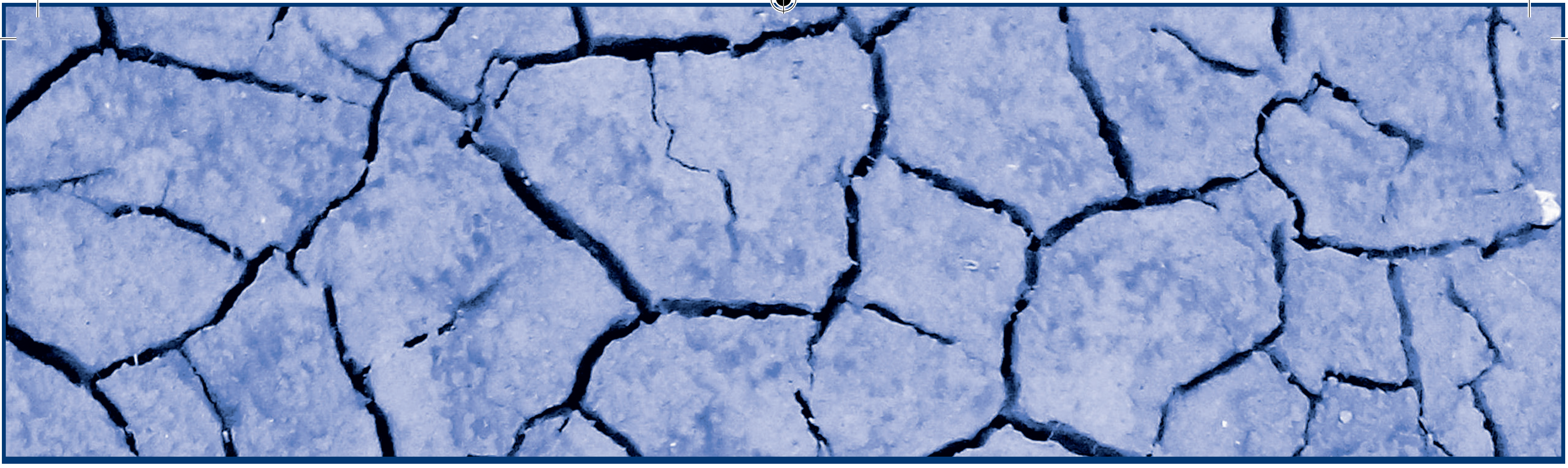
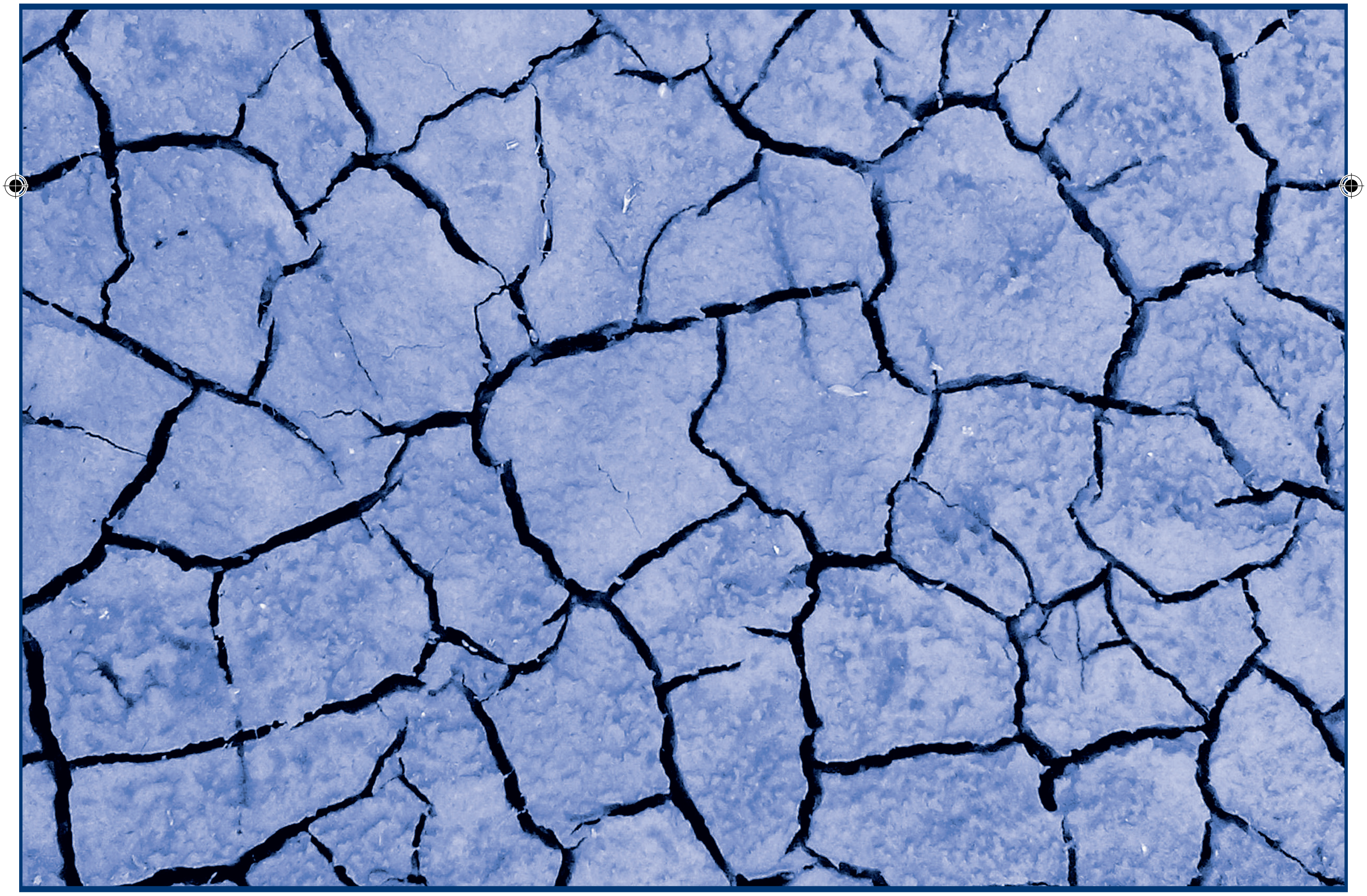


AGS VICTORIA 2017 SYMPOSIUM

Reactive clays and light structures

Wednesday, 25 October 2017, 8:15am – 7:00pm

Rydges Hotel, 186 Exhibition Street, Melbourne



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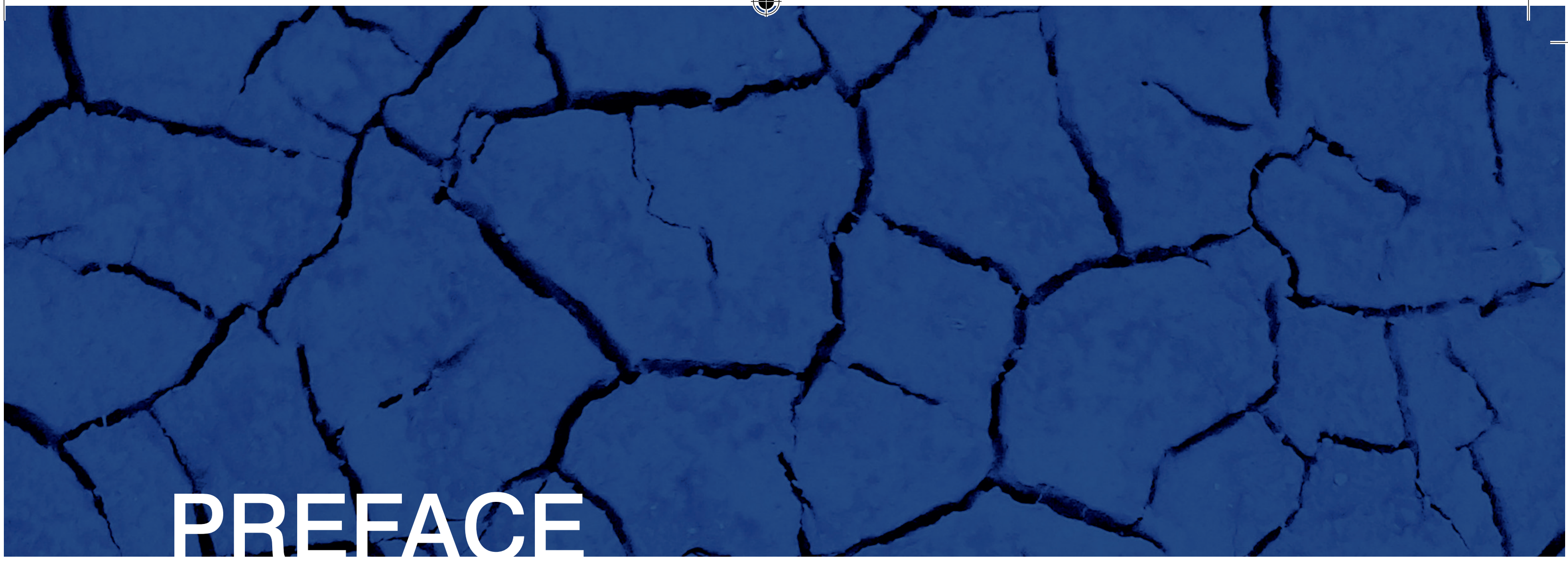

PREFACE

The Victorian chapter of the Australian Geomechanics Society invited academics and practitioners in the field of geotechnical and ground engineering to attend the 2017 Australian Geomechanics Society Victorian Symposium on 'Reactive clays and light structures' held on 25 October 2017.

The reactive soils of the Melbourne region form a large portion of its complex and variable geology. In particular, the basaltic volcanics situated to the north and west of Melbourne, which cover some 40% of the Melbourne region present numerous geotechnical challenges, particularly for lightly loaded structures. The geotechnical design and behaviour of lightly loaded structures on reactive soils is one aspect of geotechnical engineering where the public tend to have greater awareness, which is often not the case for the variety of soil and rock mechanics problems geotechnical engineers deal with. This is often borne out through their experience with their own residence, and rightly or wrongly, this contributes greatly to the public's perception of the geotechnical profession.

The 2017 Australian Geomechanics Society Victorian Symposium covered a variety of geotechnical challenges associated with reactive soils including residential slabs and footings, roads, pavements and other sensitive infrastructure that interact with reactive soils. The Symposium brought together practitioners from consulting, construction and academia to share and discuss their experiences on the topic of reactive soils and their related geotechnical applications.

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Keynote Address

Are the AS2870 standard designs for residential rafts on reactive clay satisfactory?

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ABSTRACT

The standard raft designs set out in AS2870 are adopted for a significant proportion of residential buildings being built around Melbourne (if not in other Australian cities). Of recent years there has been increasing media coverage relating to the poor performance of footings for residential buildings, particularly in areas underlain by Newer Volcanics basaltic clays. There are many aspects which govern the performance of footings founding on or in reactive clays, and questions regarding the appropriateness of the recommendations in AS2870 are being raised. One such question is whether or not the standard raft designs in AS2870 are satisfactory for reactive clay sites. This paper presents the results of three dimensional finite element soil structure interaction analyses of the performance of standard type waffle and stiffened rafts founded on reactive clay. The performance of the rafts analysed is shown to be unsatisfactory with respect to vertical differential movement and structural capacity when subjected to design characteristic surface movements. Whilst significantly more analyses and research is required, the results of these analyses has significant implications for all of the standard footing designs contained in AS2870 for reactive clay sites. This is particularly relevant given the projected levels of population growth in the coming years in the greater Melbourne area which are underlain by highly reactive basaltic clays.

Keywords: Reactive, finite element analysis, waffle raft, stiffened raft, settlements

1 INTRODUCTION

Soils which exhibit volume changes due to variations in moisture content are termed reactive soils. Such soils swell and shrink in response to an increase or decrease, respectively, in moisture content. Changes in soil moisture content may result from a number of environmental factors, including:

- Climatic factors (i.e. seasonal variations in temperature and rainfall);
- Human influences (including changes in land use, site drainage, backfilling of service trenches with gravel, leaking services, watering of gardens, and construction activities); and
- Trees and vegetation.

Design of footings for dwellings is currently carried out to Standards Australia (2011) document AS2870 “Residential slabs and footings” (herein referred to as AS2870).

The basaltic clays of the Newer Volcanics to the west and north of Melbourne are associated with the sites of highest reactivity, although the basaltic clays of the Older Volcanics are also highly reactive. Damage to structures constructed on such soils is routinely reported in the media, and it has been claimed that over 4,000 homes in the suburbs to the west and north of Melbourne have been subject to such damage (Johanson, 2014). Although residual Silurian soils and the Brighton Group soils can be reactive (and highly reactive in some areas), these are typically less problematic, although some minor damage to dwellings is relatively common.

Projections of growth for Victoria indicate that the population of the state is set to almost double over the next fifty years from 5.5 million people in 2011 to 10.1 million people in 2051 (Victoria State Government, 2016). The top five metropolitan growth areas are, in decreasing order, Wyndham, Casey, Melton, Whittlesea and Melbourne. Three of these areas (Wyndham, Melton and Whittlesea) are in part underlain by the highly reactive basaltic clays of the Newer Volcanics, while Casey is underlain by Brighton Group soils. The issue of reactive clay is less relevant to Melbourne, as this area typically has undergone and continues to undergo high-rise development.

There are many aspects which govern the performance of footings founding on or in reactive clays, and many questions regarding the appropriateness of the recommendations in AS2870 have been raised. One such question is whether or not the standard raft designs in AS2870 are satisfactory for reactive clay sites.

This paper presents the results of three dimensional finite element soil structure interaction analyses of the performance of standard type waffle and stiffened rafts founded on reactive clay. Whilst significantly more analyses and research is required, this assessment may provide some preliminary insights and information to inform the debate regarding the suitability of these footing types and associated guidance provided in AS2870, such that damage to homes which are yet to be built is limited to acceptable levels.

2 BACKGROUND INFORMATION

2.1 Site classification

AS2870 provides guidance on the classification of sites where ground movement is predominantly due to soil reactivity "under normal moisture conditions". The soil classification is based on a calculated characteristic surface movement (y_s).

The characteristic surface movement (y_s) may be calculated using Equation 2.3.1 from AS2870, in which the products of the instability index (I_{pt}), the soil suction change (Δu) and the thickness of the layer under consideration, are summed for all soil layers within the depth of design soil suction change (H_s).

AS2870 recommends that, in the absence of more detailed information, the instability index (I_{pt}) is related to the soil shrinkage index (I_{ps}) using a parameter (α), which in turn is dependent on the depth of the cracked zone. The soil shrinkage index (I_{ps}) may be derived using laboratory tests for soil reactivity, correlations with clay index tests, or visual-tactile identification by an engineer or engineering geologist with suitable expertise and local experience.

Jaksa et al. (1997) and Delaney et al. (2005), based on investigations in Adelaide and the Newcastle-Hunter region, respectively, conclude that the visual-tactile method is highly unreliable. Despite this, AS2870 allows the method to be adopted, and in the experience of the authors, it is still the most commonly used method in Victoria for residential dwellings.

The site classification by characteristic surface movement (y_s) according to AS2870 is summarised in Table 1.

2.2 Footing design

2.2.1 General

AS2870 presents standard designs for sites classified as Class S to H2 (although some exceptions apply to this). If constructed accordingly, it is implied that these standard designs satisfy both Serviceability Limit State (SLS) and Ultimate Limit State (ULS).

Sites for which the standard designs are not suitable (including but not limited to Class E and P sites) must satisfy tolerable limits for differential movements (refer Table 2).

Table 1: Site classification to AS2870

Characteristic surface movement, y_s (mm)	Site classification [a]
0 - 20	S
> 20 - 40	M
> 40 - 60	H1
> 60 - 75	H2
> 75	E

[a] S = slightly reactive, M = moderately reactive, H = highly reactive, E = extremely reactive

Table 2: Differential movement limits to AS2870

Construction type	Relative (-)	Absolute (mm)
Clad frame	1 / 300	40
Articulated masonry veneer	1 / 400	30
Masonry veneer	1 / 600	20
Articulated full masonry	1 / 800	15
Full masonry	1 / 2,000	10

2.2.2 Standard footings design

The systems presented as standard designs in AS2870 include waffle rafts, stiffened rafts, stiffened slabs with deep edge beams, and strip footings. Only waffle rafts and stiffened rafts are considered further for the purposes of this paper, as they appear to be amongst the most widely adopted for residential dwellings in Victoria.

Both waffle rafts and stiffened rafts comprise a grid of internal and external beams running in both the transverse and longitudinal directions, connected to an overlying slab. The suitability of the footing type, the dimensions of its individual components, and the steel reinforcement required, are dependent on the individual site classification and type of construction of the dwelling. Although exceptions apply, typical details of the waffle raft and stiffened raft are presented below.

2.2.3 Waffle raft

The beams of a waffle raft are founded on the ground surface, with the voids between the beams and underneath the slab formed using polystyrene void forms (i.e. little to no excavation is required during construction). The internal beams are typically 0.11 m wide with one steel bar reinforcement (either 12 mm diameter or 16 mm diameter), and with a maximum allowable span between beams of 1.09 m.

2.2.4 Stiffened raft

The beams of a stiffened raft are founded at some depth below the ground surface. The minimum required depth of the footing is a function of the site classification and ranges from 0.3 m to 1.1 m. Excavation works during construction are therefore required. The beams of the stiffened raft are typically 0.3 m wide, with a maximum allowable centre-to-centre spacing between beams of 4 m to 6 m. More steel reinforcement is required by AS2870 for the stiffened raft than for the waffle raft. The volume of concrete required for the stiffened raft is also greater than for the waffle raft.

2.2.5 Relative bending stiffness

The bending stiffness of both the waffle and stiffened rafts were approximately calculated to assess the relative difference in stiffness between the two footings which could both be used on the same site. The bending stiffness was assessed by considering the sum of the second moment of area of the individual components of the rafts. The influence of the ribs in the transverse direction were not considered. The result of this simple calculation is that the stiffened raft is approximately four times stiffer in bending about the horizontal axes than the waffle raft.

2.2.6 Structural strength

The performance of the waffle and stiffened rafts was assessed with respect to calculated vertical differential movement and structural capacity. The computer program AdSec (Oasys, 2016) was used to establish the yield envelope of the structural elements (in terms of axial force and bending moment) to Standards Australia AS3600 (2009) “Concrete Structures” (herein referred to as AS3600), as shown in Figure 1. The calculated axial forces and bending moments are compared to the yield envelope to check if the raft structural design is satisfactory. A shear check of the structural elements has not been carried out.

2.2.7 Summary

The stiffened raft is stiffer and stronger that a waffle raft. The stiffened raft is also founded at depth within the soil profile and hence is likely to experience less movement due to shrink / swell of the underlying soil than a waffle raft. Even in the simple comparison presented in Section 2.2.5, it would appear that the waffle raft is either significantly under-designed or that the stiffened raft is significantly over-designed.

3 SOIL STRUCTURE INTERACTION ANALYSES

3.1 Introduction

Soil-structure interaction analyses of waffle and stiffened rafts with a plan dimension of 12 m x 12 m were undertaken using a commercially available finite element analysis software called PLAXIS 3D (PLAXIS, 2016). For the reasons set out below, the limitations of the PLAXIS 3D software means that some structural aspects of the raft cannot be modelled to the same level of detail as provided by some structural analysis packages. Nevertheless, the analyses provide some important insights into the performance of the rafts. More detailed three dimensional finite element analyses using structural engineering packages should be undertaken to better understand the performance of the rafts.

A typical PLAXIS 3D model is shown in Figure 2. The analyses set out below have been undertaken for a Class H2 site. The analyses model the differential shrinkage of the soil between the edge of the raft and the centre of the raft, with the edge of the raft experiencing the full design suction change and the middle of the raft experiencing zero suction change. This scenario represents the worst design situation for a Class H2 site as set out in AS2870.

3.1.1 Details of analyses

3.1.2 Stratigraphy

The stratigraphy adopted in the numerical analyses consisted of 4 m of reactive clay overlying weathered rock. This is summarised in Table 3. The ground water table was considered to be at 2.3 m below ground level resulting in a maximum soil suction change design depth of 2.3 m.

All geological units were modelled using the Mohr-Coulomb constitutive model. The reactive clay was modelled with an effective cohesion (c’), angle of friction (ϕ'), and stiffness (E’) of 5 kPa, 28°, and 15 MPa, respectively. These parameters are however largely irrelevant to the results of the analyses.

3.1.3 Applied volume change

Seddon (1992) showed how the instability index (I_{pt}) can be related to the site classification limits by assuming a constant instability index with depth. By adopting a depth of design soil suction change (H_s) and a soil suction change (Δu) of 2.3 m and 1.2 pF, respectively, the instability index has been related to the site classification limits. This is presented in Table 4.

The adopted depth of design soil suction change (H_s) of 2.3 m corresponds to the maximum value proposed in AS2870 for the Melbourne area. The adopted soil suction change (Δu) value of 1.2 pF corresponds to that proposed in AS2870 for the Melbourne area.

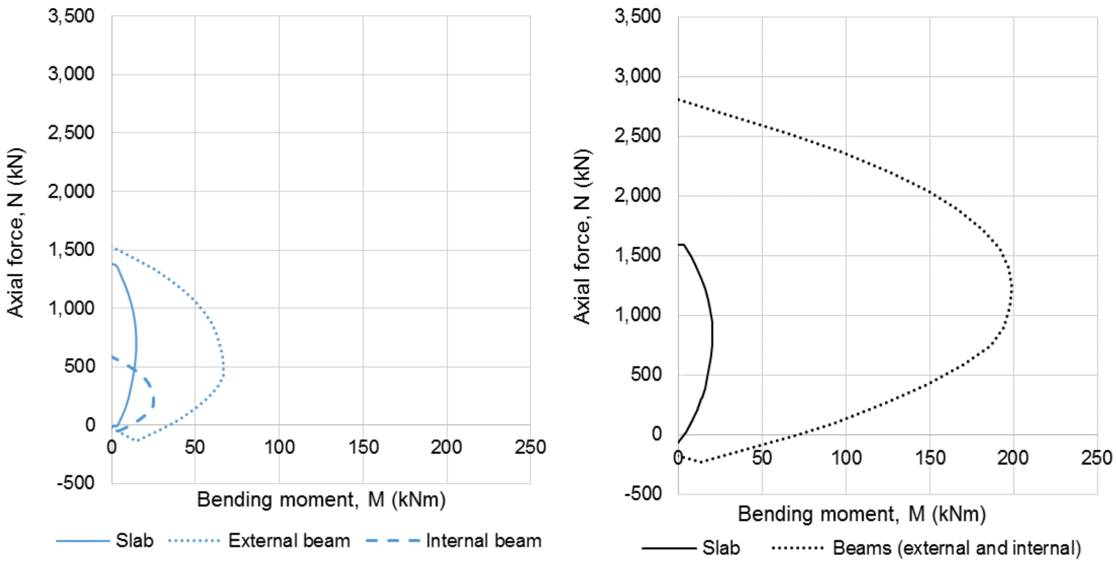

Figure 1. Yield envelopes for waffle raft (left) and stiffened raft (right)

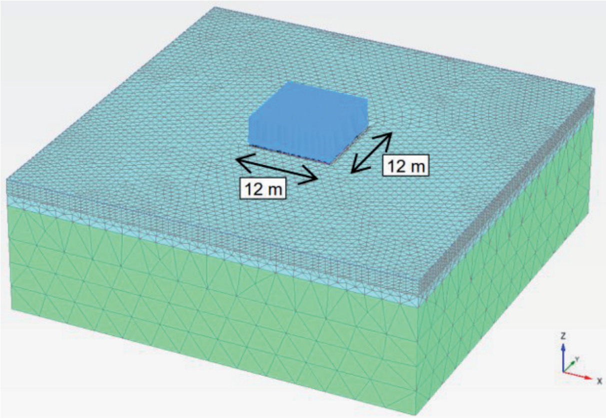

Figure 2. Typical PLAXIS 3D model

Table 3: Adopted stratigraphy in PLAXIS 3D analyses

Geological unit	**Depth (m) below ground level**	
	from	**to**
Reactive clay	0	4
Weathered rock	4	-

The instability index (I_{pt}) value adopted to calculate the appropriate shrinkage to apply in the PLAXIS 3D analyses was the mid-point of the range presented in Table 4 for a Class H2 site (= 4.9% strain / pF).

The movement profile (and corresponding vertical volume strain profile) calculated using the method proposed by AS2870 is non-linear over the depth of design soil suction change. This has been modelled as shrinkage of the reactive clay unit in the PLAXIS 3D analyses by dividing the reactive clay unit into a number of sub-layers. A volumetric strain was then applied to each of the sub-layers. The shrinkage movement was assumed to vary in the lateral direction linearly, from zero at the centre of the footings to a maximum of approximately 70 mm at the edge of the footings at the ground surface (i.e. the full characteristic surface movement, y_s, has been assumed to occur at the edge of the raft). This is shown in Figure 3, in which the raft is represented by the black line at the surface.

Table 4: Site classification to AS2870 and Seddon (1992)

Instability index, I_{pt} (% strain / pF)	**Site classification [a]**
0 - 1.4	S
> 1.4 - 2.9	M
> 2.9 - 4.3	H1
> 4.3 - 5.4	H2
> 5.4	E

[a] S = slightly reactive, M = moderately reactive, H = highly reactive, E = extremely reactive

The soil movement shown in Figure 3 is dependent on the assumptions outlined above. Changes to these assumptions will result in a different soil movement profile, with a corresponding change in the behaviour of the footing system.

3.1.4 Structural

The waffle raft and stiffened raft were modelled as square in plan, with a side length of 12 m, and assumed clad frame construction with an applied load of 5 kPa. No allowance has been made for the stiffness of the dwelling super-structure as this is likely to be minimal.

The rafts were modelled using plate elements with a concrete stiffness of 30 GPa. This corresponds to a 28 day characteristic compressive strength (f'_c) of 32 MPa according to AS3600. The authors consider that the adopted concrete stiffness value of 30 GPa is likely to be an upper-bound for residential dwellings in Victoria, as:

- Concrete with a 28 day characteristic compressive strength (f'_c) of 20 MPa is more commonly adopted on site (which has a stiffness to AS3600 of 24 MPa); and
- The impact of creep and shrinkage on the concrete stiffness have not been considered.

The adoption of a lower concrete modulus will likely marginally increase the calculated deformations of the raft and decrease the calculated bending moments in the raft and edge beams.

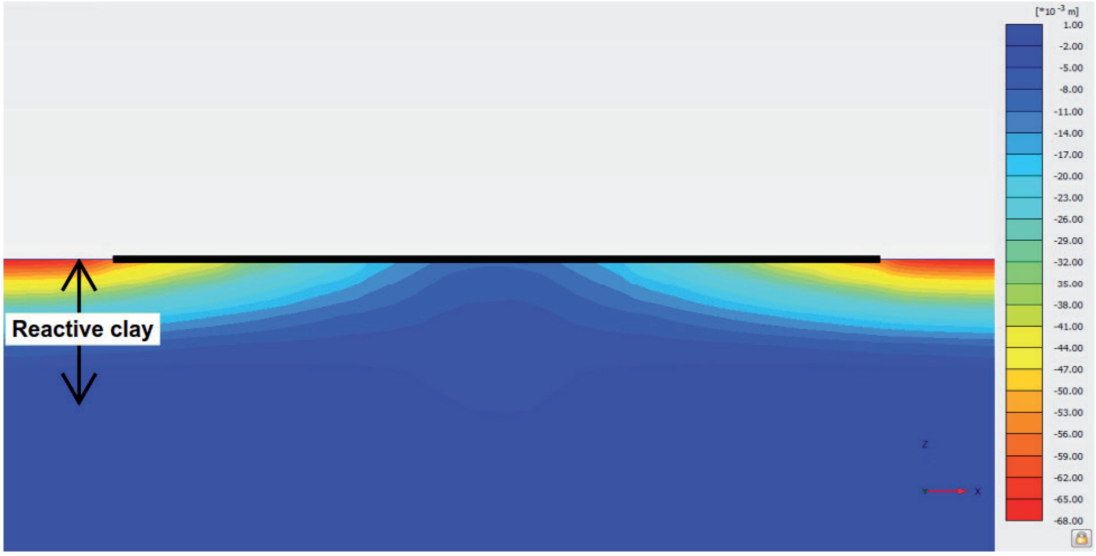

Figure 3. Coloured contours of soil vertical movement

The waffle raft was modelled with the following structural details:

- Slab thickness = 0.085 m;
- Beam depth = 0.310 m;
- Internal beam width = 0.110 m;
- External beam width = 0.300 m; and
- Void dimensions (plan) = 1.04 m x 1.04 m.

The stiffened raft was modelled with the following structural details:

- Slab thickness = 0.100 m;
- Beam depth = 0.550 m;
- Internal beam width = 0.300 m;
- External beam width = 0.300 m; and
- Beam centre-to-centre spacing = 4 m.

The rafts were modelled as a series of plates. The plates have been orientated such that their axes lie parallel to the ground surface. This was required to allow the bending moments of interest (i.e. bending about the horizontal axes) to be quantified.

A limitation of PLAXIS 3D is that it is not possible to consider yielding of plates, i.e. the maximum axial force and bending moment which may be generated in a plate element cannot be specified. This means that the full elastic stiffness of the raft is maintained irrespective of the deflection of the raft. As a result, analysis will underestimate the differential movements of the rafts and overestimate the bending moments (if greater than the yield moment). This is because the elastic assumption allows the calculated bending moments to increase above the yield moment rather than be limited to the yield moment value (as would occur if yielding of the plates could be modelled).

3.1.5 Construction stages

The construction stages adopted in the numerical analyses were:

- Establish the initial stress state under coefficient of earth pressure at rest (K_0) conditions;
- Wish-in-place the raft;
- Reset the displacements; and
- Apply the volumetric strain to model the shrinkage of the reactive clay layer.

3.2 Results of analyses

3.2.1 Vertical differential movements

The vertical movement of the waffle and stiffened rafts are shown in Figure 4 and Figure 5, respectively. The maximum vertical differential movements calculated in the horizontal planes are summarised in Table 5. The relative vertical differential movements across the rafts are shown graphically in Figure 6. The relative vertical differential movement is defined as the quotient of the difference in vertical movement between two points and the horizontal distance between the two points, expressed as a fraction.

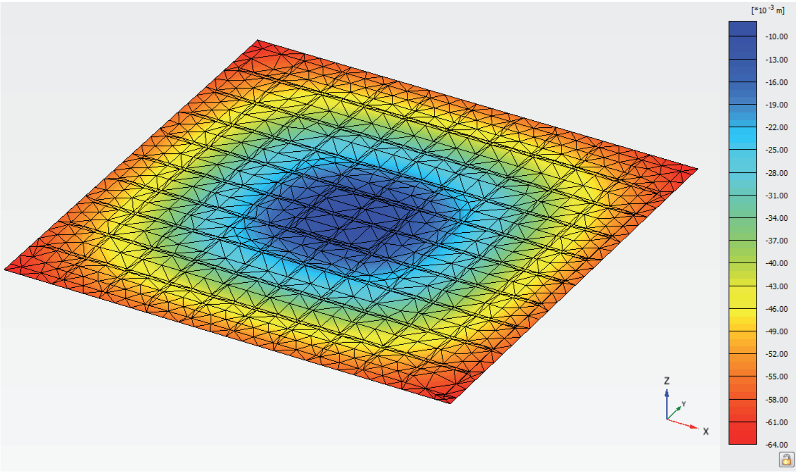

Figure 4. Calculated vertical deflection of waffle raft

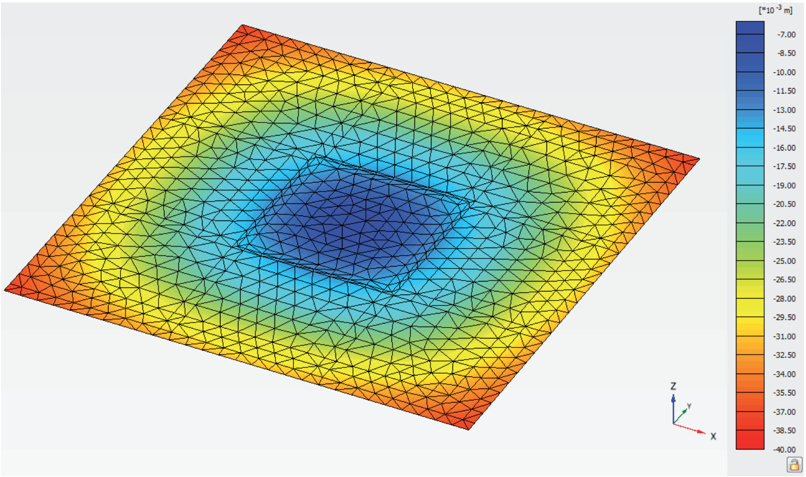

Figure 5. Calculated vertical deflection of stiffened raft

Table 5: Maximum calculated differential movement

Raft	Relative (-)	Absolute (mm)
Waffle	1 / 105	42
Stiffened	1 / 190	26

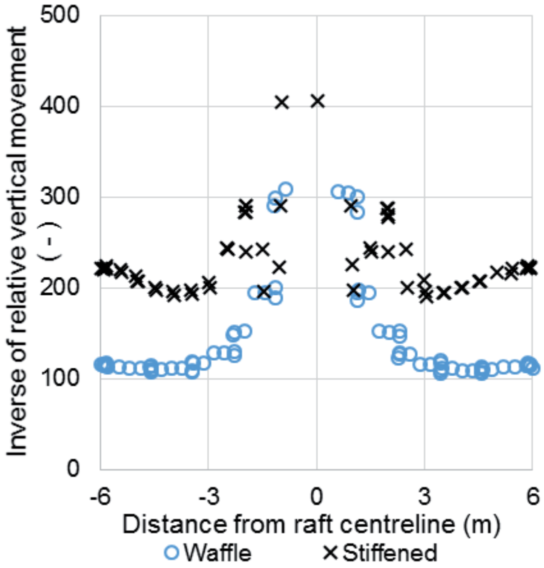

Figure 6. Calculated relative vertical movement

That is, the waffle raft has a calculated relative vertical differential movement of approximately 1 / 100, whereas that of the stiffened raft is approximately 1 / 200.

3.2.2 Structural capacity

The maximum calculated axial forces and bending moments with respect to the yield envelopes are presented for the slab (i.e. top element of the footing), external beams, and internal beams in Figure 7 to Figure 9, respectively. No partial factors have been applied to the axial force and bending moment values calculated from PLAXIS 3D. That is, the data points presented are working load values.

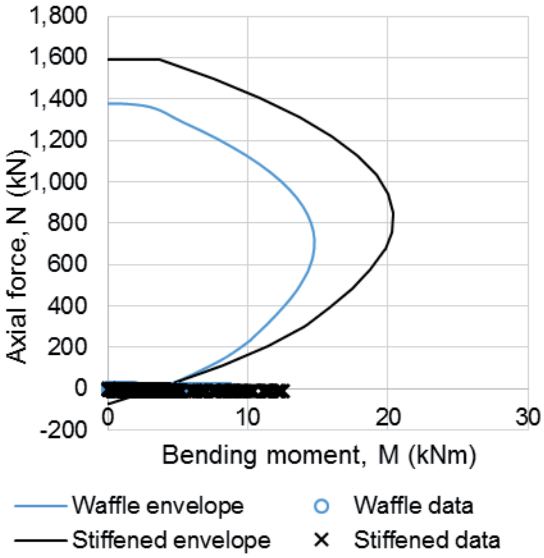

Figure 7. Structural capacity check – slabs

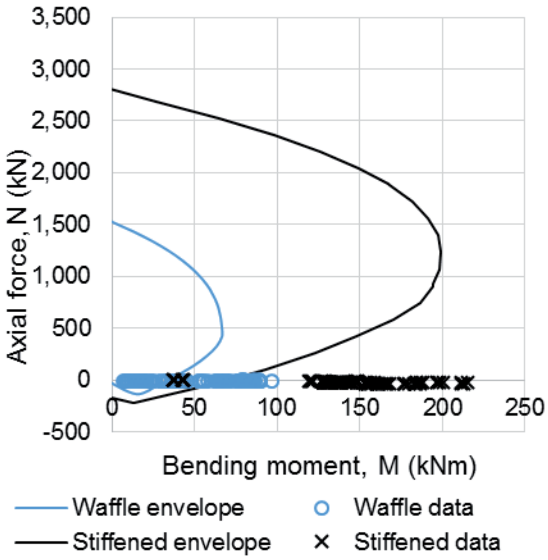

Figure 8. Structural capacity check – external beams

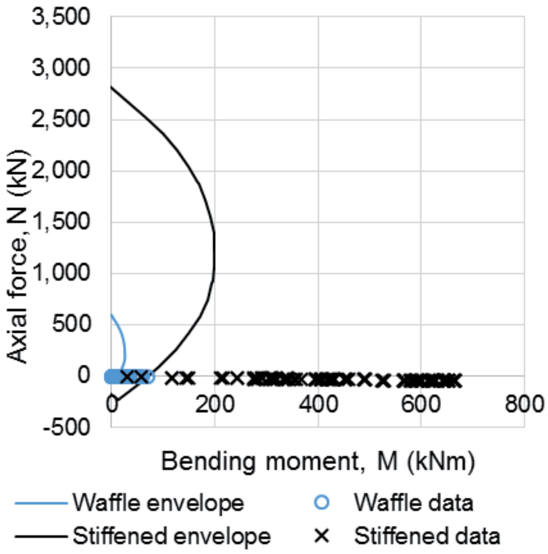

Figure 9. Structural capacity check – internal beams

The above figures show that the waffle and stiffened rafts do not have satisfactory structural strength for the conditions modelled.

3.3 Discussion of results of analyses

The stiffened raft has a stiffer response to the shrinkage of the reactive clay layer than the waffle raft with respect to both calculated relative differential movements (1 / 190 compared to 1 / 105, respectively) and vertical differential movements (26 mm compared to 42 mm, respectively). This is partly due to the higher stiffness of the stiffened raft compared to the waffle raft, but more importantly due to the stiffened raft being founded more deeply within the soil profile than the waffle raft, and therefore subject to lower shrinkage movements.

The maximum calculated relative vertical differential movement for both the waffle and stiffened rafts lie above that allowed by AS2870 for even the least onerous condition of clad frame construction (= 1 / 300, refer Table 2). The maximum calculated absolute vertical differential movement for the waffle raft (= 42 mm) is greater than that allowed by AS2870 for all construction types, whilst that for the stiffened raft are only acceptable to AS2870 for clad frame and articulated masonry veneer.

The structural actions in all elements (i.e. slab, external and internal beams) of both the waffle and stiffened rafts exceed their structural capacity.

As stated in Section 3.2.3, the plates representing the footings have been considered to be elastic elements. In reality, should the concrete elements be subjected to the structural actions shown in Figures 7 to 9 they would crack, resulting in an increase in the vertical movement of the footings compared to those presented in Section 3.3.1.

Based on the results of the numerical analyses presented herein, it would appear that the standard designs recommended by AS2870 for Class H2 sites are inadequate to limit both relative and absolute vertical differential movements to the limits proposed by AS2870, and to limit the structural actions in the footings such that their structural capacities are not exceeded. The standard designs for waffle and stiffened rafts for a Class H2 site do not appear to satisfy the requirements in AS2870 for design by engineering principles. In the authors' view, it is also likely that the other standard designs for site classifications of M and H1 may also be unsatisfactory.

The analysis presented in this paper has considered the relatively onerous condition of the characteristic surface movement (y_s) occurring at the edge of the raft, with nominal movement occurring at the middle of the raft. The analysis indicates that if such conditions occurred, significant damage would likely occur to every dwelling built using these standard designs. Significantly more work is required to confirm the results of these analyses and to investigate the suitability of all of the standard raft designs set out in AS2870 to a range of characteristic surface movements (y_s).

Some minor damage to dwellings constructed on reactive clays is to be expected. Such damage is likely to consist of hairline and fine cracks, which correspond to the damage categories set out in AS2870 of 0 (negligible) and 1 (very slight), respectively. This appears to be rarely clearly communicated to potential home owners. Such cracking is significantly less than would likely occur from the calculated movements presented in Section 3.3.1.

Whilst a significant number of dwellings have suffered damage due to reactive soils, the damage usually observed would appear to be less than would be indicated by the calculated performance of the rafts set out above. In the authors' view, this is most likely due to most rafts in practice not being subjected to the full design differential movement as indicated by the design characteristic movements set out in AS2870.

It would appear therefore that there is a significant inconsistency between the specified design characteristic movements and the raft designs. This inconsistency needs to be urgently addressed because of the risk to the significant number of dwellings on reactive clays planned for the immediate future.

The revision of AS2870 is likely to be a lengthy process. In the interim, the authors propose that it become a requirement that members of the public are adequately informed of the risks (with respect to the extent of movement and cracking which could reasonably be expected to occur), as well as the differing maintenance requirements, associated with various footing types. This could be achieved by the preparation of a guidance document, which would be mandatory for engineering professionals and building contractors to supply to potential new home owners.

4 CONCLUSION

The relative performances of a waffle raft and stiffened raft founded on reactive clay with a H2 site classification undergoing edge shrinkage have been compared using three-dimensional soil structure interaction analyses.

The results of the analyses indicate that the calculated maximum absolute relative movement of the waffle raft is approximately 50% higher than that of the stiffened raft. The performance of the footings in terms of the relative vertical differential movement is inadequate to satisfy the requirements of AS2870 for even the least onerous condition of clad frame construction. The structural capacity of both of the footing types considered was inadequate to satisfy the requirements of AS3600.

The standard designs for waffle and stiffened rafts for a Class H2 site do not appear to satisfy the requirements in AS2870 for design by engineering principles.

In the authors' opinion, it is also likely that the other standard designs for site classifications of M and H1 may also be unsatisfactory.

The analyses have demonstrated that there appears to be a significant inconsistency in AS2870 between the characteristic surface movement (y_s) values, the differential movement limits, and the standard designs provided. At this stage, it is not clear if amendments to the characteristic surface movements (y_s), to the standard designs, or to both, are required to resolve this inconsistency.

The authors consider that further investigations and analyses which utilise advanced soil-structure interaction analyses are required, to allow amendments to AS2870 to be made such that the standard footing designs presented are satisfactory under the specified ground movements in both SLS and ULS and at least meet the minimum requirements for design of rafts by engineering principles. This should be carried out with close collaboration between geotechnical and structural engineering specialists. In the interim, the authors recommend that members of the public are informed of the risks associated with various footing types through a guidance document, and that it would be mandatory for engineering professionals and building contractors to supply this to potential new home owners.

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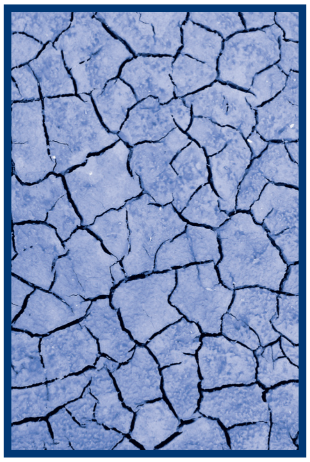
AGS VICTORIA 2017 SYMPOSIUM

Reactive clays and light structures



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