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Title:	Review of residential footing design on expansive soil in Australia
Editor:	Bijan Samali, Mario M. Attard and Chongmin Song
Conference name:	22nd Australasian Conference on the Mechanics of Structures and Materials (ACMSM22)
Conference location:	Sydney, Australia
Conference dates:	11-14 December 2012
Series title and volume:	From materials to structures: advancement through innovation: a collection of peer reviewed papers
Publisher:	Taylor & Francis
Year:	2013
Pages:	575-579
URL:	http://hdl.handle.net/1959.3/310676
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Review of Residential Footing Design on Expansive Soil in Australia

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ABSTRACT: Many of the new housing subdivisions in Victoria are on expansive soils with the majority of houses built being timber-framed brick-veneer with slab on ground. Given the sensitivity of expansive soils to change of ground moisture content and the light nature of these domestic structures, significant cracking and damage to newly constructed houses has been reported following the end of the drought and above-average rainfall received in the last couple of years. This paper is part of an ongoing major research project which aims to improve the design and performance of residential footing systems. The paper presents a review of some of the related design assumptions in the Australian Standard AS2870 for slabs and footings.

1. INTRODUCTION

Expansive soils are widely distributed all over Australia. It is estimated that 20% of the Australian surface soils are expansive (Richards et al., 1983). Light structures on expansive soils may experience problems due to settlements or heave as a result of soil movements.

Research studies on expansive soils commenced in early 1950's in Australia. Aitchison and Holmes (1953) investigated soil suctions and ground movements and examined the compatibility of the relationship between soil moisture and movement in clay soils. Holland. et al. (1975), Cameron (1977), Walsh (1978), Mitchell (1979 and 1980), and Pitt (1982) investigated the performance of footings on expansive soils and derived relevant design concepts. These research efforts led to the establishment of a standard to design residential footings in Australia, AS2870 which was first published in 1986. Two following editions of AS2870 have been published in 1996 and 2011 which refined the design process as a result of new research and field investigations.

The standard provides a simplified approach to calculate the free surface movement in expansive soil. When a slab is placed on expansive soil, the slab becomes a moisture barrier and differential ground movement occurs across the slab. The differential movement along the slab is called mound profile and the mound profile can be predicted based on Walsh (1978) method or Mitchell (1979) method. A mound profile will have two main shapes of centre heave and edge heave in two different moisture conditions under the slab. Centre heave would occur in footings by having high soil moisture condition under the slab centre while edge heave would occur by having high soil moisture condition at the perimeter of the slab. Both Walsh (1978) and Mitchell (1979) methods use the calculated free surface movement and depth of moisture change as the only parameters to predict the mound profiles. Based on the mound profiles, the stiffness of the slab and dimensions (slab thickness, beam depth and reinforcement) can be calculated. These methods are used for three decades in Australia and being improved time to time by assessing the performance of footings.

Aitchison and Richards (1965) studied the effect of climate on soil moisture condition. They used meteorological data from more than 600 stations and produced a climate based soil moisture map for Australia. There are many studies that followed the work done by Aitchison and Richards, e.g. Mitchell (1984), Barnett and Kingsland (1999), Fityus et al. (1998), Fox (2000). Those studies considered the effect of climate which in turn affects the moisture condition under the footing. AS2870 (1996) considered the climate effect through the use of the climate map provided by Aitchison and Richards (1965).

In recent months, there have been several reports in the media (THE-AGE, 2011, ACA, 2012) regarding footing movements associated with edge heave.

This paper reviews specific factors affecting the footing design procedure described in AS2870 with particular emphasis on climate conditions.

2. FOOTING DESIGN IN ACCORDANCE WITH AS2870

AS2870 classifies the expansiveness of soil by the characteristic surface movement (y_s), which corresponds to ground settlement or heave within the design life of the structure due to change in soil moisture content. The design life of a structure is 50 years for residential buildings. AS2870 specifies y_s as a function of instability index (I_{pt}), soil suction change at ground surface (ΔU) and design depth of suction change (H_s) as shown in Equation 1. Expected vertical movement of a soil layer of thickness 'h' is calculated and the total surface movement is the summation of each layer movement up to H_s.

$$y_s = \sum(I_{pt} \times \Delta U \times h) \quad (1)$$

The footing design procedure described in AS2870 is based on site classification. AS2870 (1996) classifies the sites from slightly reactive to highly reactive. Highly reactive sites are further divided into H1 and H2 in AS2870 (2011). Areas having more than 3 m H_s values are categorised as deep seated moisture variation sites and further classified as S-D, M-D, H-D and E-D.

AS2870 (1996 and 2011) provides suitable footing types according to the site classification in deemed to comply provisions. Furthermore, AS2870 allows designing footings using engineering principles for any site classification.

3. FACTORS AFFECTING Y_S

Expansive properties of a soil are represented by the Instability Index, I_{pt}. The I_{pt} depends on the vertical strain of soil per unit change in suction which termed as shrinkage index, I_{ps}. Expected swelling and shrinkage of soil is estimated by shrink-swell index test. Walsh and Cameron (1997) specify that shrink-swell test described in AS1289 (1992) is the most appropriate method to obtain I_{ps} with significant lower coefficient of variation compared to other tests such as loaded shrinkage, core shrinkage etc. The shrink-swell test consists of axial swell strain obtained from one dimensional consolidation test and axial shrinkage strain obtained from an unrestrained core shrinkage test (AS1289, 1992). Then the total vertical strain can be calculated by adding these two quantities. AS1289 (1992) assumes that during the one dimensional consolidation test the suppressed lateral expansion of the sample inside the ring would be transmitted into vertical direction. This fundamental difference between free shrinkage and one dimensional swelling is corrected by dividing the swell result by a factor of 2 before adding them together. Suction variation during swelling and shrinking is taken as 1.8 pF which is used to calculate the strain per unit suction. Detailed description of the shrink-swell index estimation and shortcomings are covered in Fityus et al. (2005).

I_{pt} is derived from I_{ps} by considering a specific lateral restraint factor (α) depending on the site condition. The lateral restraint factor accounts for the cracked and the uncracked zones up to H_s. It is assumed that no soil movement occurs below 10 m depth from the ground surface and hence AS2870 defines the factor α at depth 'Z' from the ground surface using Equation 2 for the uncracked zone. The factor, α is taken as 1 for the cracked zone to neglect the effect of lateral restraint.

$$\alpha = 2.0 - \frac{z}{5} \quad (2)$$

Soil suction profile can be defined from suction measurements at different depths during wet and dry periods. The observed wet and dry suction values usually decrease rapidly with depth (Fityus et al., 2004, Fityus et al., 1998). Mitchell (1980) assumed a "trumpet" shaped suction profile (Figure 1) to derive concept of swelling of expansive soil. Suction profile is approximated to a triangular shape in AS2870 (1996 and 2011) and recommends ΔU values for certain locations in Australia. However, higher ΔU values have been recorded in some continuous field monitoring (Fityus et al., 1998, Fityus et al., 2004). Under estimation of ΔU would lead to underestimation of y_s. Vegetation which is adjacent to the structures may affect the suction profile and hence increases the y_s. However, effect of vegetation is beyond the scope of this paper.

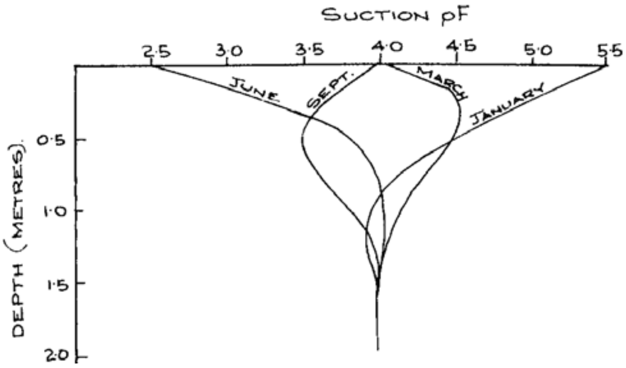

Figure 1: Theoretical suction profiles given in Mitchell (1980)

In soil physics, the soil suction is referred to as the potential energy state of water in the soil (Jury et al., 1991). Therefore, the soil suction and H_s depend on the soil moisture condition. H_s variation correlates to the climate condition in AS2870. It specifies that H_s may be estimated based on calculation of the Thornthwaite Moisture Index (TMI) for at least 25 years using the relationship given in the standard. A TMI map for Victoria is provided in AS2870 which was originally produced by Aitchison and Richards (1965). The original map was based on climatic data for the 20 year period of 1940- 1960.

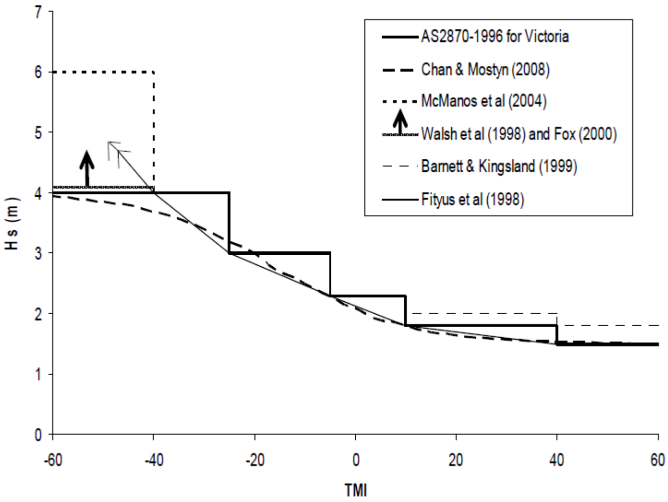

Figure 2: Relationship between Hs and TMI (Mitchell, 2008)

The climate of Victoria has been changing in particular with respect to prolonged severe droughts. The last drought was followed by a period with above average rainfall which made a significant change in the weather pattern (BoM, 2012). The influence of change in climate condition directly affects the soil moisture condition. There are several studies (Fityus et al., 1998, Walsh. et al., 1998, Barnett and Kingsland, 1999, Fox, 2000, McManus et al., 2004, Chan and Mostyn, 2008) focusing on the effect of climate on H_s, which produced different relationships of H_s and TMI. Those studies were based on field investigations of H_s and TMI calculation. Mitchell (2008) provides a summary of those studies. Figure 2 shows a graphical representation of the relationship between H_s and TMI given in Mitchell (2008). Mitchell (2008) recommends a 3.7 m – 6.0 m range for H_s in arid climate (TMI<-40) areas instead of the AS2870 (1996) provision of 4.0 m depth of H_s for arid climates. The Figure 2 indicates that the H_s increases with increasing aridity of the climate. Therefore, it is advisable to consider the corresponding effect of H_s on the y_s estimation in 2011 edition of AS2870.

4. THORNTHWAITE MOISTURE INDEX

C.W. Thornthwaite introduced a moisture index to quantify the climate variations (Thornthwaite, 1948). It consists of two indices to account for aridity, I_a and humidity, I_h. These indices are defined by soil moisture deficit (D) and surplus or run off (R) which are related to precipitation (P) and evapotranspiration (PE). Equations 3 to 5 show the definition of I_a, I_h and PE which are given in Thornthwaite (1948),

$$I_a = 100 \times \frac{D}{PE} \tag{3}$$

$$I_h = 100 \times \frac{R}{PE} \tag{4}$$

$$PE = 1.6 \times \left(\frac{10 \times t}{I}\right)^a \tag{5}$$

where ‘t’ is mean monthly temperature and ‘I’ is annual heat index which is taken as summation of monthly heat index values (i).

$$i = (0.2 \times t)^{1.514} \tag{6}$$

$$a = 6.75 \times 10^{-7} \times I^3 - 7.771 \times 10^{-5} \times I^2 + 0.01792 \times I + 0.49239 \tag{7}$$

PE shown in Equation 5 is given for 30-day month for a location having 12 hour daylight. Therefore, it needs to be multiplied by two factors which account for daylight hours for the location for a given month (f_1) and number of days per month (f_2),

$$f_1 = \frac{d}{12} \tag{8}$$

$$f_2 = \frac{N}{30} \tag{9}$$

where,‘d’ is the number of hours in a day between sunrise and sunset in a month and ‘N’ is the number of days for a particular month. Values for ‘f_1’ are tabulated in Thornthwaite (1948) for different latitudes.

I_a and I_h are correlated with a water balance approach for consecutive periods. Equation 10 gives the TMI formula introduced by Thornthwaite (1948).

$$TMI = I_h - 0.6 \times I_a \tag{10}$$

The TMI calculation has some assumptions to obtain potential evapotranspiration, actual evapotranspiration, moisture surplus and deficit. The steps of the calculation procedure are described below. More detailed description is included in Chan and Mostyn (2008) and McKeen and Johnson (1990). In 1955, the TMI formula was modified by Thornthwaite and Mather (Mather, 1974) by removing the factor of 0.6 from the aridity index. It was further modified by Mather (1974) and produced a simplified equation. Equation 11 shows the Mather’s simplified TMI equation which avoids the calculation of surplus and deficit and requires only the precipitation (P) and potential evapotranspiration (PE).

$$TMI = 100 \times \left(\frac{P}{PE} - 1\right) \tag{11}$$

Three common approaches of TMI calculation were identified which are based on different assumptions related to water balance calculation. Thornthwaite and Mather (1955) and Mather (1978) assumed that water removal from the soil becomes increasingly difficult as the soil becomes drier (when P – PE becomes negative) and soil moisture storage never becomes zero. Accordingly, Thornthwaite and Mather (1955) produced tables to calculate the soil moisture retention. In this paper this method is referred to as Method 1. An alternative approach used by several other researchers assume that when a soil becomes drier, the additional requirement for the evapotranspiration can be extracted from soil moisture storage until the soil moisture becomes zero (Fityus et al., 1998; Barnett and Kingsland, 1999; Fox, 2000; McManus et al., 2004; Chan and Mostyn, 2008; Lopes and Osman, 2010; Mitchell 2008 & 2009). This method is referred to as Method 2 in this paper. Finally, AustRoads (2004) adopted the assumption used in Method 2 but used different definition for the moisture surplus. AustRoads (2004) defines surplus as both soil moisture recharge and excess moisture over the maximum storage while Methods 1 and 2 define it as only the excess moisture over the maximum storage. The AustRoads method is referred to as Method 3.

Soil moisture storages need to be assumed in all three methods. Fityus et al. (1998) investigated the sensitivity of assumed soil moisture using two different methods of TMI calculation called 'year-by-year' analyses and 'average year' analysis. The calculation procedure of TMI using 'year-by-year' method proceeds as follows.

1. Monthly rainfall and temperature data are collected from climate records for the required 20 year period.
2. Mean monthly temperature, (t) is obtained by calculating the average of mean minimum and mean maximum temperatures for each month.
3. Monthly potential evapotranspiration, (PE) is calculated using Equation 5.
4. (P_i-PE_i) is calculated for each month, 'i'.
5. Soil moisture storage (S) is calculated using assumed initial moisture storage (S_0) and maximum soil moisture storage (S_{max}). When (P-PE) is positive and soil moisture is less than S_{max} then the positive value is added to the previous month soil moisture.
6. Change in soil moisture (ΔS) is calculated. ΔS is equal to (S_{i-1} - S_i) for month 'i'.
7. Actual Evapotranspiration, (AE) is calculated. When (P_i+ΔS) is greater than or equal to PE_i, then AE_i is equal to PE_i. Otherwise AE_i is equal to (P_i+ΔS).
8. Moisture surplus or Run off (R) is calculated. When P_i is greater than AE_i, then R is equal to (P_i-AE_i). Otherwise R is equal to zero.
9. Moisture deficit (D) is calculated and is equal to (PE_i-AE_i).
10. Annual PE, S and R values are taken as the summation of monthly calculations.
11. Annual I_h, I_a calculated based on annual PE, S and R using Equations 3 and 4.
12. TMI is calculated using Equation 10 for each year.
13. Average TMI value is taken for the considered 20 year period.

On the other hand, the calculation procedure of TMI using 'average year' method proceeds as follows.

1. Monthly rainfall and temperature data are collected from climate records for the considered 20 year period.
2. Rainfall and temperature data are averaged and arranged into single year to represent the 20 year data.
3. Calculate monthly PE, S, R for that single year. (Using step 2 to 11 described in year-by-year method) and then calculate TMI for that single year.

Fityus et al. (1998) concluded that the 'average year' analysis is more sensitive to the initial and maximum soil moisture storage values. Aitchison and Richards (1965) assumed S_{max} of 100 mm to obtain the TMI for more than 600 locations in Australia. Chan and Mostyn (2008) concluded that the S_0 depends on the climate and proposed the use of 0 mm for dry, 50 mm for temperate and 100 mm for wet conditions.

The effect of climate variation on H_s has been considered in several studies in different states (Smith, 1993; Fityus et al., 1998; Barnett and Kingsland, 1999; Fox, 2000; McManus et al., 2004; Chan and Mostyn, 2008; Lopes and Osman, 2010). Fityus et al. (1998) correlated the TMI and H_s. They used Equation 4 to obtain TMI for 38 locations and proposed detailed TMI map for the Hunter Valley area. McManus et al. (2004) produced TMI maps for Queensland, South Australia, Western Australia, New South Wales and Victoria. They created different TMI maps for 1940-1960 and 1960-1991 periods to illustrate the changes in climate zones. Their results highlighted that those areas have shown a trend of drying since 1964.

Lopes and Osman (2010) calculated TMI for certain Victorian towns for three different time periods 1948-1967, 1968-1987 and 1988-2007. Lopes and Osman (2010) used evapotranspiration data from SILO (SILO, 2011). It is based on Morton's (1983) model which uses different parameters to obtain PE and AE such as incoming and outgoing solar radiation data, vapour transfer coefficient, mean temperatures, etc. Based on the results, Lopes and Osman (2010) concluded that TMI values of those towns have changed and Aitchison and Richards (1965) TMI map is not valid for the climate condition in the period of 1988 - 2007. Furthermore, Lopes and Osman (2010) proposed H_s values corresponding to the TMI results

Table 1: Calculated TMI and AS 2870 specified values for selected towns in Victoria

Town	Climate Zone	Time period 1940-1960			Time period 1991-2011		
		Calculated		TMI values given in AS2870 (1996)	Calculated		TMI values given in AS2870 (2011)
		Average	Stdv		Average	Stdv	
Ballarat	2	37	19	10≤TMI<40	21	19	-5≤TMI<10
Bacchus Marsh	3	-4	17	-5≤TMI<10	-	-	-15≤TMI<-5
Bundoora	2	-	-	10≤TMI<40	11	19	-5≤TMI<10
Echuca	4	-15	16	-25≤TMI<-5	-	-	-25≤TMI<-15
East Sale	2	19	18	10≤TMI<40	1	16	-5≤TMI<10
Essendon	3	10	15	-5≤TMI<10	-	-	-15≤TMI<-5
Kyabram	4	-	-	-25≤TMI<-5	-14	16	-25≤TMI<-15
Laverton	3	6	13	-5≤TMI<10	-8	15	-15≤TMI<-5
Lismore	2	22	16	10≤TMI<40	-	-	-5≤TMI<10
Longerenong	4	-14	14	-25≤TMI<-5	-15	14	-25≤TMI<-15
Melbourne	2	18	14	10≤TMI<40	1	18	-5≤TMI<10
Mildura	5	-33	9	TMI<-25	-35	13	-40≤TMI<-25

for 1988 - 2007. They concluded that H_s have increased to 3.0-3.5 m for some locations in Victoria which in turn would result in about 25-30% increase in y_s.

The Victorian climate map in AS2870 is identical in the 1996 and 2011 editions. The climate zones 1-5 are the same for the Victorian cities in both maps. However, the standard changed the TMI range of each zone from 1996 to 2011. The values of each zone are reduced to accommodate the trend of drying climate in Victoria. In addition, AS2870 (2011) introduced a new climate zone (Zone 6). In 1996, AS2870 recommended H_s range of 1.5m – 2.3m for Melbourne. In 2011 edition, H_s values are increased slightly for certain locations and for Melbourne it increased to a range of 1.8m - 2.3 m.

For the study produced in this paper, variations of climate condition in certain Victorian towns have been considered. Equation 10 which was used by Aitchison and Richards (1965) was used to obtain TMI values. Resulting TMI calculations showed that the assumed value for S_0 has no significant effect on TMI when using “year-by-year” analysis for 20 year period. Therefore, S_0 and S_{max} are taken as 100 mm for all considered locations. TMI values were calculated for the period of 1940-1960 to check the compatibility of results with AS2870 (1996). New TMI values were calculated for 1991-2011 period to include the effects of the recent prolonged drought in Victoria. TMI values were calculated for more than 30 locations in Victoria. Methods 1 and 2 produced similar values and are lower than the values produced by Method 3. However, values from Method 3 are more consistent with the values given in AS2870 (1996). Hence TMI values obtained from Method 3 are compared in this paper. Table 1 compares the TMI values obtained by Method 3 and given ranges in Victorian climate zone map in AS2870 (1996 and 2011). Table 1 includes only 12 locations due to space limitation.

The TMI values in Table 1 show that the climate of selected Victorian cities has changed and those cities have lower TMI values than they had in 1960’s. Furthermore, Table 1 shows that the calculated TMI values for most of the selected locations for the period of 1991 - 2011 are within the limits specified in AS2870 (2011).

Austroads (2004) predicted the expected changes in Australian climate to the year 2100. It concluded that most of Australian cities will have dryer climatic condition in 2100 than they had in 2000. According to the prediction, current TMI values in most of Victorian cities will be reduced by 15 in 100 years. Indeed, based on the results presented in Table 1, some locations have seen a reduction in TMI value of 15 in the last 50 years. Therefore, given that TMI and subsequently H_s values are based on historical data, there should be an allowance for potential changes during the design life of the structure. It is therefore proposed to adopt a H_s value for design that is based on a probabilistic design event rather than using a single value which represent current status as opposed to future conditions.

5. CONCLUSIONS

Factors affecting the estimation of y_s in AS2870 including climate change are reviewed in this paper. AS2870 uses TMI to account for the effects of climate on footing design. TMI can be calculated using different approaches which are based on certain assumptions. Effects of the climate change since 1960 are adopted in 2011 edition of AS2870 in terms of TMI and slightly increased the H_s limits for certain locations. However, the increase introduced in AS2870 (2011) in some locations may be insufficient to cover the resulting effects on y_s during the design life of a structure.

This research is continuing which in the near future will cover extensive field monitoring and modelling to better estimate the design parameters to take into account future design events.

6. ACKNOWLEDGEMENTS

This research is funded by ARC linkage Project - LP100200306. The authors gratefully acknowledge the financial and technical support provided by the collaborating organizations, namely; Building Commission (BC), Victorian Office of Housing (OoH), Foundation and Footing Society of Victoria (FFSV), Association of Consulting Structural Engineers Victoria (ACSEV) and Housing Engineering Design and Research Association (HEDRA).

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