. Both commercial and residential buildings not supported by piled foundations on these soils have been constructed on stiffened raft footings based on the requirements of AS 2870 (1996) with the complexity of analysis proportional to the cost of the project. Moore and Spencer (1969) discussed very large settlements characteristic of buildings founded on the CIS based on the observed settlement of the Boyd College. A simplified approach for design of stiffened raft footings founded on NEF was presented by Holland (1975, 1981) and Holland & Lawrance (1980) which was termed as the 'Soft Spot' method. Since its proposal, the 'Soft Spot' method was adopted by structural engineers in Victoria to design footings on NEF and CIS. The 'Soft Spot' method is currently considered to be an acceptable design method in soil reports throughout Victoria. For larger commercial projects, which have large footprints with low loads, stiffened rafts have been adopted for sites on CIS and also NEF with simple designs based on the 'Soft Spot' method. The 'Soft Spot' design results in stiffening beams designed for tension to the top surface of the raft footing and slab panels in compression to the top surface of the raft footing. No consideration is given to the aspect ratio (length to width) of the raft footing or for unusual plan layouts which are not rectangular.

Day (1994) presented a level survey for a slab on ground footing founded on NEF with organic matter. The floor level survey of a dwelling located in San Diego, U.S.A. had a maximum differential settlement of 98 mm. The NEF depth ranged between 4.6 m and 6.9 m with an age of about 11 years. The study did not present any analysis of the footing system, however it does present laboratory test results on fill soils which contain organic matter. A maximum strain of 17% was reported for a soil with 13.6% organic matter.

A similar effect to the development of a 'soft spot' is the formation of sinkholes under a footing. The effect of the development of a sinkhole under a building was discussed by Sputo (1993). However, this phenomenon occurred in natural formations which dissolve from the long term effect of ground waters. Sputo (1993) identified 'soft spots' within the foundation and reported that even though sinkholes formed under the middle of a school building, most of the differential settlement occurred to the perimeter masonry walls.

Davis and Poulos (1968) described a method of determining the total settlement of a highly compressible soil under 3D conditions using an effective modulus of soil skeleton (E′=Youngs modulus, ν′=Poissons ratio) with a linear analysis. Payne (1991) undertook another study of a raft footing on a natural swelling soil using a simplified elastic spring model. These methods give confidence in utilizing commercial FE analyses with elastic parameters on natural soils such as CIS. Even though these methods consider settlement as predominantly elastic and excludes creep, they may be appropriate to analyse raft footings founded on NEF. Therefore it is considered there is a great need to assess the available design options for a stiffened raft on NEF in conjunction with sophisticated numerical analysis due to its highly variable settlement behaviour (Charles, 1984).

In this paper the results of numerical analyses of raft footings are presented based on a number of analysis methods, such as the simplified 'Soft Spot' method, the Effective Elastic modulus method using STRAND6 (G & D computing, 1993) and a more rigorous analysis using non linear constitutive law with a commercial FD (Finite Difference) program FLAC 3D (Itasca, 2002). The numerical models were calibrated with the available settlement data of a raft footing monitored over a 4 ½ year period (Holland, 1978). Finally, attempts were made to understand the behaviour of a stiffened raft footing on NEF by varying the raft geometry and necessary changes to the current design approaches are proposed.

2 ‘SOFT SPOT’ DESIGN CONCEPT

A ‘soft spot’ concept as used in designing a stiffened raft on highly compressible soils, fills and land fills is discussed in detail by Holland (1978), Holland and Lawrance (1980), and Holland (1981). Together with the first author’s experience of working directly with Dr J. E. Holland, it appears that the ‘Soft Spot’ design method is based on a visual interpretation of settlement contours, taken from an extensive level survey of constructed raft footings founded on various fill soils.

Holland (1978) identified the critical positions of a ‘Soft Spot’ as shown in Figure 1, which is taken as a void forming under the footing system at separate times. The ‘Soft Spot’ has a nominated diameter, which is based on a qualitative assessment of the depth of filling, type of filling and variability under the proposed footing. This method of assessment leads to highly varied ‘Soft Spot’ diameters because of differing qualitative judgments of the assessing engineer. The concept presented by Holland (1978) is only used for stiffened raft footings based on residential type specifications typically designed on reactive clays. The stiffened raft footing is designed to cantilever over a circular void with a nominated diameter called a 'soft spot' at the corner of the raft and then for the same diameter void (‘Soft Spot’) under all individual slab panels. The required beam and slab panel design is then applied to all beams and slab panels throughout the entire raft footing.

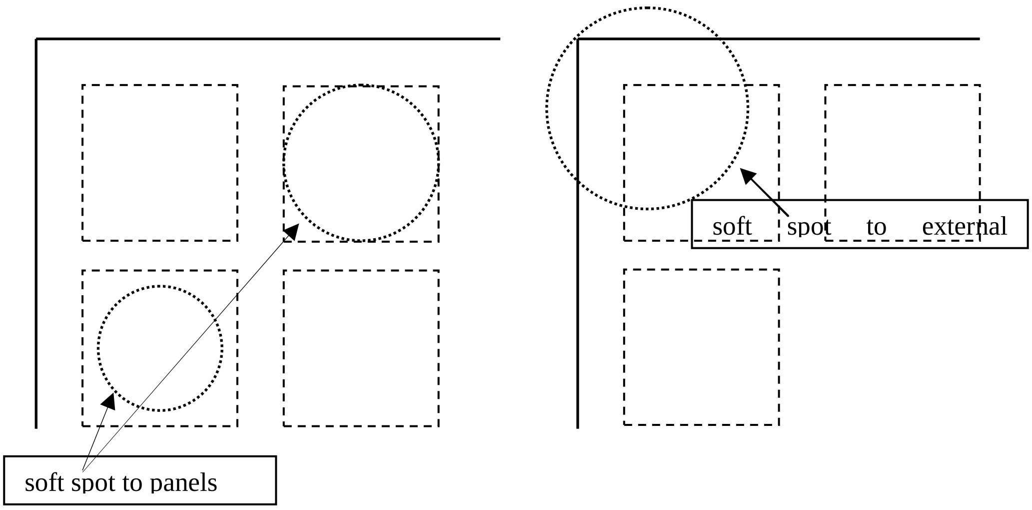

Figure 1: Critical soft spot locations (Holland, 1978).

3 FIELD BEHAVIOUR OF RAFT ON NEF

Holland (1978) and Holland & Lawrance (1980) reported the monitored settlements of stiffened raft footings installed at five locations in Melbourne including the Chelsea site used in this study. The Chelsea site was chosen because of the simple footing design and known characteristics of the site. The fill soils and footing design are detailed in Holland (1978). However the provided description of NEF is minimal, which is common practice due to the variable properties of NEF. Typically no laboratory or *in situ* testing was undertaken. The type of fill within the Chelsea area is known to have been dredged from adjacent low lying areas, which consist of alluvial or paludal clays, peaty clays and sandy clays (Geological Survey Victoria, 1980). The natural clays identified at this site are sandy clays, which is consistent with the site geology. The NEF contains building rubble mixed with sandy clays to very sandy clays.

The NEF at this site varies in depth from 1.2 m to 1.5 m, however the variation of NEF throughout the site is unknown. It is shown that the slab panels were formed on 50 mm of compacted sand fill over the NEF, which was about 2½ years old at the time of construction. The raft footing is rectangular with plan dimensions of 21.6 m x 8.4 m with 300 mm deep edge and internal stiffening beams at approximately 4.2 m centres. A cross section of the modelled raft footing is presented in Figure 2. The slab on ground footing is reinforced with F72 mesh (square grid of 7Ø plain wire @ 200 mm centres) to the top and 4 bars of 8Ø plain wire to the bottom of all beams. The supported structure is a single level brick veneer dwelling with a metal flat and skillion roof. Calculations indicate dead loads of 7.0 kN/m exist on external longitudinal walls, 6.0 kN/m on end walls and 2.6 kN/m on the internal longitudinal stiffening beam. An additional stiffening beam to one end of the footing was not included in the model for simplification, however this beam is the furthest from the end where maximum settlement occurred.

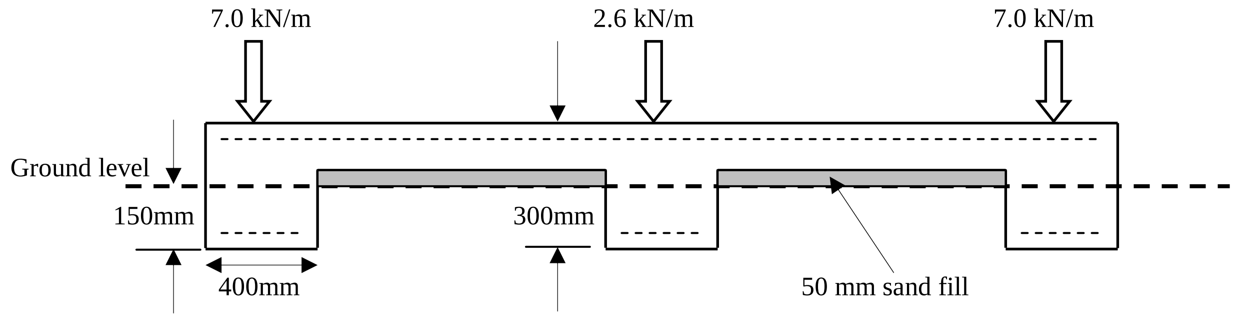

Figure 2: Raft footing cross section.

At the Chelsea site, the relative floor levels were monitored over periods of up to 4½ years (Figure 3). Details on structure type and loadings were not reported, however the data gives a good record of actual performance of NEF under three dimensional loading conditions. Monitoring by Holland (1978) shows the greatest deflection to the surface of the stiffened raft half way through the 2½ year's period with the greatest settlement occurring at the end of the 2½ year's period. This behaviour is consistent with the footing loads producing greater short term effects and NEF properties contributing to the longer term behaviour. Therefore, the structural design of the stiffened raft is more sensitive to the short term behaviour, with services and perimeter attachments most sensitive to the long term behaviour of the raft footing. The difference between maximum surface deflections and settlements is shown in Figure 4.

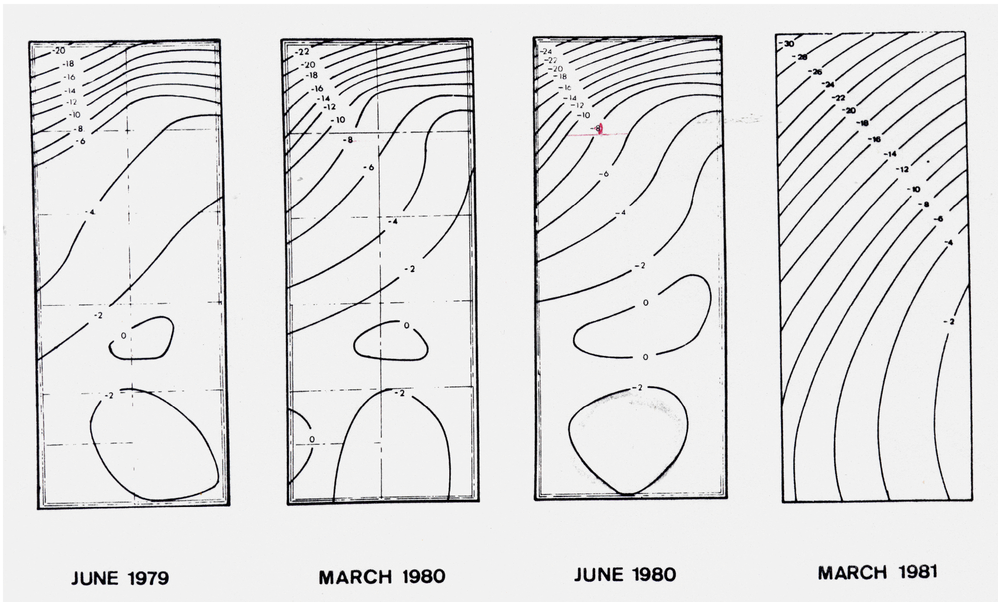

Figure 3: Surface settlement of a raft footing (in mm) on NEF at Chelsea Site (Holland, 1978).

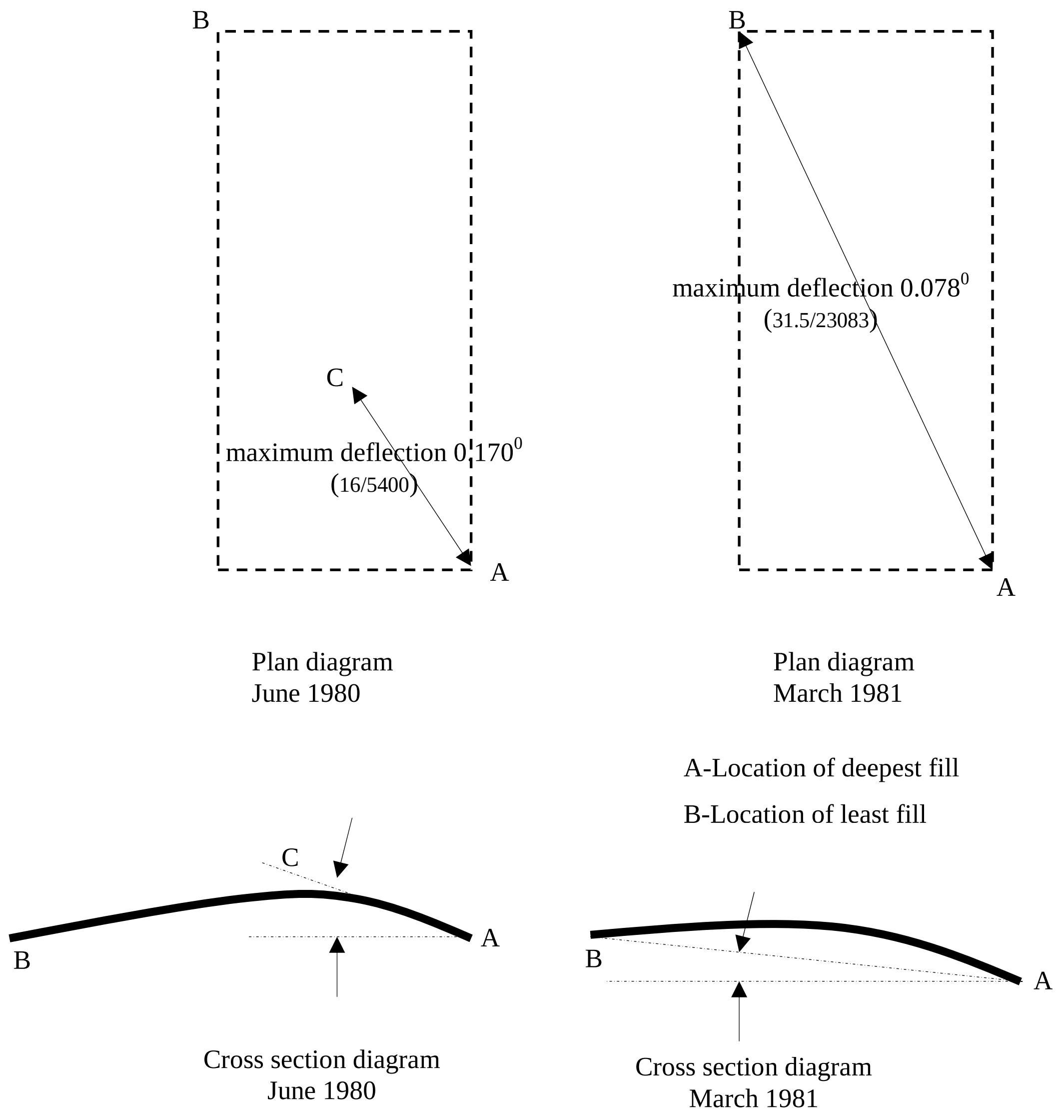

Figure 4: Chelsea raft footing deflections (not to scale).

4 NUMERICAL MODELLING

4.1 FINITE ELEMENT – LINEAR ELASTIC ANALYSIS (STRAND6)

A 3D analysis of the Chelsea site monitored by Holland (1981) was undertaken using STRAND6, a commercial FE analysis program from G+D Computing (1993). The analysis adopted brick elements to simulate both the concrete raft footing and the soil mass with a total of 1203 elements. Aspect ratios of the brick elements were kept close to unity to minimize errors in the analysis. Boundaries of the soil mass were fixed in all directions at the base of the model with the vertical extents of the soil mass fixed in all directions except for the vertical direction. The properties for the natural clays and sand fill were based on generalized values such as those given in CCAA (1997), which, as shown later, are not critical given the low elastic modulus. This was determined by changing the modulus of elasticity for the fill in conjunction with variations in Poisson's Ratio.

In the numerical analyses a 400mm wide stiffening and edge beams were used compared to the constructed Chelsea site which were 375mm wide at their base and taper to 525mm at the underside of the slab panels (Figure 5). A more regular section was adopted to simplify the model. The modelled footing system with straight beam edges and 400mm wide has a stiffness of 9% less than the actual footing system if there is no rebate. However, the constructed Chelsea footing has a masonry external wall, which would require at least a single brick depth rebate to pass the building regulations. The size of the rebate was not reported, therefore it is likely that the stiffness of the actual footing is similar to the modelled footing.

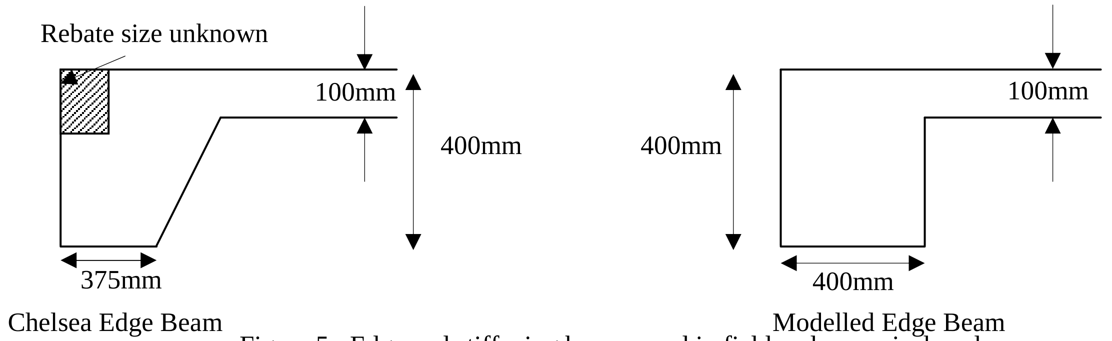

Figure 5: Edge and stiffening beams used in field and numerical analyses.

The effects of a tapered or haunched edge beam are also considered in the numerical analyses. To account for the stiffening effects of the steel mesh reinforcement in the slab top, a composite modulus of elasticity of 22.6 x10^3 MPa was adopted for the concrete raft footing. This value was determined in accordance with AS3600 (1988) using a concrete compressive strength of 20 MPa and allowing for the steel reinforcement as a percentage of the footing. Holland (1981) suggested that a modulus of elasticity of half this value (11.5x10^3 MPa) should be adopted to include the effects of cracking and creep. It is acknowledged that the analysis of creep and the effects of variable cracking in the concrete footing is a complex problem worthy of much further research, but this paper will not discuss it. The NEF soil mass and raft model is presented in Figure 6.

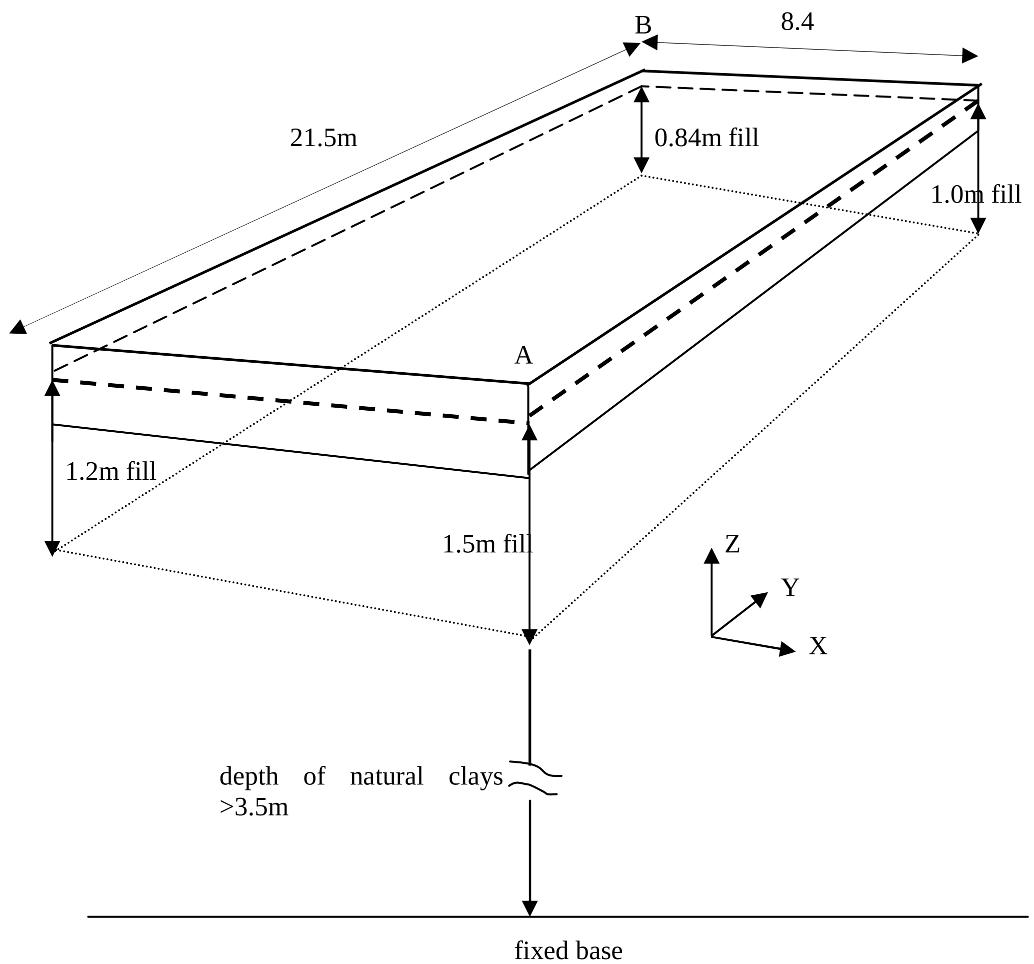

Figure 6: Simplified soil-raft model.

The numerical modelling attempted to match both the greatest deflection in the raft footing and also the greatest settlement of the deepest NEF. In both the monitoring by Holland (1978, 1981) and the numerical modelling, the largest deflection of the surface of the raft footing and the greatest settlement do not occur under the same conditions.

The parameters which simulated the closest match of the greatest deflection of 0.17^0 (16 mm/5400 mm) over the raft footing surface (between points A and C) as monitored by Holland (1981) are given in Table 1.

Table 1: Linear analysis parameters for maximum deflection (between A and C).

Material	Density (kg/m^3)	Young's modulus (MPa)	Poisson's ratio (ν)
Concrete	2.464×10^3	11.5×10^3	0.20
Sand fill	1.600×10^3	35	0.30
Natural clay	1.800×10^3	20	0.25
Fill soil	1.800×10^3	0.06*	0.20**

*Long Term Young’s modulus ** by trial and error

The maximum monitored differential settlement of 31.5 mm between the extreme corners of the raft footing (between points A and B) was matched with the properties as given in Table 2.

Table 2: Linear analysis parameters for maximum differential settlement (between A and B).

Material	Density (kg/m^3)	Young's modulus (MPa)	Poisson's ratio (ν)
Concrete	2.464×10^3	11.5×10^3	0.20
Sand fill	1.600×10^3	35	0.30
Natural clay	1.800×10^3	20	0.25
Fill soil	1.800×10^3	0.0215*	0.20**

*Long Term Young’s modulus ** by trial and error

With the above parameters, calculated differential settlements matched those of the Chelsea raft footing at the end of the 4½ years monitoring period. However the total settlements at the deepest fill location (A) exceeded the reported value by approximately 26 mm (86%). The reported data by Holland (1978) does not identify the total settlements or the settlement of the surrounding surfaces, so a comparison can only be made between differential settlements on the surface of the raft footing. The modulus of elasticity required to match the deflections and settlements of the raft footing appear to be extremely low compared to natural soils. However a detailed analysis of the NEF was not undertaken by Holland (1978) and these results are not too extreme when compared to some fill sites and soils containing organic matter (e.g., Charles, 1984; Day, 1994).

For the analysis that matched the deflection in the area near the deepest filling, the highest stresses where located in the areas are shown in Figure 7.

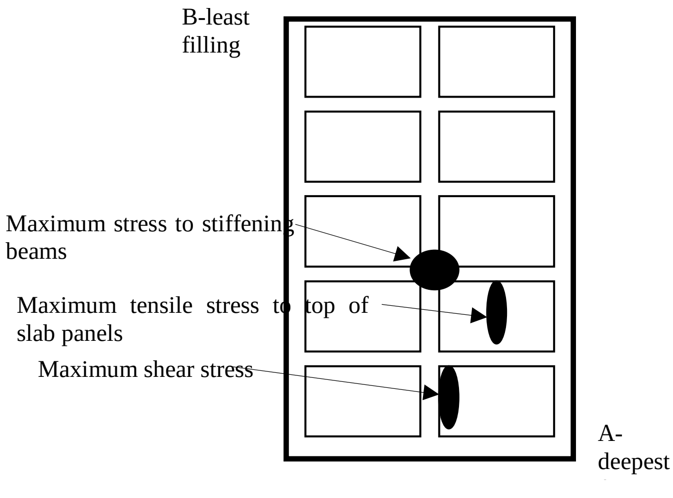

Figure 7: Finite element model – maximum stress locations (not to scale).

4.2 FINITE ELEMENT ANALYSIS - DIFFERING ASPECT RATIO MODELS

The effect of the layout of the concrete raft on settlement variations of the footing system was examined using the STRAND6 program. Varying aspect ratios (length/width) of the raft were analysed using the model developed for the entire slab layout with consistent NEF properties. The differing aspect ratios are defined as shown in Figure 8. The analysis was limited to rectangular plan dimensions. The results of the analysis are summarised in Table 3.

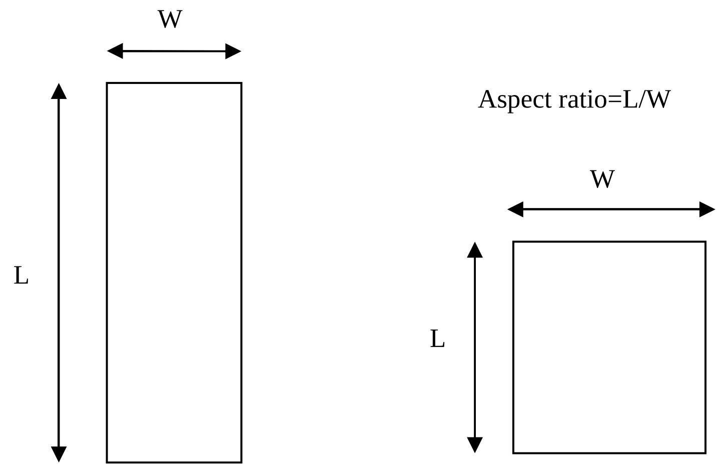

Figure 8: Definition of aspect ratio.

Table 3: Linear elastic analysis for various aspect ratios.

Aspect ratio (L/W)	3.581	2.571*	1.562	1.057
Settlement @ deepest fill corner A (mm)	71.39	56.72	53.96	51.14
Surface deflection between A-B (θ^0)	0.139	0.100	0.100	0.002
Maximum panel stress (MPa) - due to bending	1.30	0.90	0.80	0.60

θ = maximum differential settlement/length of settlement (degrees) * Simulation of Chelsea site

Table 3 shows an increase in slab panel stresses with an increase in aspect ratio. This analysis also shows that changes in the layout of a raft footing affects stresses, settlements and deflections without changes to the stiffness of the footing or changes in the foundation soils. This indicates that soil behaviour is not the single dominant parameter in the performance analyses of a stiffened raft footing supported on NEF.

4.3 FINITE DIFFERENCE - NON LINEAR ANALYSIS (FLAC3D)

An assumption of no 'flow' or re-distribution of the stress-strain relationship is not correct in soil materials. Therefore, in order to capture the true non linear behavior of NEF, a FLAC3D model (Itasca, 2002) was established for the Chelsea site using the Mohr-Coulomb model (NEF: c=5kPa and $\phi=0^o$; Natural clay: c=75kPa and $\phi=10^o$). Furthermore, the model will help to understand the effect of linear and non linear analyses on the overall behaviour of raft footing on NEF.

The 3D model had a total of 14,257 elements to simulate the raft footing and the differing fill depths under the footing. The elements were arranged to model the concrete raft, sand fill under panels and the sloping NEF under the raft. A large perimeter soil volume extending 10m horizontally away from the raft perimeter was adopted to limit the influence of boundary restraints. The 3D slope of the NEF was not continued to the perimeter 10m soil mass. Initially, the FLAC analysis was undertaken for the soil model without the applied footing, sand filling and building loads and stepped for 60,000 cycles to obtain a converged model of the settlements over the raft-soil model under gravity loads. After convergence of the soil model without the raft footing, the model was then stepped for an additional 60,000 cycles with the footing and building loads applied (Figure 2).

As with the elastic FE analysis, a series of trial and error runs were undertaken using varying NEF properties (e.g. E, ν) to match both the maximum deflections (over the surface of the raft) and the maximum corners settlement of the Chelsea raft footing, adopting the same initial properties for the concrete, sand and natural clays. The maximum deflection of the surface of the stiffened raft footing was obtained by the difference in level between locations A and C as shown in Figure 4. The final non linear parameters which most closely match the maximum deflection of the surface of the stiffened raft footing (ϴ = 0.17^0) are summarised in Table 4. The contours of the settlements of the raft footing for a Young's modulus of 0.4MPa for the NEF are shown in Figure 9. The final non linear parameters for maximum settlement are presented in Table 5. It should be noted that the E values of NEF obtained in this analysis are much higher (in the order of 6 to 10 times) than the linear elastic analysis. The principal stresses throughout the soil-raft system that match the maximum deflection (ϴ) are presented in Figure 10. The distribution of shear stresses on both the X plane and the Y plane are shown in Figures 11 and 12.

Table 4: Non linear analysis parameters (FLAC3D) for maximum deflection (A-C, ϴ = 0.17^0).

Material	Density (kg/m^3)	Young's modulus (MPa)	Poisson's ratio (ν)
Concrete	2.464×10^3	22.6×10^3	0.20
Sand fill	1.600×10^3	35	0.30
Natural clay	1.800×10^3	20	0.25
Fill soil	1.800×10^3	0.40*	0.20*

* by trial and error

Table 5: Non linear analysis parameters to match maximum differential settlement (A-B, 31.5 mm).

Material	Density (kg/m^3)	Young's modulus (MPa)	Poisson's ratio (ν)
Concrete	2.464×10^3	22.6×10^3	0.20
Sand fill	1.600×10^3	35	0.30
Natural clay	1.800×10^3	20	0.25
Fill soil	1.800×10^3	0.20*	0.20*

* by trial and error

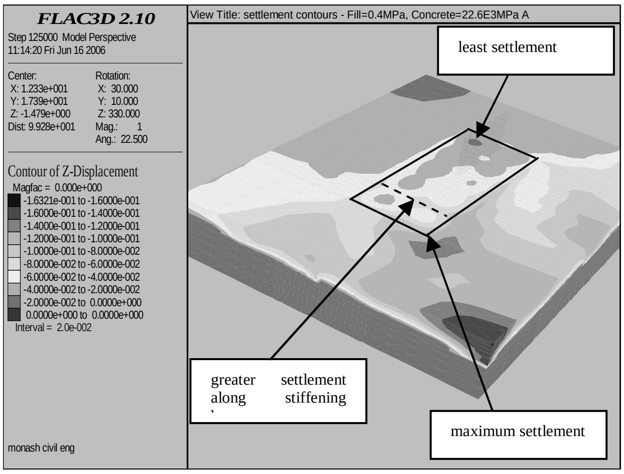

Figure 9: Contours of maximum deflection (ϴ).

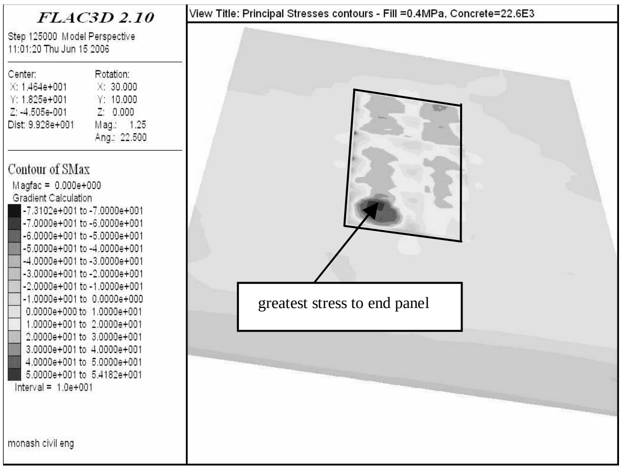

Figure 10: Contours of principal stresses corresponding to maximum deflection (ϴ).

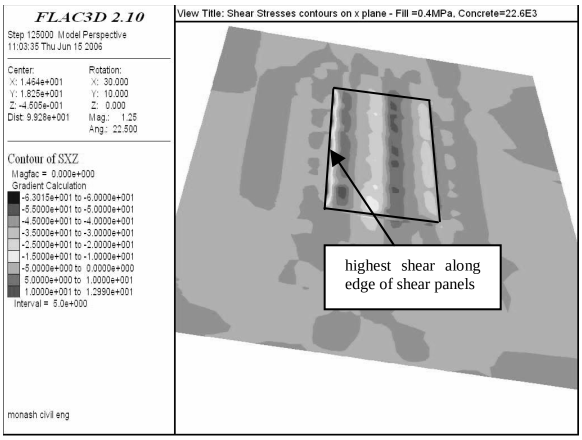

Figure 11: Contours of X plane shear corresponding to maximum deflection (ϴ)

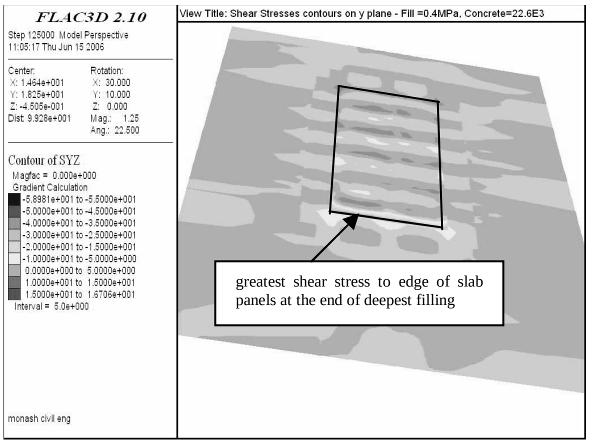

Figure 12: Contours of Y plane shear corresponding to maximum deflection (ϴ)

5 DISCUSSION ON NUMERICAL ANALYSES

The non linear FLAC3D analysis was found to match the actual monitored Chelsea site more closely than the elastic FE analysis. Both numerical analyses show least settlement occurring on the outer edge approximately mid-length of the raft whereas the final settlement contours by Holland (1978) shows the least settlement to the corner of least filling thickness. The numerical models closely simulate the settlement contours reported by Holland (1978) ¾ through the monitoring period but the final settlement contours differ from the actual site readings showing a near constant settlement from the deepest to least fill thickness. The accuracy of this study might have been improved if more data on the NEF of the Chelsea site was available. There is also some reason to believe that the original soil investigation method using backhoe test pits may have caused disturbance of the NEF and therefore resulted in a site with filling of different ages and degree of compaction and hence some questions about the quality of the monitoring data remain.

A significant difference between the two numerical models is the settlement of the surface surrounding the raft footing. The elastic FE analysis shows the perimeter surface to settle significantly only near the edge of the concrete raft whereas the non linear FLAC3D analysis shows an increased overall settlement of the raft. The non linear analysis also shows greater settlement under the edge and along a stiffening beam near the deepest fill area (Figure 9). This reflects the effect of raft footing stiffening beams and variations in fill depth, whereas the elastic analysis could not incorporate this behaviour.

The modulus calculated to match the maximum Chelsea raft settlement is 0.2 MPa for the non linear analysis and for the elastic analysis it is 0.0215 MPa. Both parameters are significantly less than typical values reported for filling materials (Charles, 1984). The significantly lower modulus compared to the reported data by Charles (1984) may be due to several factors: the age of filling, the level of compaction, the variability of the filling and, at the Chelsea site, the limited depth of filling and its proximity to the surface. The proximity of the NEF to the surface results in the surface loadings applying higher stresses to the fill horizon with long term settlement occurring more quickly than for a deeper soil profile. The greater difference compared to the Charles (1984) data occurred with the elastic analysis which showed little settlement of the surrounding surface, suggesting an estimated long term elastic modulus is less accurate than the non linear analysis using the Mohr-Coulomb constitutive model.

Both analyses predict the most severe deflection of the raft footing and also the constant tensile stress across the surface of the footing. However, the long term behavior of the filling was not accurately modeled in either numerical analysis. Both analyses presented show an upward pressure on slab panels consistent with the contours of the Chelsea site, which is opposite to the 'soft spot' design approach, i.e., compressive stresses in the top of the slab panels. The higher stresses in the raft footing from the elastic FE analysis occur in the slab panels in the mid length of the raft, whereas with the non linear FD analysis the maximum stresses occur at mid length in the edge stiffening beams. However, the highest stresses in the slab panels occurred near the ends of the model corresponding with deeper filling. A comparison of the stresses in the concrete raft footing between the elastic FE analysis, the non linear FD analysis and the 'soft spot' design are presented in Table 6. As indicated above, the numerical analyses have some accuracy in matching the monitored levels of the Chelsea site where the most severe deflection occurred, however the total deflections show a wide discrepancy, which is consistent with the highly variable properties of NEF.

Table 6: Comparison of concrete stresses in uncracked section.

Analysis type	Soft spot*	Elastic**	Non linear**
Maximum tensile stress to top of slab panels (MPa)	-1.30	0.30	0.10
Maximum tensile stress to top of edge beams (MPa)	1.10	0.20	0.10
Maximum shear stress to beam-slab connection (MPa)	0.10	0.30	0.10

* 1.6 mØ ** 0.17^0 deflection

6 MODIFICATIONS TO STIFFENED RAFT

Given the discrepancy between the 'Soft Spot' model and both numerical models, it is reasoned that a general guideline for raft footing design on NEF would be either to increase slab panel thickness or the amount of steel in the top of slab panels above that for any code based stiffened raft footing. An increase in stiffness of the raft footing appears not to reduce differential settlements of the footing and therefore any increase in concrete volume should be provided to the slab panel thickness rather than to the stiffening beam depths. An increase in shear stresses at the interface between slab panels and stiffening beams is shown in both numerical models and the 'soft spot' method, albeit in a different direction with the 'Soft Spot' method. The actual Chelsea raft footing has tapered edge beams which were simplified straight edge beams in both the numerical analyses. The tapering would appear to increase the capacity of the footing system to resist the increased shear stresses which occur with the raft footing supported on NEF.

A comparison of a tapered edge or haunch to the stiffening beams with the increasing slab panel thickness of 125mm was modelled in FLAC3D using the previously estimated soil parameters at the Chelsea site. The results of the predicted shear stresses and settlements for both models are presented in Figures 13 and 14. With haunches, the 3D complete raft shows a 30% decrease in shear stresses to the middle of the slab panels and no change in shear stresses with increased slab panel thickness when compared with the previous results. Furthermore, the 3D model with haunches gives a reduction in settlements of 6% compared to a reduction of 14% by adopting an increased slab panel thickness. Therefore, based on this analysis, it can be seen that the most efficient use of materials is to provide a concrete haunch at all edges and stiffening beams, however where settlements are critical, an increase in slab panel thickness is more effective. It is to be noted that the maximum shear stresses determined in the raft footing without haunches are in the order of 20% of those allowed under AS3600 (1988) and therefore even with an allowance for major variations of NEF parameters, shear stresses are within an acceptable range. It is therefore argued that an improvement in the design of a stiffened raft can be achieved by an increase in the slab panel thickness.

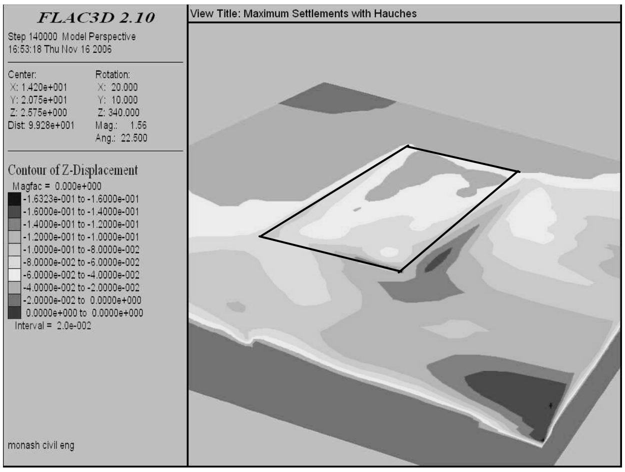

Figure 13: Settlement in footing with haunches throughout.

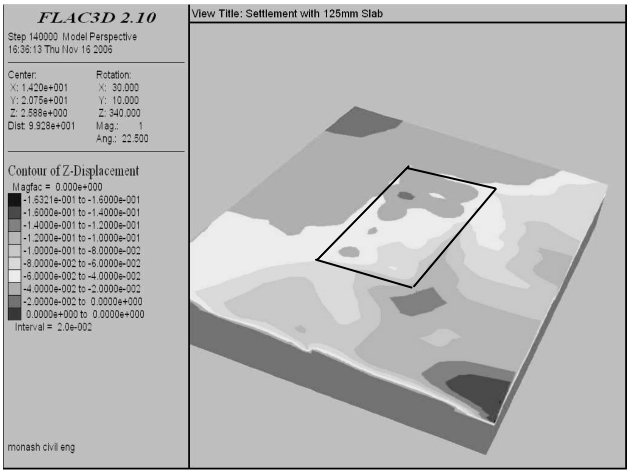

Figure 14: Settlement in footing with 125 mm slab panels throughout.

The numerical modelling and all monitored data presented by Holland (1978, 1981) and Holland & Lawrance (1980) show an increase in deflection to the top of all slab panels and stiffening beams. The procedure of designing all stiffening beams for cantilevering over a 'soft spot' is in agreement with the findings of this study. However, currently there is no capacity to design for differing aspect ratios or size of the stiffened raft footing. Therefore, caution should be taken in the design of large, non rectangular or even non square stiffened raft footings unless detailed analysis and modelling is undertaken. Furthermore, an increase in the steel reinforcement at the top of all stiffening beams could be adopted in order to carry the tensile stresses developed at that location. However, this appears to be less efficient and a more costly use of materials in comparison to increasing the concrete slab panel thickness. Minimum reinforcement requirements given in AS2870 (1996) are sufficient.

Even though the 'soft spot' method appears to incorrectly design for compressive stresses rather than tensile stresses in slab panels, it does provide a simplified approach to the design of smaller raft footings founded on NEF. This study has shown that linear analysis using a commercial FE program is simple to use and predicts correct mechanisms in the raft-soil mass, however it does appear to predict excessive stresses in the footing and hence could lead to increased costs. Furthermore, the linear FE analysis requires an estimated long term Young's modulus which is found to be some orders of magnitude smaller than reported data for NEF. Hence, this method is only of value when analysing a constructed footing where level monitoring data is available and therefore appears to have a limited application. On the other hand, the non linear FD analysis (FLAC3D) is a more sophisticated method of predicting soil behaviour and, given more knowledge of the fill soils together with some *in situ* testing, there is a greater likelihood the input data required in the program can be estimated with correlation to reported data. Hence, the FD or similar method can be used to assess worst scenario stresses and deflections in a raft footing. This method has limitations in that the overall predicted settlements appear higher than those recorded and that the method requires detailed modelling with an expensive and complex computer code.

7 CONCLUSIONS

This study has focused on the behavior of raft–soil mass behavior without a detailed study of Non-Engineered Fill (NEF). The study of NEF is always problematic due to its variability and the uncertainty of all parameters and any study at best can only provide broad guidelines. Similarly, the findings of this study are presented only as broad guidelines but given the deficiencies of the current design methods, these findings may assist experienced geotechnical engineers in the art of footing design. The following conclusions can be drawn from this study:

- Both elastic and non linear analysis using a finite element and finite difference codes provide differing results from the 'Soft Spot' method.
- Increases in tensile stresses occur to the top of the entire raft footing system as the NEF settles with the highest stresses occurring in shear where slab panels join the stiffening beams.
- The 'Soft Spot' method does not predict the upward pressure in slab panels produced as the stiffened raft settles.
- An elastic modulus of 0.4 MPa and Poisson's ratio of 0.2 best approximates the raft deflection at the Chelsea site for a given strength parameters of the Non Engineered Filling (NEF) at the study site.
- The non linear analysis using the FLAC3D program best matched the monitored deflections of the raft footing on NEF.
- Both the provision of haunches between stiffening beams and slab panels and also an increase in slab panel thickness reduce deflections and settlements in a raft footing founded on NEF. The most efficient use of materials appears to be an increase in slab panel thickness to the entire raft footing.

8 REFERENCES

AS 2870 (1996). Residential slabs and footings - construction, Standards Association of Australia
AS 3600 (1988). Concrete structures, Standards Association of Australia
CCAA (1997). Industrial pavements- guidelines for design, construction & specigfications. Cement and Concrete Association of Australia.
Moore, P.J., Spencer, G.K. (1969). Settlement of building on deep compressible soil. Journal of the Soil Mechanics and Foundation Division, ASCE, Vol. 95, No. SM3, pp.769-790
Holland, J. E. (1978). Residential slab research - Recent findings, Swinburne College Press, Hawthorn, Australia.
Holland, J. E., and Lawrance, C. E. (1980). Behaviour and design of housing slabs on filling. 3rd Australia - New Zealand Conference on Geomechanics, Wellington, New Zealand, Vol. 1, pp.25 -31
Holland, J. E. (1981). The design, performance and repair of housing foundations, Swinburne College Press, Hawthorn, Australia.
Davis, E. H., and Poulos, H. G. (1968). The use of elastic theory for settlement prediction under three-dimensional conditions. Geotechnique, Vol. 18, pp. 67-91
G & D Computing P/L (1993). Strand 6.16, Finite Element System
Itasca Consulting Group Inc. (2002). FLAC 3D (**F**ast **L**agrangian **A**nalysis of **C**ontinua in **3 D**imensions), version 2.1
Payne, D. C. (1991). Three dimensional analysis of stiffened raft footings on swelling clay soil. Transactions of the Institution of Engineers, Australia: Civil Engineering, Vol. CE33, No. 3, pp.159-168
Day, R. W. (1994). Performance of fill that contains organic matter. Journal of Performance of Constructed Facilities, Vol. 8, No. 4, pp.264-273
Sputo, T. (1993). Sinkhole Damage to Masonry Structure. Journal of Performance of Constructed Facilities, Vol. 7, No. 1, pp.67-72
Charles, J. A. (1984). Settlement of fill in ground movements and their effects on structures. Attewell P.B. and Taylor, R. K. eds. Surrey University Press (SW/1806), pp.26-45
Geological Survey of Victoria (1980). Map sheet of Chelsea & Keysborough, scale 1:63,360.