Australian Standard AS 2870 – Time for a change

With specific reference to the slab heave problem with waffle rafts

Author: Frank Van der Woude, B.E., Ph.D.

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ABSTRACT

The purpose of this paper is to review the efficacy of Australian Standard AS 2870 [1] to regulate site classification, design, construction and maintenance of residential slabs and footings. This review identifies a number of issues with AS 2870 relating to the slab heave problem with waffle rafts. It demonstrates how AS 2870 may be applied to hold home owners responsible for damage to their new homes, caused by foundation movement as a result of abnormal soil moisture conditions developing after the owners have taken possession of their new homes. It also demonstrates that slab heave, popularly believed to be caused by deficiencies in the stormwater drainage systems of the dwellings, is not the principal cause of damage. A limit state methodology for ultimate strength design of residential slabs is recommended as a cost-effective way to mitigate the slab heave problem with waffle rafts. Graphs are included to address the issues with AS 2870.

Keywords: AS 2870, design, moisture reactivity, raft slabs, ultimate strength

1 BACKGROUND OF AS 2870

Prior to the introduction of AS 2870 in 1986, builders largely determined the construction of residential slabs and footings, often with relatively minor input from engineers, and usually without Local Authority supervision. Slab-on-ground construction in the early years consisted of a shallow perimeter strip footing, a bricked up base, and an in-fill slab. Steel reinforcement was minimal, just enough to control concrete shrinkage cracking. Soon problems emerged. First came the problem of soil moisture reactivity related damage. Then came the problem of litigation. Around the 1960s Local Authorities started to exercise a more regulatory and supervisory role. They began accumulating site details in the form of local maps, using the past performance of houses constructed in areas of similar site characteristics as a guide. Then they began specifying the type and size of slabs and footings they deemed applicable to those characteristically similar building sites. In so doing, Local Authorities became potentially legally liable in the event of subsequent damage.

The first edition of AS 2870 claimed *'Adherence to this Standard will reduce litigation'*. However, there is a growing body of evidence denying this claim. The Queensland Building Services Authority (QBSA) [2] reported in May 1998, '*A large percentage of damage compensation claims involved subsidence problems'.* A subsequent QBSA press release revealed, *'The cost of subsidence problems was doubling each year'*. The Sydney Morning Herald newspaper published an article on 11 February 2007, *'A survey of 75,000 homes across Australia by Archicenter, the building advisory service of the Royal Australian Institute of Architects, revealed that, in most states, more than 35 per cent of homes had experienced cracking'*. The Victorian Building Authority (VBA) [3] reported in May 2014, *'Research found that 5.3 percent of dwellings built in an area of Melbourne's western suburbs between 2003 and 2011 showed some form of distress (such as cracks in the floor and walls) attributed to slab heave'*. The VBA concluded, *'The key issues relating to slab heave were associated with deficiencies in the stormwater drainage systems of the dwellings'*. The Age newspaper published an article on 08 June 2014, *'Estimates suggest up to 4,300 homes in Wyndham, Melton and Hume Local Government areas may be suffering from slab heave'.*

Many, if not all, reported slab heave problems occurred within a few years after construction, some even within a few months, all well short of the prescribed 50 years design life. AS 2870 acknowledges that buildings constructed on sites subject to *'Abnormal moisture conditions'* have a higher probability of damage than those on normal sites. AS 2870 stipulates that site classifiers, qualified engineers, designers and builders are responsible for abnormal moisture conditions existing prior to or resulting from building construction, and home-owners are responsible for abnormal moisture conditions developing after construction. AS 2870 Section 1.3.3 lists the following examples of abnormal moisture conditions developing after construction:

- The effect of trees too close to a footing.
- Excessive or irregular watering of gardens adjacent to the building.
- Failure to maintain site drainage.
- Failure to repair plumbing leaks.
- Loss of vegetation from near the building.

Anecdotal evidence suggests that when AS 2870 has been applied and there is a damage investigation, home-owners are all too often blamed for abnormal moisture conditions developing after construction, and are thereby effectively prevented from proceeding to litigation. This has left many new home-owners with no avenue of recourse after their homes have suffered damage.

Whilst there is no doubt whatsoever that foundation movement due to soil moisture changes is the principal cause of damage, investigators are not in a position to determine the quantum of moisture changes that actually caused the damage. Nevertheless, bearing in mind that site characteristic surface movements are defined and determined in accordance with AS 2870 as occurring between extreme moisture changes that have less than 5% chance of being exceeded in 50 years, it is very surprising that many, if not all, investigators to date have not looked for other explanations of damage. Moreover, the fact that cracking is one of the main symptoms of damage, suggests that insufficient strength is the most likely explanation. However, and with due respect, damage investigators are reasonably entitled to expect that standard deemed-to-comply slab design solutions have sufficient strength to sustain foundation movements at the design levels prescribed in AS 2870. Unfortunately, this is not the case.

2 THE SLAB HEAVE PROBLEM

The first edition of AS 2870 had a Clause, *'Slabs and footings shall be designed to withstand the most severe combination of loading and foundation movement'*. Whilst AS 2870 references *'Centre heave'* and *'Edge heave'* foundation movements, it does not identify which is most severe. The following paragraphs arguably identify edge subsidence as the most severe foundation movement.

From the day the slab is constructed, it effectively seals the soil beneath it against moisture changes. Thereafter, normal weather-induced soil moisture changes happen only outside the soil-slab domain. Therefore, foundation movements due to normal weather-induced soil moisture changes can only be either edge heave or edge subsidence, but not centre heave.

When construction of the house is practically complete, the static weight of the house, most of which is supported on the edges of the slab, has pushed the slab deeper into soil at the edges than in the centre, distorting the slab in a dome shape. It takes a long period of wet weather for swelling soil outside the soil-slab domain to heave the edges of the slab to level with the centre, and more continuing wet weather to distort the slab into a dish shape deep enough to cause damage. Moreover, dishing distortion produces invisible cracking on the bottom of the slab. Cracking of masonry walls is unlikely, because the outside walls tend to tilt inwards when the slab is dished, putting them in compression from the top down. Compression in the outside walls also provides some physical restraint against dishing distortion of the slab.

In dry weather after construction of the house is practically complete, shrinking soil outside the soil-slab domain immediately exacerbates the initial doming distortion of the slab due to the static weight of the house. Relative to edge heave, it takes less subsiding soil movement to distort the slab from the initial shallow dome shape into one high enough to cause damage. Moreover, doming distortion of the slab produces visible cracking on the top of the slab. Cracking of masonry walls is very likely, because the outside walls tend to tilt outwards when the slab is domed, putting them in tension from the top down, and it is a well-known fact that masonry walls crack at relatively low levels of distortion.

3 ISSUES WITH AS 2870

- Applicable ranges of design Y_S values in AS 2870 Table 2.3 are too broad.
- Deemed-to-comply slab design solutions are independent of soil stiffness.
- Deemed-to-comply slab design solutions are independent of floor plan dimensions.
- Designs are based on a one-way action beam model for what is a two-way action plate problem.

4 LIMIT STATE METHODOLOGY [4]

4.1 Slab failures

Limit state methodology is based on the *'Worst-case'* scenario of identifying and analyzing the critical failure mechanism, and applying appropriate factors of safety and criteria to ensure adequate in-service performance. The self-evident conditions for slab failure are:

- ***Yield condition:*** Slab is significantly cracked.
- ***Mechanism condition:*** Slab distortion is geometrically compatible with crack pattern.
- ***Equilibrium condition:*** Resultant soil pressure equals total foundation load.

In the context of slabs on moisture reactive soil, the yield condition is taken as significant cracking. Whilst cracking due to concrete shrinkage is not significant, it should be noted that concrete shrinkage cracks may trigger yield line cracks. Taking a rectangular slab as an example, the yield line crack patterns for global doming and dishing failure mechanisms develop as follows: The first yield line crack more than likely starts along the centreline parallel to the long side of the rectangle, where the bending moment is greatest. As foundation movement increases, the central yield line crack widens and lengthens, and then splits into two yield lines heading at about 45^0 angles to the corners.

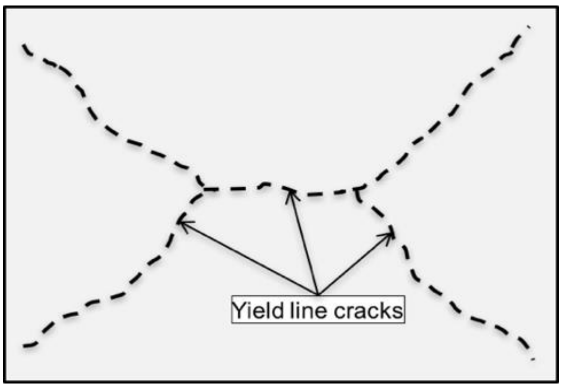

Figure 1 - Fully developed yield line crack pattern

The fully developed yield line crack pattern in Figure 1 looks like a shallow hipped roof. Distortion of the slab is like the motion of a three-dimensional mechanism consisting of four approximately plane segments hinged together along the yield line cracks and rotating relative to each other about the yield line cracks. In subsiding soil conditions, the distorted slab is domed and cracked on the top, and in heaving soil conditions it is dished and cracked on the bottom.

4.2 Ultimate strength performance

The ultimate strength performance of slabs on reactive soil is a complex function of dynamic surface movement, static loading, floor plan size and shape and soil stiffness. Figure 2 shows a characteristic graph of ultimate bending moment (M_U value) versus surface movement (Y_S value) at which the slab fails, covering both subsidence (Positive Y_S values) and heave (Negative Y_S values). This graph comprises a straight line for a short distance on either side of the vertical axis, followed by exponential curves to subsidence and heave ultimate strength asymptotes at infinite Y_S values.

4.3 Ultimate strength design

Design ultimate bending moments are determined by interpolating the performance graph in Figure 2 at specific and appropriately factored Y_S values applicable to the building site. Designers can then work out the slab dimensions, stiffening rib layout, steel reinforcement and other details in accordance with conventional structural design practice, including compliance with Australian Standards AS 2870 and AS 3600 [5] and other relevant documents.

It can be demonstrated that graphs of ultimate deflection versus Y_S are always straight lines with a gradient equal to exactly 0.5, enabling designers to assess the potential damage category of slab designs in accordance with AS 2870 Table C2. Whilst the necessary mathematical process for the recommended ultimate strength design methodology is quite tedious, the number-crunching can be easily programmed in a spread sheet for routine application in practice.

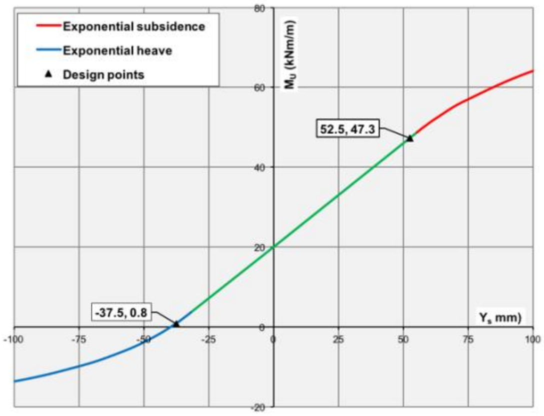

Figure 2 - Ultimate strength performance graph

4.4 Slab design example

The following example is applicable for waffle raft slabs for single-storey articulated masonry veneer houses on Class H2-D building sites with a top of the range Y_S = 75 mm. The following design data input values and design factors have been used:

Actual floor plan details
Area: 142.56 m^2; Overall length: 15.07 m; Overall width: 12.33 m

Equivalent rectangular floor plan details
Calculations are in the Appendix.
Area: 142.56 m^2; Length: 13.20 m; Width: 10.80 m

Loading
Total weight of superstructure Note 1: 490 kN
Uniformly distributed dead load: 3.5 kPa
Uniformly distributed live load: 1.5 kPa

Material properties
Concrete strength grade: N20; Reinforcing steel yield strength: 500 MPa; Soil stiffness: 1000 kPa/m

Design factors
Subsidence Y_S: 0.7 Note 2; Heave Y_S: 0.5 Note 2
Dead load: 1.25; Live load: 1.5
Strength capacity reduction: 0.8
Serviceability deflection reduction: 0.8

Note 1: This dead load is conservatively assumed to act around the entire slab perimeter.

Note 2: These Y_S factors are consistent with AS 2870 Clause F2(a).

4.5 Design results

Table 1 compares the standard AS 2870 design and ultimate strength design.

4.6 Observations

The key differences between the standard AS 2870 design and ultimate strength design are:

- Increasing the maximum spacing of stiffening ribs from 1.2 m to the effective flange widths of the internal ribs in both directions reduced the number of ribs in the short direction from 12 to 7, and from 10 to 5 in the long direction (Including edge ribs).
- Increasing the stiffening rib width from 110 mm to 180 mm, and increasing the top reinforcement from SL82 mesh to 370 mm^2/m in the short direction, and from SL82 mesh to 307 mm^2/m in the long direction increased M_U^+ by 27% and increased the Y_S capacity by 24%. It should be noted that stiffening rib width and top reinforcement have been calculated to avoid neutral axis ratios greater than 0.4 at the design ultimate strengths (See AS 3600 Clause 8.1.3).
- The ultimate strength design is 14% cheaper than the standard AS 2870 design.

Table 1 – Compare standard AS 2870 design & ultimate strength design

Slab details	Standard AS 2870 design	Ultimate strength design
Overall depth	460 mm	460 mm
Slab thickness	85 mm	85 mm
Stiffening rib width	110 mm	180 mm
Maximum spacing of stiffening ribs in short direction	1.20 m	2.34 m
Maximum spacing of stiffening ribs in long direction	1.20 m	2.82 m
Top reinforcement in short direction	SL82 Mesh	370 mm^2/m
Top reinforcement in long direction	SL82 Mesh	307 mm^2/m
Bottom reinforcement in internal stiffening ribs	1N16	210 mm^2
Bottom reinforcement in edge ribs	3N16	631 mm^2
Ultimate strength		
Doming (M_U^+)	38.2 kNm/m	48.4 kNm/m
Dishing (M_U^-)	-40.5 kNm/m	-27.6 kNm/m
Ultimate performance		
Y_S Capacity	42.6 mm	52.5 mm
Ultimate deflection	36.5 mm	36.3 mm
Ultimate soil pressure	58.1 kPa	88.8 kPa
Damage category	1	1
Material cost estimate	$10,750	$9,250

4.7 Effect of soil stiffness on slab design

The graphs in Figure 3 show that slabs on hard soils fail at significantly lower Y_S values than those on soft soils. Conversely, for the same design Y_S value, slabs on hard soils need to be stronger than those on soft soils.

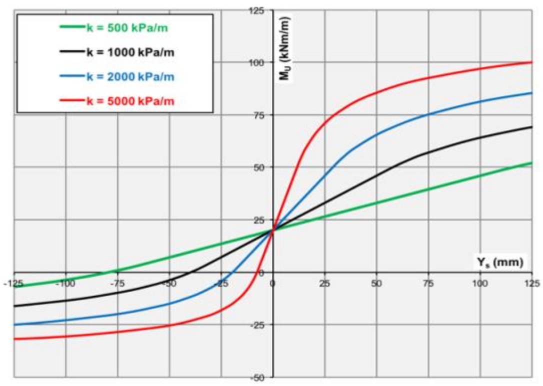

Figure 3 - Effect of soil stiffness

It should be noted that under normal weather-induced moisture changes, the supporting soil will dry and harden. Therefore, houses built on sites that are abnormally wet at time of construction of the slab are at abnormally high risk of damage.

4.8 Effect of floor plan area on slab design

The graphs in Figure 4 show that design ultimate bending moments increase significantly with floor plan area.

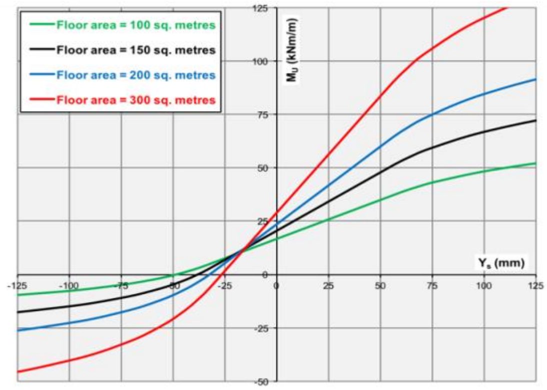

Figure 4 – Effect of floor plan area

4.8 Plate model versus beam model

The graphs in Figure 5 show that the two-way action plate model calculates significantly lower design ultimate bending moments than the beam model.

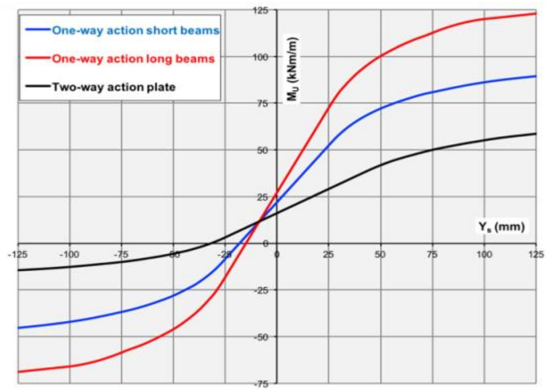

Figure 5 – Plate model versus beam model

5 CONCLUSION

This paper has outlined sufficient grounds for changing AS 2870 from a prescription of standard deemed-to-comply slab designs to a proper engineering code based on limit state ultimate strength design. This recommended change will align AS 2870 with other similar engineering design codes, like the concrete structures code (AS 3600), the steel structures code (AS 4100), and the timber structures code (AS 1720).

Ultimate strength designs will, over time, reduce the incidence of premature waffle raft slab failures.

It has been demonstrated that soil stiffness has an equally significant effect as surface movement on the performance of raft slabs on moisture reactive soil.

Last, but by no means least, a change to ultimate strength design of slabs will generate immediate nett cost benefits to the home building industry.

6 REFERENCES

1. Standards Australia, Australian Standard AS 2870 - *Residential Slabs and Footings*, (2011).
2. Queensland Building Services Authority, Subsidence of Residential Buildings – A Case Study, (May 1998).
3. Victorian Building Authority, *Research Findings on Slab Heave*, (May 2014).
4. Van der Woude F, *Limit State Slab on Mound Model*, Australian Geomechanics, Volume 39, Nº 4, pp. 97-101, (December 2004).
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7 APPENDIX - EQUIVALENT RECTANGULAR FLOOR PLAN

For the purpose of two-way action plate analysis of a slab on ground, most house floor plan shapes can be reasonably approximated to rectangles. Figure 6 shows the slab design example in Section 4.4.

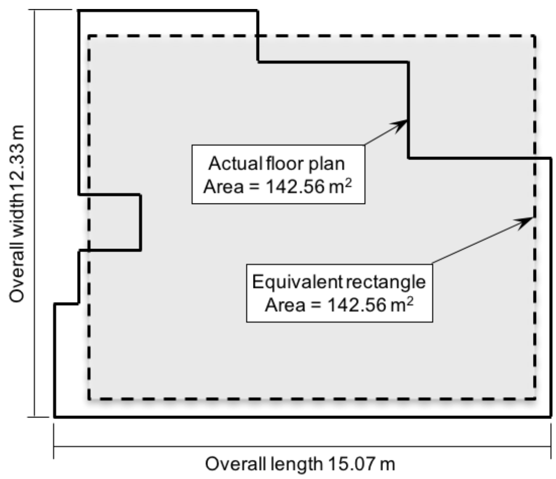

Figure 6 - Equivalent rectangular floor plan

The dimensions of the equivalent rectangle are calculated as follows:

$$\text{Aspect ratio} = \frac{15.07}{12.33} = 1.222$$

$$\text{Width} = \sqrt{\frac{142.56}{1.222}} = 10.80 \text{ m}$$

$$\text{Length} = 1.222 \times 10.80 = 13.20 \text{ m}$$