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Structural performance, analysis, and design of residential slabs on moisture reactive soil

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ABSTRACT

Whilst this paper has been written from a structural mechanics viewpoint it covers a lot of common ground with geomechanics because the structural performance of residential slabs is entirely driven and governed by soil moisture reactivity. It graphically illustrates that a typical standard stiffened raft and waffle raft on highly reactive residential building sites cannot sustain soil moisture variations such as have been experienced in Australia in severe drought conditions over the past few decades. Results are included to compare structural design modifications to extend the ultimate surface movement capacities of the typical standard rafts to within the extreme limits prescribed in Australian Standard AS 2870. Structural design based on ultimate strength is shown to be a much more cost-effective option than modification of standard designs based on elastic stiffness.

1 TYPICAL PERFORMANCE

The frequently referred to typical example in this paper is a single storey articulated masonry veneer dwelling on a Class H residential building site. The overall length of the floor plan has been taken as 16.3m and the overall width as 12.3m. Figure 1 shows typical graphs of deflection and bending moment versus surface movement. The solid lines have been derived from elastic analysis of a beam model (Van der Woude 2003). The markers at the end of the solid lines identify the upper limit of validity of elastic analysis, taken as the cracking capacity. Entering the bending moment graph at the cracking value on the vertical axis and scaling off the surface movement and deflection values on the solid lines determine the cracking capacity. The dashed lines have been derived from ultimate strength analysis of a plate model (Van der Woude 2004). The markers at the start of the dashed lines identify the lower limit of validity of ultimate strength analysis, taken as lift-off. The upper limit of validity of the dashed lines is taken as the ultimate capacity. Entering the bending moment graph at the ultimate value on the vertical axis and scaling off the surface movement and deflection values on the dashed lines determine the ultimate capacity.

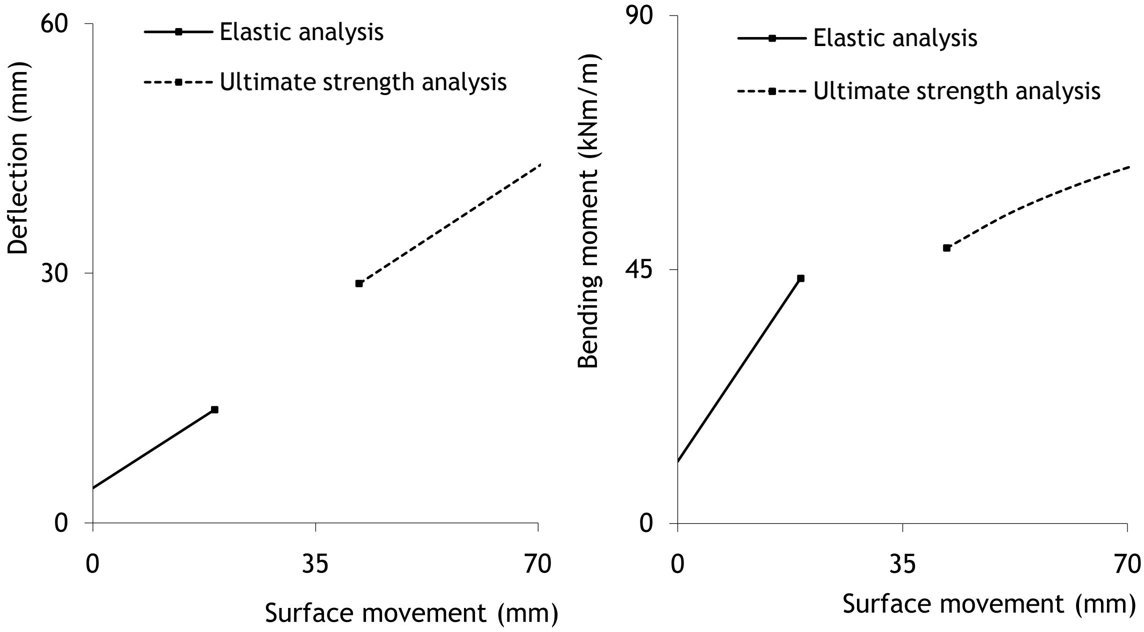

Figure 1: Deflection and bending moment versus surface movement

2 TYPICAL RESULTS

Structural design parameters for the typical standard rafts have been taken from Australian Standard AS 2870 (Standards Australia 1996). Structural performance outcomes have been determined by application of Figure 1. Modified structural design parameters have been selected to achieve performance outcomes highlighted in shaded cells. Ultimate damage categories and material cost estimates have been included for comparison.

Table 1: Typical results

Structural design parameters	Standard Waffle Raft	Standard Stiffened Raft	Modified Raft (1)	Modified Raft (2)	Modified Raft (3)
#Stiffening beams in short direction	14	5	5	5	6
#Stiffening beams in long direction	11	4	4	4	4
Overall stiffening beam depth (mm)	385	500	1000	700	500
Stiffening beam web width (mm)	110	300	300	300	250
Slab thickness (mm)	85	100	100	100	85
Slab mesh	SL72	SL82	SL82	SL82	SL72
Additional top reinforcement	None	None	None	None	43-N12
Bottom reinforcement	1-N12	3-L12TM	3-L12TM	3-L12TM	3-L11TM
Structural performance outcomes					
Cracking y_s capacity (mm)	23	20	**40**	25	18
Ultimate y_s capacity (mm)	18	21	87	**40**	**40**
Cracking deflection (mm)	21	14	6	9	12
Ultimate deflection (mm)	18	18	53	29	27
Ultimate damage categories	0	0	2	0	0
Material cost estimates	$8,270	$7,990	$10,700	$9,070	$7,580

Whilst the standard rafts perform more than adequately in regard to tolerable deflection for the typical construction, the surface movements at which they crack and ultimately fail are significantly lower than the performance requirements prescribed in AS 2870. The surface movement capacities of the standard rafts would be applicable under extreme soil drying conditions on Class S sites or under normal conditions on Class M sites.

Modification (1) aimed at raising the cracking capacity to the lower limit of Class H by increasing the overall stiffening beam depth. This raised the ultimate capacity to well above the upper limit of Class H, lowered the cracking deflection to well below the tolerable limit for full masonry construction, and raised the ultimate deflection to well above the tolerable limit for the typical construction. Modification (2) aimed at raising the ultimate capacity to the lower limit of Class H by increasing the overall beam depth. This raised the cracking capacity to just above the lower limit of Class M, lowered the cracking deflection to just below the tolerable limit for full masonry, and raised the ultimate deflection to just below the tolerable limit for the typical construction. Modification (3) aimed at raising the ultimate capacity to the lower limit of Class H by adding one more stiffening beam in the short direction, adding N12 bars to the top reinforcement, and reducing the slab thickness and beam web width. This lowered the cracking capacity to just below the upper limit of Class S, lowered the cracking deflection to just below the tolerable limit for articulated full masonry, and raised the ultimate deflection to just below the tolerable limit for the typical construction.

Modification (3) stands out as the most cost-effective solution in regard to surface movement capacities and tolerable deflection limits prescribed in AS 2870 for the typical construction and site Class.

3 GENERAL CONSIDERATIONS

3.1 Soil-structure interactive stiffness

Transition from validity of elastic analysis to ultimate strength analysis generally involves a complex relationship between the elastic stiffness and ultimate strength of the soil-structure interactive foundation system. The non-dimensional stiffness ratio $\frac{EI}{kL^4}$ (See Appendix for notation and units) generally governs the elastic performance outcome. The higher this ratio the flatter the elastic deflection graph in Figure 1 and the steeper the elastic bending moment graph. In comparison, the ultimate deflection graph slopes at a constant rate of 0.5, and the ultimate bending moment graph slopes at a gradually diminishing rate dependent on the soil stiffness parameter kL^2, overall floor plan length to width ratio, and total foundation load.

3.2 Lift-off distance and edge distance

Figure 2 shows typical graphs of lift-off distance applicable in ultimate strength analysis and edge distance generally used in elastic analysis versus surface movement.

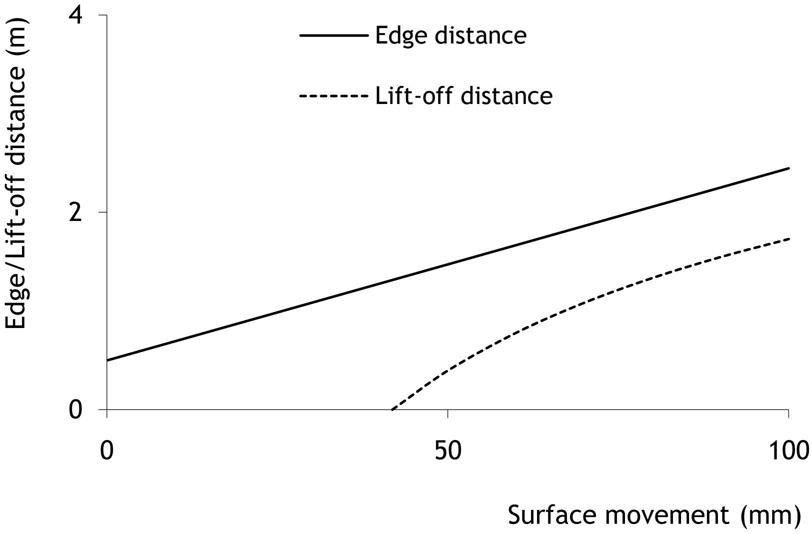

Figure 2: Edge distance and lift-off distance versus surface movement

3.3 Effective flange width and stiffening beam spacing

Effective flange width of stiffening beams generally has a significant effect on the determination of elastic stiffness, cracking bending moment, and ultimate bending moment, and hence on the cracking and ultimate surface movement capacities. For internal beams the effective flange width is taken as $0.2L+B_w$ and for edge beams as $0.1L+B_w$. In no case can the effective flange width be taken as greater than the distance halfway to the adjacent parallel beams. It follows that the optimum spacing of stiffening beams is the effective flange width of internal beams in the direction being considered. Standard waffle rafts generally have more stiffening beams than the optimum number and standard stiffened rafts generally have fewer.

3.4 Slab thickness and stiffening beam web width

Concrete cover to steel reinforcement generally governs lower limits of slab thickness and stiffening beam web width, so that the concrete can be properly placed and compacted. In some cases the lower limit of slab thickness may be governed by unusual loading, such as for example high concentrated load in the middle of an isolated slab panel.

3.5 Additional top reinforcement

Additional top reinforcement bars should be tied to the conventional slab mesh and be evenly spaced in bundles within the effective flange widths of internal stiffening beams in the short direction, to cover most of the region of potentially wide cracks, as shown in Figure 3. N12 bars can generally be spaced so that the concrete can be properly placed and compacted within the clear distance between parallel bars; if not, N16 bars of equivalent area can be used. The length of the bars should be at least 0.6 times the width of the slab. The slab mesh can generally be reduced to the next lower wire diameter than specified in AS 2870, provided it meets the minimum ductility requirement. The maximum amount of additional top reinforcement should be limited to avoid crack depths greater than 0.6 times the overall stiffening beam depth to avoid a neutral axis ratio greater than 0.4 (See AS 3600, Standards Australia 2001). The wider the stiffening beam webs the higher the maximum amount of additional top reinforcement.

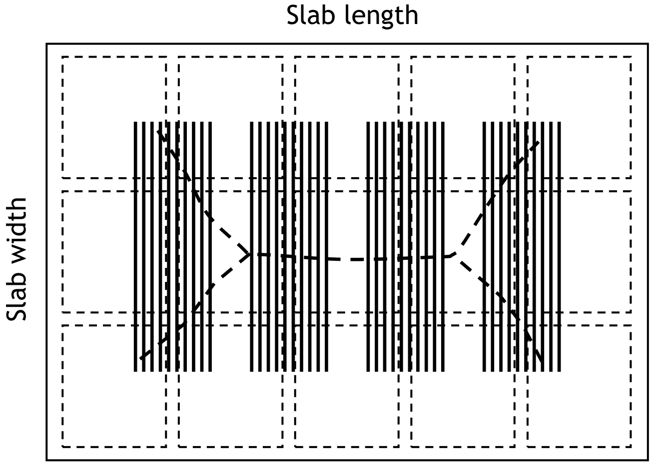

Figure 3: Ultimate crack pattern and additional top reinforcement

3.6 Ultimate crack pattern

The first structurally significant cracks generally appear within the first few metres from the edges of the floor plan, within which elastic bending moments are generally maximum. As structural distortion increases with further surface movement, more and wider cracks appear closer to the middle of the floor plan. Ultimately the widest cracks form in a pattern shown in Figure 3 in heavy dashed lines superimposed on light dashed lines representing the stiffening beam layout. Further structural distortion is in the form of a geometric mechanism consisting of essentially plane segments bounded by the edges of the floor plan and ultimate crack lines, and rotating relative to one another about the ultimate crack lines.

3.7 Ultimate damage category

Table C2, AS 2870 presents structural damage categories with reference to concrete floors in terms of change in offset from a three metre straight edge centred over a major crack, and in terms of crack width. Geometric analysis of the ultimate crack pattern in Figure 3 relates the two criteria as follows, involving crack depth, ultimate deflection, and overall floor plan width:

$$\frac{\text{Change in offset (mm)}}{3000} = \frac{\text{Crack width (mm)}}{\text{Crack depth (mm)}} = \frac{\text{Ultimate deflection (mm)}}{1000 \times [\text{Overall width (m)}]}$$

Assuming AS 2870 damage categories with reference to concrete floors correlate with reference to superstructure walls, Category 0 or 1 should be the limit under normal conditions, Category 2 should be expected under adverse conditions, and Category 3 or worse is considered as significant damage.

The stiffness based modified raft (1) in Table 1 shows up with the most severe damage Category.

3.8 Design factors

Structural design generally involves the following factors: Heave and subsidence surface movement reduction factors, strength capacity reduction factor, dead load factor, live load factor, and serviceability deflection factor.

3.9 Design criteria

3.9.1 Strength: Effective overall cracking strength
Effective overall ultimate strength
Isolated slab panel strength

3.9.2 Serviceability: Ultimate deflection
Ultimate damage category

3.9.3 Soil bearing capacity: Ultimate soil pressure

4 STRUCTURAL DESIGN OPTIONS

4.1 Application of AS 2870

Some engineers simply select a deemed-to-comply standard design given in AS 2870 for the applicable site Class. Engineers routinely involved in the selection and design of rafts use the graph of non-dimensional movement ratio $\frac{y_s}{\Delta}$ versus unit stiffness $\log\{\Sigma(\frac{B_w D^3}{12})/W\}$, given in AS 2870 to modify standard designs. It must be applied in each direction for each rectangular component making up the floor plan, and it is important to be careful with units and counting the edge beams as well as internal beams in the summation within the log function. AS 2870 does not require using a design stronger than the standard design given for the applicable site Class, nor does it permit using a design weaker than the standard design for the next lower site Class.

The modification procedure generally presents a significant potential savings in material construction costs, particularly when the site characteristic surface movement is significantly less than the upper limit of the applicable site Class, or when the stiffening beam layout provides spacing less than the minimum required. Reduction in reinforcement would also be possible because the amount is governed by ductility of the reduced overall beam depth and/or increased number of beams. The ductility requirement in AS 2870 is that the ultimate bending moment calculated on the basis of a reinforced concrete section is at least 20% greater than the cracking bending moment calculated on the basis of an un-reinforced section.

AS 2870 permits determination of design bending moment and elastic stiffness using soil-structure interactive analysis methods (Mitchell 1984 and Walsh 1986). Both methods are based on the elastic beam model and involve the following design parameters:

$$e = \frac{H_s}{8} + \frac{y_m}{36} \qquad m = \frac{1.5L}{(D_{cr} - D_e)} \qquad D_{cr} = \frac{H_s}{7} + \frac{y_m}{25}$$

The Mitchell and Walsh methods generally produce very similar results.

Some engineers use elastic finite element analysis of a plate model, using the Walsh method edge distance as the lift-off distance. Plate analysis generally predicts significantly lower bending moments than beam analysis, and hence higher surface movement capacities. The elastic finite element method generally presents similar potential savings in material construction costs as the modification method.

4.2 Ultimate strength design

Structural design based on ultimate strength of a plate model applies Figure 1 in reverse to analysis. Entering the design value of surface movement on the horizontal axes of the graphs and scaling off the deflection and bending moment determine the ultimate design values. Ultimate strength designs can always be made strong enough to sustain soil moisture variations up to any level applicable to any site Class, and they generally tolerate deflections within the limits prescribed in AS 2870. Ultimate strength based designs generally present significantly greater savings in material construction costs than elastic stiffness based designs. It should be noted in closing that whereas AS 2870 uses reduced values of concrete modulus of elasticity and tensile strength to determine elastic stiffness, cracking strength, and ductility, ultimate strength design uses the full values in AS 3600.

5 CONCLUSION

The most important outcome of this paper is that elastic stiffness based structural design of residential slabs on moisture reactive soil is an expensive option to achieve structural performance levels within extreme limits of soil moisture variations. Whilst this conclusion is based on results for a typical single storey articulated masonry veneer dwelling on a Class H site, the author believes it is generally applicable to other types of construction, house sizes, site Classes, and other relevant parameters. The author's view of the practical implication of results in this paper is that a shift in structural design emphasis from elastic stiffness to ultimate strength is the most cost-effective option to achieve structural performance requirements prescribed in Australian Standard AS 2870.

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APPENDIX: Notation and units

B_w = Stiffening beam web width (mm)
D = Overall stiffening beam depth (mm)
D_e = Depth of embedment of edge beam from finished ground level (m)
e = Walsh mound edge distance (m)
E = Concrete modulus of elasticity (kPa)
H_s = Depth of design suction change (m)
I = Effective un-cracked concrete section stiffness parameter per metre width (m^3)
k = Soil modulus of elasticity (kPa/m) (Also known as Winkler modulus)
L = Stiffening beam length in the direction being considered (m)
m = Mitchell mound exponent
W = Overall slab width normal to the direction being considered (m)
y_m = Design differential mound movement (mm)
y_s = Site characteristic surface movement (mm)
Δ = Maximum design differential footing movement (mm)
$\sum$ = Summation