FOOTING DESIGN FOR RESIDENTIAL TYPE STRUCTURES IN ARID CLIMATES

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ABSTRACT

The parameters required for the design of footings on expansive (or reactive) soil by AS2870-1996 for arid regions of Australia are derived theoretically from established relationships based on experiences in the more temperate climates. Two critical parameters required for a footing design by AS 2870-1996 are the surface soil suction change (Δu_s) and the depth of the design soil suction change (H_s), and current recommendations for arid climates have a range Δu_s = 1.2pF to 1.8pF, and H_s =3.7 m to 6.0 m. Using the results of solutions of the diffusion equation, with values for the diffusion coefficient for a soil profile in an arid climate that are extrapolated from the established relationships between the Thornthwaite Moisture Index, the annual cycle of wet/dry months and H_s in the more temperate climates, it was found that for an arid climate, Δu_s =1.8pF and H_s =2.5 m. This finding was supported by a case history of a building in the Jackson oil-field, south west Queensland that had been distorted by the effects of an expansive soil profile. Three worked examples, using Δu_s =1.8pF and H_s =2.5 m for the design of a footing for a residential type building on an expansive soil in an arid area, are given.

1 INTRODUCTION

Although the hot, arid regions of Australia are thinly populated, geotechnical engineers are often required to carry out a geotechnical investigation and footing design in these regions for a residential, light industrial, commercial and institutional building. This has increased in recent years due to such aspects as increased mining activity and associated infrastructure, and increased government expenditure on aboriginal housing.

The arid regions of Australia are characterised by summers with very high day-time temperatures and hot nights, with low relative humidity day and night, and winters comprising warm to hot days and cool to cold nights (Drysdale 1975). The low rainfall is very irregular, but usually occurs as storms comprising short heavy rainfall periods which cause the ephemeral creek and river systems to flow, often leading to regional flooding.

Figure 1 (from Aitchison 1970) shows the pattern of mean annual climate throughout main-land Australia in terms of the Thornthwaite Moisture Index, abbreviated as TMI (Thornthwaite 1948). Regions of extreme aridity are characterised by a TMI of around -50 (increasing TMI is associated with increasing humidity with extreme humidity characterised by TMI > +50), and it can be seen from Figure 1 that aridity covers a vast area of central Australia. Equilibrium soil suction values (i.e. the constant soil suction at depth below the nearer surface active zone) are typically much higher in the arid regions than those in the more temperate regions, as shown in Figure 2.

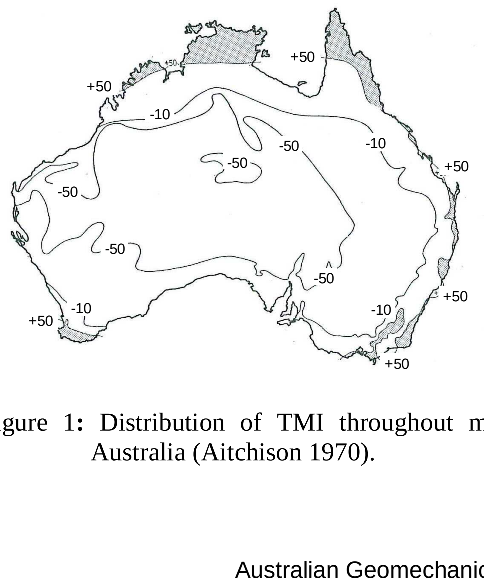


Figure 1: Distribution of TMI throughout main-land Australia (Aitchison 1970).

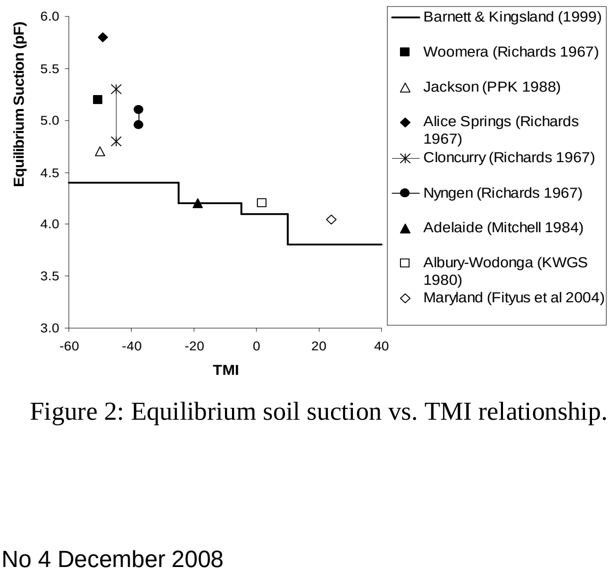


Figure 2: Equilibrium soil suction vs. TMI relationship.

Although general principles for footing design and construction in arid areas has been developed for many years (e.g. Cheney 1970), little guidance is available for geotechnical engineers when using AS 2870-1996 'Residential slabs and footings' code in the arid regions of Australia.

This paper describes the background to the procedure adopted by the author for the routine design of footings on expansive (or reactive) soils by AS2870-1996 for buildings located in arid regions of Australia (say TMI<-40), with a case history of a structure located in south west Queensland. Several worked examples of the design approach are given.

2 PREDICTION OF EXPANSIVE SOIL MOVEMENT

The conventional method of predicting expansive soil movement assumes a linear relationship between the soil vertical strain and the change in log soil suction (u) through a soil parameter, the Instability Index I_{pt}, which is taken as a soil constant. By AS 2870-1996 'Residential slabs and footings' the design change in soil suction (Δu) is taken as the difference between the characteristic dry suction and the characteristic wet suction over the depth of design suction change H_s. The characteristic surface movement (y_s) is therefore given by Equation **(1).**

$$y_s = \sum_{h=0}^{H_s} I_{pt} \Delta u \Delta h \tag{1}$$

where u = logarithm soil suction (taken as units of pF)
h = depth

The design suction change is assumed to be a triangular distribution with depth, with the maximum value of suction change occurring at the soil surface (Δu_s), and decreasing linearly with depth to h = H_s (sometimes called the 'active depth'), below which a constant soil suction occurs (the equilibrium soil suction u_{eq}), as shown in Figure 3. Two important variables are therefore Δu_s and H_s which vary according to locality and climate as defined by the TMI.

Figure 4 shows published values of Δu_s as a function of TMI. For an arid climate with TMI < -40, the recommended values for Δu_s vary from 1.2 to 1.8.

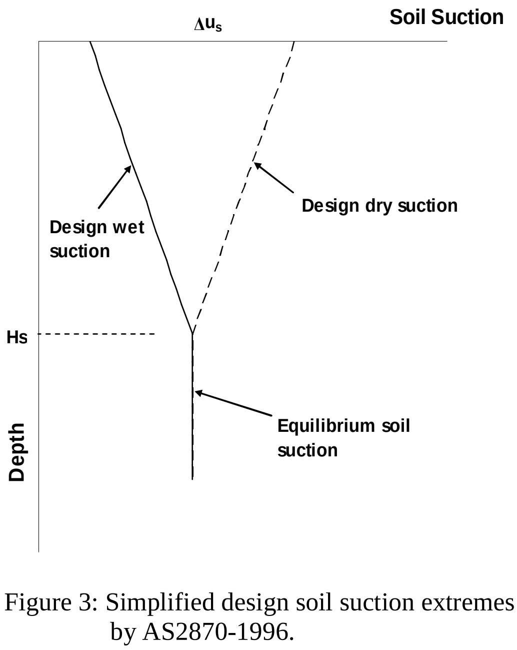


Figure 3: Simplified design soil suction extremes by AS2870-1996.

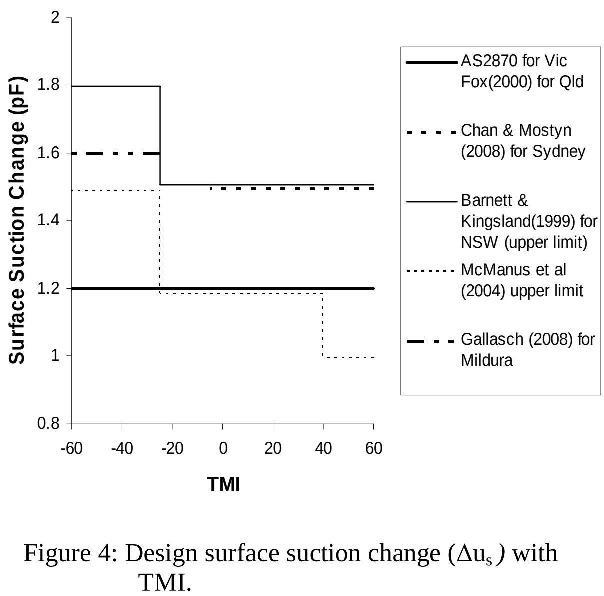


Figure 4: Design surface suction change (Δu_s) with TMI.

It is generally accepted that as the aridity of the climate increases, the depth of suction change (H_s) increases. Under extreme circumstances of very inadequate drainage, recorded depths of suction change have been as deep as about 13 m as shown in Figure 5 for a case example in South Africa (Williams 1980, Williams & Donaldson (1980). Figure 6 shows several published Australian relationships between H_s and TMI. For arid climates (TMI < -40) in Australia, the published values for H_s vary from about 3.7 m to 4.0 m, to "above 4.0 m", to a value as high as 6.0 m.

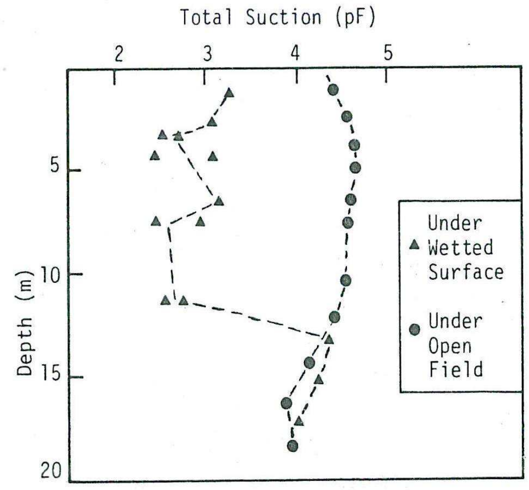


Figure 5: Deep suction changes in a fissured soil in an arid region of South Africa (Williams 1980).

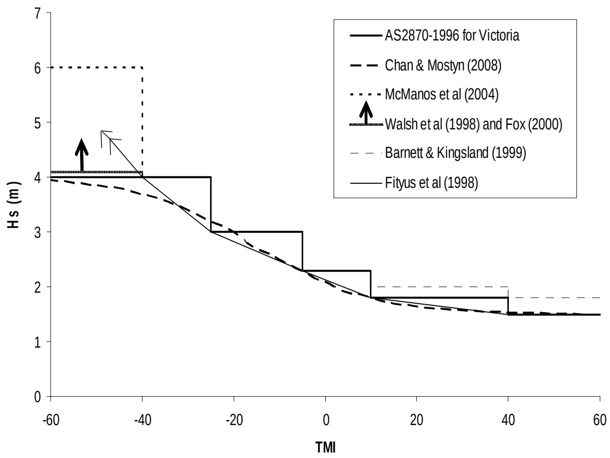


Figure 6: Relationship between H_s and TMI.

It must be recognised that little theoretical basis has been published on the derivation of the values of Δu_s and H_s in Figures 4 and 6, and this could explain the large differences in the recommended values for an arid climate. Even in more temperate climates, significant departures from the design values shown in Figures 4 and 6 have been encountered. Examples include those shown in Figure 7 for Albury-Wodonga (KWGS 1980). By AS 2870-1996 for Albury-Wodonga, Δu_s = 1.2 and H_s = 3.0 m, while the data shown in Figure 7 indicates that although H_s can be reasonably taken as 3 m, the value of Δu_s significantly exceeds 1.2. Another example (Mitchell, 1984) is shown in Figure 8 for Adelaide, where by AS 2870-1996, Δu_s = 1.2 and H_s = 4.0 m, but the data in Figure 8 indicates significant departures from these values.

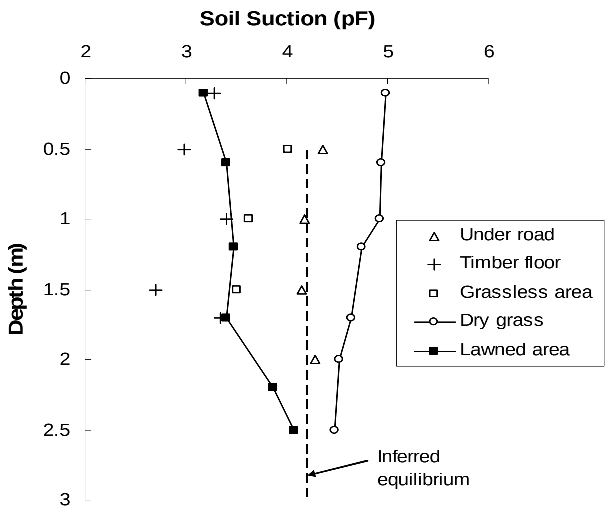


Figure 7: Measured soil suction values at Albury-Wodonga (KWGS 1980).

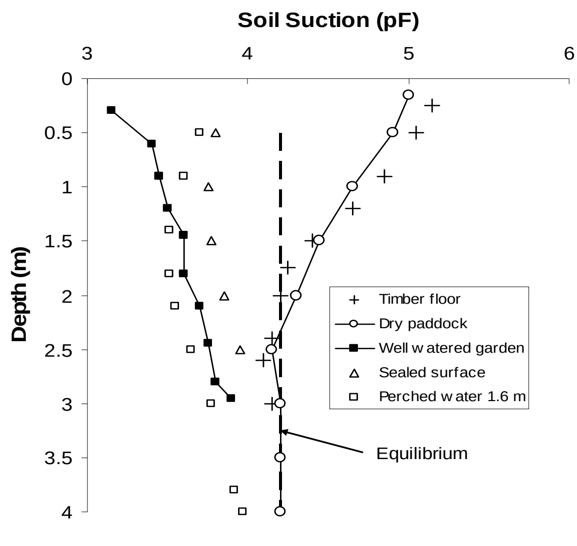


Figure 8: Measured soil suction values in Adelaide (from Mitchell 1984).

Fox (2000) used the phrase "informal correlation" when describing the relationship between TMI and H_s. Chan and Mostyn (2008) explained that although there is little published support for the values shown in Figures 4 and 6, AS 2870-1996 is a "package" where Δu_s, H_s, and other variables "combine together" to provide a reasonable estimate of y_s based on experience.

The difficulty with an empirical approach such as this is that in an area of limited experience, such as in the arid regions, uncertainties must arise when adopting the procedures of AS 2870-1996 for a footing design. An attempt to overcome these uncertainties by using a more theoretical analysis is outlined in the following sections.

3 OUTLINE OF THEORETICAL ANALYSIS

A theoretical determination of the soil suction changes at depth due to a soil suction change (Δu_s) at the soil surface can be determined from the solution of the diffusion equation (Richards 1967, Mitchell 1979, 1980, 1984, McKeen & Johnson 1990). One form of the diffusion equation is that given by Equation **(2)** after Mitchell (1979), and this equation is used in this paper to determine the appropriate value of H_s in an arid climate.

$$\frac{\partial^2 u}{\partial h^2} = \frac{1}{\alpha}\frac{\partial u}{\partial t} \qquad \textbf{(2)}$$

where u = logarithm soil suction (pF)
α = diffusion coefficient in units of $(\text{length})^2$/time
t = time
h = depth

Two main difficulties with the use of Equation (2) are the determination of appropriate values of the diffusion coefficient and the determination of the boundary conditions of the problem. However, Richards (1967) pointed out that "common sense and ingenuity on the part of the engineer can overcome [these difficulties] in most cases", and this was successfully demonstrated by McKeen & Johnson (1990) who used the diffusion equation to derive a method to determine the active depth due to seasonal surface suction changes for the United States of America.

The depth of soil suction variation H_s depends largely on the magnitude of the diffusion coefficient α, and the imposed surface suction change Δu_s with time (the boundary condition for Equation 2). The approach adopted in this paper is to use the established empirical relationships between H_s and TMI as shown in Figure 6 for more temperate climates, to derive from Equation (2) an appropriate value for the diffusion coefficient. The analysis can then be extrapolated to determine H_s for an arid climate, where the magnitude of H_s is less certain.

The determination of the appropriate surface suction (u_s) with time for the more temperate climates of Victoria is outlined in the next section.

4 RELATIONSHIP BETWEEN PERIOD OF SURFACE SUCTION CHANGES AND CLIMATE

A convenient representation of the variable seasonal wetting and drying cycles of different climates is from the monthly rainfall records and the monthly potential evapo-transpiration (Ep) values determined by the Thornthwaite (1948) method. A representation for an 'average' year in Adelaide is shown in Figure 9. When the rainfall exceeds Ep in late autumn, the soil moisture is recharged until a surplus is reached. When Ep exceeds rainfall in early spring, the soil moisture becomes depleted until a deficit occurs. The time of moisture recharge and surplus is a period of wetting, while the time of moisture depletion and deficit is a period of drying as illustrated in Figure 10.

Jewell and Mitchell (2008) related the period of wetting and drying with the observed seasonal shrinkage and swelling in Adelaide as shown in Figures 11 and 12 for measurements taken in 1978/9 (Mitchell 1984). Soil swell occurred during the wetting period and soil shrinkage occurred during the drying period of the year. The climate of a particular locality can therefore be separated into a drying period associated with high surface soil suction and soil shrinkage, and a wetting period associated with low surface soil suction and soil swell. By determining the average annual wet/dry month ratio for a locality, the cycle of average annual surface suction changes can be estimated. Constant but different surface soil suctions during the wet and dry periods are assumed in this paper.

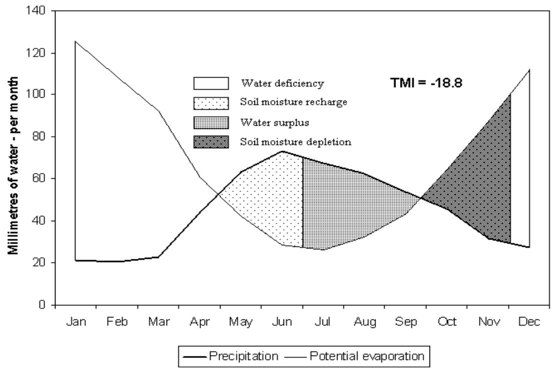


Figure 9**:** Moisture curves for average year for Adelaide

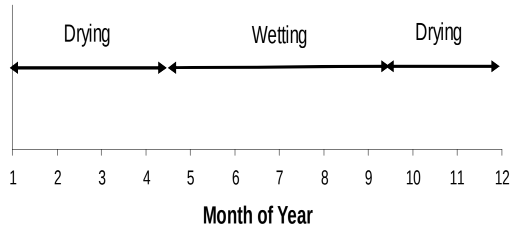


Figure 10: Drying and wetting periods based on Fig. 9

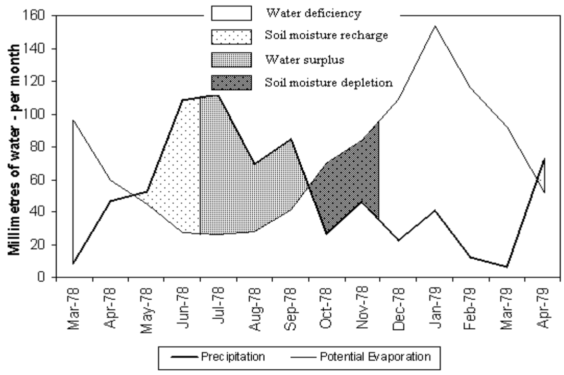


Figure 11: Moisture curves for Adelaide in 1978/1979.

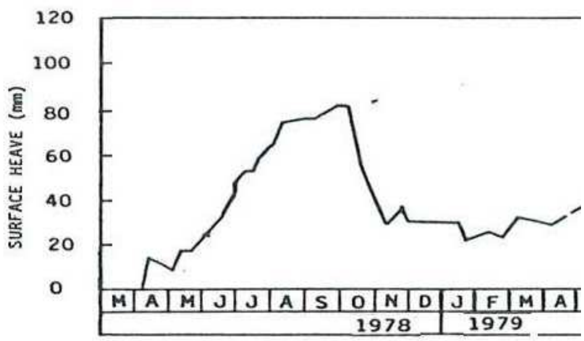
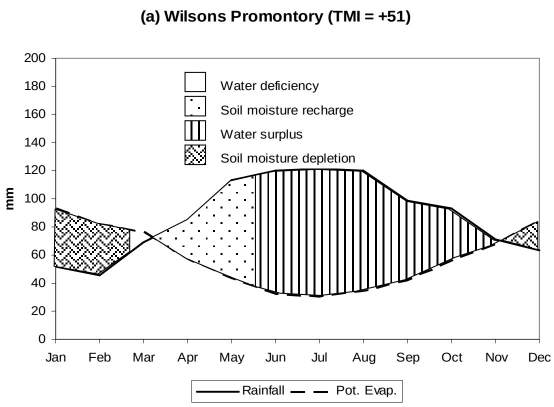
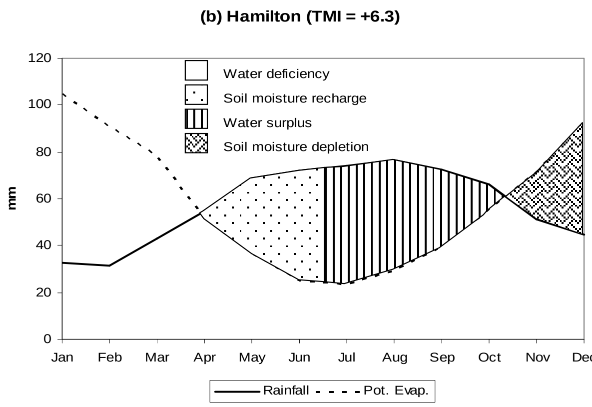


Figure 12: Seasonal movement for 1978/1979 (Mitchell 1984).

Figure 13 shows moisture curves for locations in Victoria where a relationship between H_s and TMI has been incorporated into AS 2870-1996. By AS 2870-1996, Δu_s = 1.2 for Victoria. For wet coastal Wilsons Promontory (TMI = +51), the number of wetting months is on average eight (8) per year. AS2870-1996 specifies H_s = 1.5 m for Wilsons Promontory. As the aridity of the climate increases (shown in Figure 13 as being represented by Hamilton to Horsham to Mildura), the number of wet months on average decreases, so that Mildura (TMI = -41) has on average 2½ wet months per year where AS2870-1996 specifies H_s = 4.0 m. A relationship can therefore be established between TMI, Hs and the ratio of wet/dry months of the year.





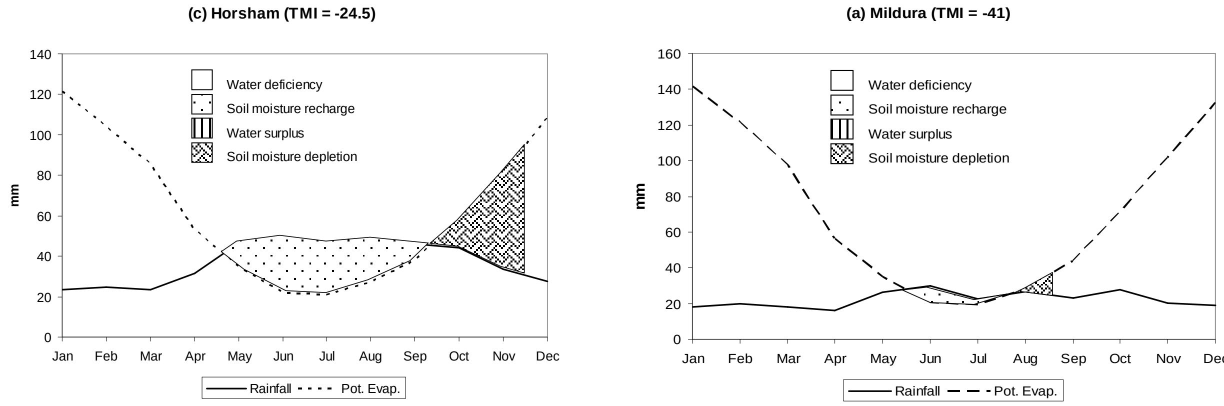


Figure 13: Moisture curves for various locations in South-East Australia.

Using Δu_s = 1.2, a relationship can also be established between TMI, u_{eq} (from Figure 2), the wet/dry month ratio, and the magnitude of wet and dry soil suction at the soil surface. For example, for Hamilton TMI = +6.3, the wet/dry month ratio = 7/5 from Figure 13(b), $u_{eq} \approx 4.1$ from Figure 2, so the surface suction ranges from 3.6 to 4.8, since Δu_s = 1.2 and u_{eq} = [(7 x 3.6)+(5x4.8)]/12 = 4.1. Table 1 summarises the relationship between locality, H_s, the values of wet and dry surface soil suction, and wet/dry times for five sites in Victoria, ranging from wet coastal to semi-arid.

Table 1: Relationships between TMI, H_s, Δu_s and wet/dry months ratio used for analysis of diffusion equation

Climate Zone	**Representative Location**	**TMI**	**H_s by AS2870**	**Δu_s (pF) (wet to dry)**	**u_{eq} (pF)**	**Wet /Dry months ratio**
Wet coastal	Wilsons Promontory	+51	1.5 m	3.7 to 4.9	4.1	8/4
Wet temperate	Hamilton	+6.3	1.8 m	3.6 to 4.8	4.1	7/5
Temperate	Albury	+1.7	2.3 m to 3.0m	3.6 to 4.8	4.2	6/6
Dry temperate	Horsham	-24.5	3.0 m	3.5 to 4.7	4.2	5/7
Semi-arid	Mildura	-41	4.0 m	3.55 to 4.75	4.5	2½/9½

The values shown in columns 5, 6 and 7 in Table 1 can be adopted as the boundary conditions for the Diffusion Equation **(2)** to determine soil suction changes with depth, so that a value of diffusion coefficient can be determined to match the values of H_s given in column 4 of Table 1. This is outlined in the next section.

5 ANALYSIS FOR VALUE OF DIFFUSION COEFFICIENT

The solution of the Diffusion Equation **(2)** is obtained in this paper using the numerical method (Kreyszig, 2006) as described in Appendix A. To illustrate the process to determine the diffusion coefficient (α), consider the moisture curves for Albury Airport (TMI = 1.7) shown in Figure 14(a). The ratio of wet/dry months is 6/6. By Figure 2, $u_{eq} \approx 4.2$, and AS 2870-1996 gives Δu_s = 1.2 for Albury so that the dry surface suction = 4.8, and the wet surface suction is 3.6 since [(6x4.8)+(6x3.6)]/12 = 4.2. These values are shown in Table 1. Assuming a constant but different surface suction during the wet and dry periods, Figure 14(b) shows the idealised surface suction changes [u(o,t) in Appendix A] as the required boundary condition for the solution of the Diffusion Equation **(2).**

Figure 15 shows the solution of the Diffusion Equation **(2)** for the surface suction changes of Figure 14(b) for a value of diffusion coefficient α = 0.0004 cm^2/sec. Figure 15 indicates theoretical suction changes to a depth of 2.3 m to 3.0 m. AS 2870-1996 indicates Albury is at a boundary of H_s = 2.3 m to 3.0 m so that α = 0.0004 cm^2/sec for the diffusion coefficient is appropriate for Albury Airport.

The above process was repeated for Wilsons Promontory, Hamilton, Horsham and Mildura using the boundary conditions for each locality shown in Table 1. For each case, the value of diffusion coefficient (α) was found so that the theoretical H_s matched the AS 2870-1996 value of H_s for the locality. The process is summarised in Appendix B.

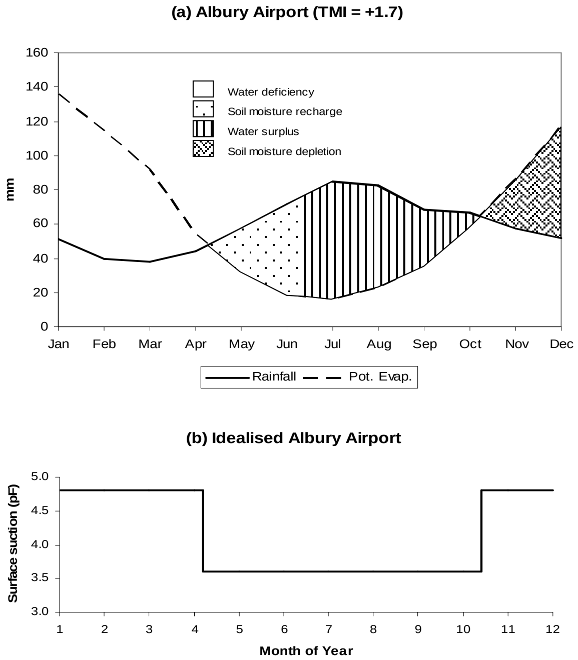


Figure 14(a): Moisture curves for Albury Airport, and 14(b) Idealised surface suction changes for Albury Airport

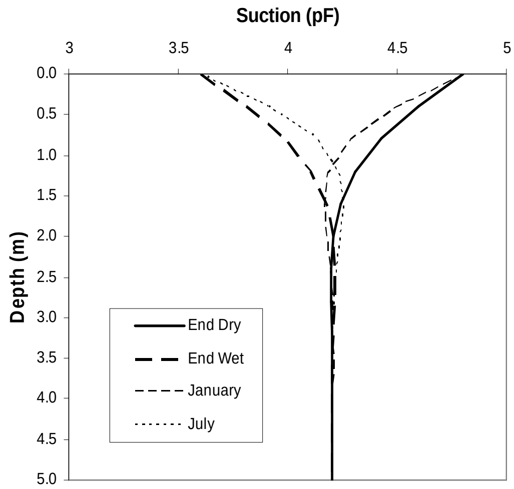


Figure 15: Calculated soil suction changes with depth for surface suction changes in Figure 14(b) for $\alpha = 0.0004$ cm^2/sec.

Figure 16 shows the results of the analysis for the diffusion coefficient (α) as a function of the TMI for each site. It can be seen that the diffusion coefficient (α) increases with aridity. This would be expected as the degree of cracking and fissures in the soil profile increases with increasing aridity, thus increasing the permeability of the soil profile, so that the diffusion coefficient would also increase.

From Figure 16, extrapolating to an arid climate (represented as TMI = -50), the diffusion coefficient will be about 0.004 cm^2/sec. This value is used in the Diffusion Equation (2) to determine the expected value of H_s for an arid area, as explained in the next section.

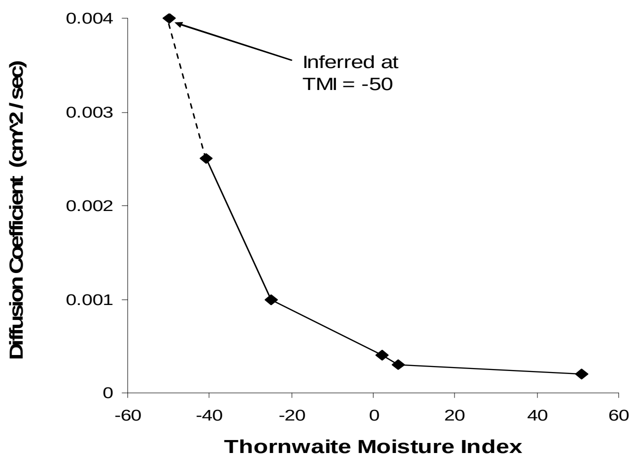


Figure 16: Relationship between diffusion coefficient and TMI.

6 ANALYSIS FOR DEPTH OF SOIL SUCTION CHANGE IN ARID AREAS

Figure 17 shows the moisture curves for Woomera (TMI = -48.5) based on long-term monthly averages, and these moisture curves are typical of an arid climate. It can be seen that the potential evapotranspiration exceeds the rainfall, so that there is always a deficit. However using average monthly records of rainfall in arid regions of Australia is misleading because rainfall occurs on a very irregular basis, and is associated with intense rain periods in short periods of time, as shown for example by the June 2001 rainfall record for Woomera in Figure 18.

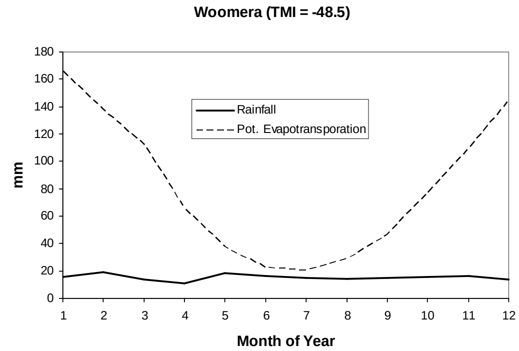


Figure 17: Moisture curves for Woomera based on average monthly rainfall and temperature.

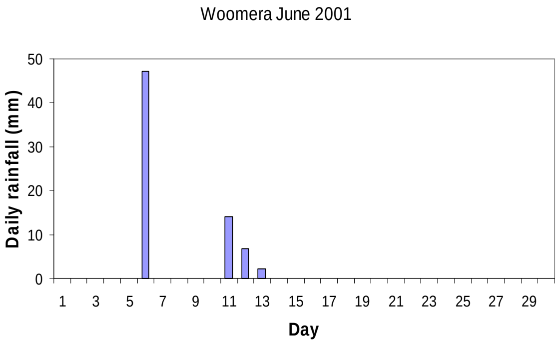


Figure 18: Rainfall record for Woomera June 2001.

By Figure 18, an appropriate wet/dry month ratio for an arid climate is therefore 0.5/11.5. For an arid region, Figure 4 indicates an appropriate value of $\Delta u_s = 1.8$ is consistent with the measured values of Barnett & Kingsland (1999), and this value is adopted here. By Figure 2, $u_{eq} \approx 4.9$, so that the dry surface suction = 5.0, and the wet surface suction is 3.2 since $[(11.5x5.0)+(0.5x3.2)]/12 \approx 4.9$. Figure 19 shows the idealised surface suction changes [u(o,t) in Appendix A] as the surface boundary condition for the solution of the Diffusion Equation **(2).**

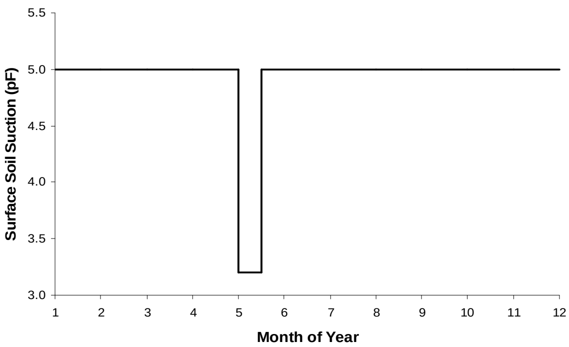


Figure 19: Idealised surface suction changes for an arid area based on $\Delta u_s = 1.8$.

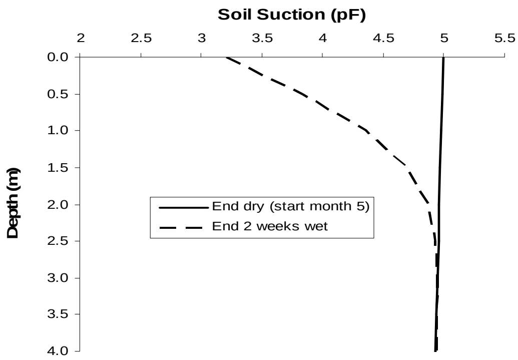


Figure 20: Suction changes with depth for surface changes in Figure 19 for $\alpha = 0.004$ cm^2/sec.

Using the surface boundary condition shown in Figure 19, and the determined $\alpha = 0.004$ cm^2/sec for the diffusion coefficient from Figure 16, the Diffusion Equation can be solved to obtain the appropriate value of H_s for an arid climate. The results of the analysis are shown in Figure 20. The variation of soil suction occurs to a depth of about 2.5 m.

The analysis has therefore predicted that the appropriate design parameters for an arid climate are $\Delta u_s = 1.8$ and $H_s = 2.5$ m. Confirmation of this prediction is given by the case history in the next section.

7 CASE HISTORY

A single storey steel frame building with light clad walls (Figure 21) was constructed on a dry site at the Jackson oilfield in south-west Queensland in 1983. The building was founded on a 110 mm unstiffened slab-on-ground, with a discontinuous perimeter 'rat-wall' in accordance with the then Queensland building regulations. The building had perimeter concrete paving. The soil profile is shown in Figure 22, and consisted of expansive soil layers to the 4 m depth investigated. A few years after construction, the slab suffered a significant edge heave (concave bending) mode of distortion, and coring through the slab indicated that a gap or 'lift-off' existed between the bottom of the slab and the soil, the extent of which is shown in Figure 23.

Figure 21: Jackson Oilfield building.

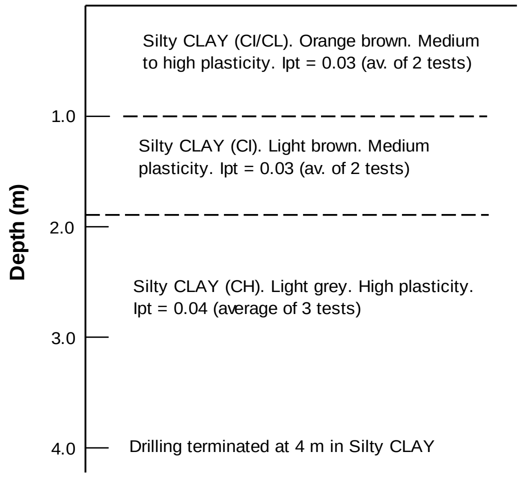


Figure 22: Soil profile for Jackson building.

Considering the measured differential movement across the slab and the thickness of the sub-floor gap, the differential edge heave soil movement with respect to the centre of the building was estimated to be 60 mm to 130 mm. This was consistent with the differential soil movement determined from $\sum I_{pt}\, \Delta u\, \Delta h$ where I_{pt} was measured by the core shrinkage method (now incorporated in AS 1289-7.1.3) and Δu from soil suction measurements on recovered samples by a psychrometer (now incorporated in AS 1289-2.2.1) shown in Figure 24.

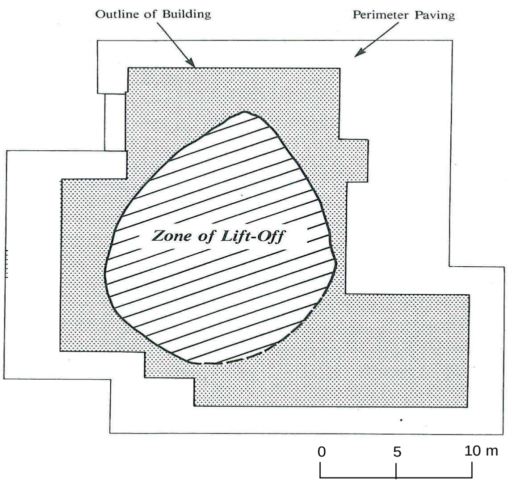


Figure 23: Observed extent of edge heave for Jackson building.

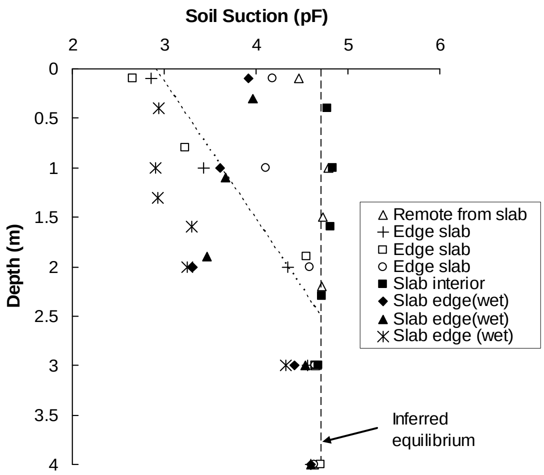


Figure 24: Measured soil suction values for Jackson building.

There were considerable drainage deficiencies at the site that contributed to the severity of the distortion. These included the perimeter paving having a reverse fall which channelled stormwater directly to the footing edge, spoon drains at the paving edge were ineffective and in fact caused runoff to collect at several locations, and discharge of stormwater occurred into open expansion joints in the perimeter paving at many locations. Therefore the subsoil around the building was subjected to a much more extreme change in soil suction than if adequate drainage measures were maintained. The locations of these drainage deficiencies coincided with the boreholes indicating much lower soil suctions than other locations and are shown as ‘slab edge (wet)’ in Figure 24.

The distortion was rectified by improvements to the disposal of stormwater around the building, and slowly injecting water into the soil under the interior of the slab (through the cored holes previously cut to investigate the extent of the void under the slab) to cause the soil under the slab to heave, thus reducing the severity of the edge heave. The building has now been performing satisfactorily for two decades.

The results of soil suction measurements from eight boreholes drilled around, under and remote from the building shown in Figure 24 indicated that soil suctions in boreholes located remote from the building and under the slab were high, consistent with an arid environment. Boreholes adjacent to the slab edge gave much lower soil suctions, consistent with a wetting up at the slab edge. If the results of the low soil suctions in boreholes marked ‘slab edge (wet)’ in Figure 24 are excluded because these were caused by drainage deficiencies which could have been prevented at the time of construction, then the results shown in Figure 24 can be modelled as a triangular distribution with Δu_s = 1.8, and H_s = 2.5 m.

The case history of the building at the Jackson oilfield in south-west Queensland indicates justification for the use of the design parameters Δu_s = 1.8 and H_s = 2.5 m for the design of footings in arid areas. The application of these findings in the design of footings in an arid area is outlined in the next section.

8 SUMMARY OF DESIGN METHOD FOR ARID AREAS

The method of analysis for the design of a footing in an arid area is the author’s method described in AS 2870-1996 Section 4 ‘Design by engineering principles’ and Appendix F ‘Soil parameters and footing design methods’.

The value of y_s is determined from Equation (1) and Figure 3, using H_s = 2.5 m, Δu_s = 1.8 and the determined I_{pt} for each soil layer in the soil profile. The depth of cracking is taken as 2.5 m. By AS 2870-1996 section F4(a), the differential mound movement (y_m) is taken as $y_m = 0.7y_s$.

The footing analysis is based on a soil-structure interaction analysis using the computer program SLOG (Mitchell 1988a, 1988b). In the analysis, the mound exponent (m) is given by AS 2870-1996 Equation F4(3) and is shown as Equation **(3)**

$$m = 1.5L/(D_{cr} - D_e) \quad \textbf{(3)}$$

In Equation (3), D_e is the depth of embedment of the edge beam from the finished ground level, and D_{cr} is given by Equation **(4).**

$$D_{cr} = \frac{H_s}{7} + y_m/25 \quad \textbf{(4)}$$

For the particular structure, the maximum design differential movement (Δ) is determined from AS 2870-1996 Table 4.1. The edge loads (W), central line loads (T) and uniformly distributed loads (w) are determined. The concrete Young’s Modulus (E_c) is taken as 15000 MPa by AS 2870-1996 section 4.4(e), and the mound stiffness is taken as k = 1000 kPa/m by AS 2870-1996 section F4(g). Concrete of grade N20 is conventionally used.

9 WORKED EXAMPLES

The following worked examples illustrate the application of the design approach.

Example 1 – Building at Olympic Dam

Design a footing for a symmetrical single storey articulated masonry structure, 16 m square with sheeting roof and conventional roof frame for the soil profile shown in Figure 25 at Olympic Dam, South Australia.

For Δu_s =1.8 and H_s = 2.5 m for the soil profile in Figure 25, at the change in soil type at depths of 0.3 m, 1.5 m, and 2.0 m, Δu = 1.58, 0.72 and 0.36 respectively.

From Equation **(1),** y_s = 0 + [0.035 x ½(1.58+0.72) x 1200]+[0.03 x ½(0.72+0.36) x 500] +[0.02 x ½(0.36) x 500] = 58.2 mm, use y_s = 60 mm

By AS2870 F4(a), $y_m = 0.7y_s$ = 42 mm.

Try sub-beam depth 700 mm. For 100 mm slab and 200 mm underfloor sand fill, D_e = (0.7 - 0.3) = 0.4 m.

From Equation **(4),** D_{cr} = (2.5/7)+(42/25) = 2.04 m.

From Equation **(3)**, m = (1.5x16)/(2.04-0.4) = 14.6
The structural loads can be determined to be as follows:

$W_W = W_E = W_N = W_S = 16.1$ kN/m, $T_{NS} = T_{EW} = 8$ kN/m, w = 5.5 kPa.

By AS2870 4.4(d) use E_c = 15000 MPa, and by AS2870 F4(c) use k = 1000 kPa/m.
The geometry is L = B =16 m, $n_L = n_B = 5$ beams.
By AS 2870 Table 4.1 for articulated masonry, Δ = L/800 = 20 mm > 15 mm, i.e. use 15 mm.
For this input, Program SLOG gives M_{CH} = 172kNm/beam, required EI_{CH} = 251 MNm^2/beam.

M_{EH} = 7 kNm/beam, required EI_{EH} = 3 MNm^2/beam.

For these bending moments and stiffnesses, sub-beams 300 mm wide x 700 mm deep, reinforced with 3-N16 bars top and bottom, W8 ligatures at 1000 mm spacing, cast integrally with a 100 mm floor slab reinforced with SL82 fabric top face with 20 MPa concrete, will meet requirements. The footing layout comprises 5 sub-beams in each direction. The specification for construction will include details of the building articulation, the drainage requirements and the provision of flexible plumbing for a soil movement of ±60 mm.

Example 2 – Building at Woomera

Design a footing for a single storey articulated masonry veneer structure, 8 m x 16 m (Figure 27) with sheeting roof and prefabricated roof frame spanning in the short direction, for the soil profile shown in Figure 26 located at Woomera South,, South Australia.

For Δu_s =1.8 and H_s = 2.5 m for the soil profile in Figure 26, at the change in soil type at depths of 0.4 m, 1.0 m, 1.6 m and 2.1 m, Δu = 1.51, 1.08, 0.65 and 0.29 respectively.

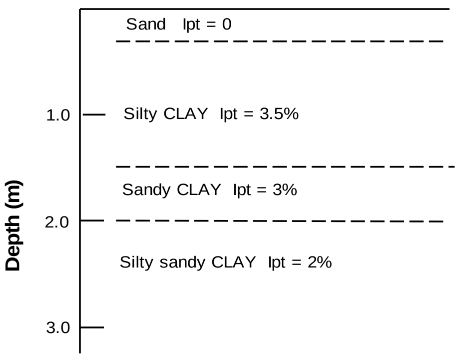


Figure 25: Soil Profile for Example 1.

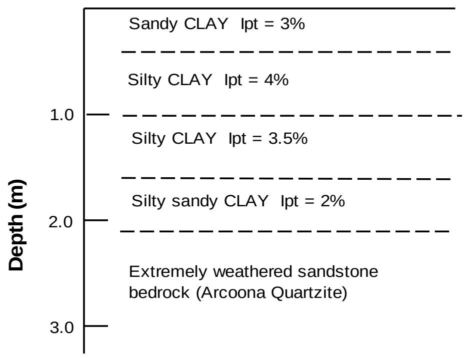


Figure 26**:** Soil Profile for Example 2.

From Equation (1), y_s = [0.03 x ½(1.8+1.51) x 400]+[0.04 x ½(1.51+1.08) x 600] +[0.035 x ½(1.08+0.65) x 600]+[0.02x½(0.65+0.29)x500] = 73.8 mm, use y_s = 75 mm

$y_m = 0.7y_s$ = 52.5mm.

Try sub-beam depth 450 mm. For 100 mm slab , 200 mm underfloor sand fill, D_e = (0.45 - 0.3) = 0.15 m.
From Equation (4), D_{cr} = (2.5/7)+(52.5/25) = 2.46 m.
The structural loads for the building can be determined to be

$W_W = W_E = 8.3$ kN/m, $W_N = W_S = 9.2$ kN/m, $T_{NS} = T_{EW} = 0$, w = 4.6 kPa;

By AS2870 4.4(d) use E_c = 15000 MPa, and by AS2870 F4(c) use k = 1000 kPa/m
In the long direction in Figure 27,

L = 16 m, B = 8 m, n_L = 3 beams, n_B = 5 beams,

From Equation **(3),** m = (1.5x16)/(2.46-0.15) = 10.4

By AS 2870 Table 4.1 for articulated veneer, Δ = L/400 = 40 mm>30 mm, i.e use 30 mm.

Program SLOG gives M_{CH} = 61 kNm/beam, required EI_{CH} = 19.7 MNm^2/beam,

M_{EH} = 14 kNm/beam, required EI_{EH} = 2.7 MNm^2/beam,

In the short direction Figure 27,

L = 8 m, B = 16 m, n_L = 5 beams, n_B = 3 beams, Δ = L/400 = 20 mm, i.e. use 20 mm.

From Equation **(3),** m = (1.5x8)/(2.46-0.15) = 5.19

Program SLOG gives M_{CH} = 112 kNm/beam, required EI_{CH} = 30.6 MNm^2/beam,

M_{EH} = 15 kNm/beam, required EI_{EH} = 3.2 MNm^2/beam, For these bending moments and stiffnesses, a sub-beam 300 mm wide x 450 mm deep, reinforced with 3-N12 bars top and bottom, W6 ligatures at 1000 mm spacing, cast integrally with a 100 mm floor slab reinforced with SL72 fabric top face and 20 MPa concrete will meet the design requirements. The footing layout comprises 3 sub-beams in the long direction and 5 sub-beams in the short direction.

The specification for construction will include details of the structure articulation, the drainage requirements and the provision of flexible plumbing catering for a soil movement of ±75 mm.

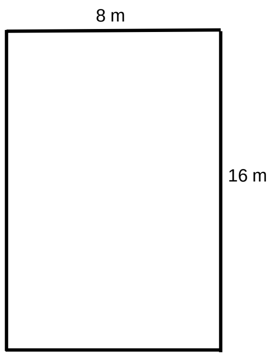


Figure 27: Geometry of Example 2.

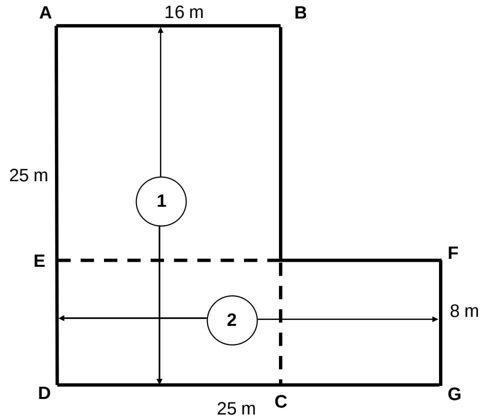


Figure 28: Geometry for Example 3.

Example 3 – Building at Jackson Oil Field

Design an appropriate footing for the Jackson oilfield building in Section 7, assuming that adequate drainage provisions are installed.

For Δu_s =1.8 and H_s = 2.5 m for the soil profile in Figure 22, Δu = 0.43 at the change in I_{pt} at 1.9 m depth.
From Equation **(1),** y_s = [0.03 x ½(1.8+0.43) x 1900]+[0.04 x ½(0.43) x 600] = 68.7 mm, use y_s = 70 mm
$y_m = 0.7y_s$ = 49 mm.
For the complex layout of the building as shown in Figure 23, take two overlapping rectangles for the single storey clad frame structure as shown in Figure 28 (ABCD defines Rectangle 1, and DEFG defines Rectangle 2).
Try sub-beam depth 300 mm. For 100 mm slab, 200 mm underfloor sand fill, D_e = (0.3 - 0.3) = 0.
From Equation **(4),** D_{cr} = (2.5/7)+(49/25) = 2.32 m.
The structural loads can be determined to be

Rectangle 1: $W_W = W_E$ = 3.1 kN/m, $W_N = W_S$ = 5.2 kN/m, $T_{NS} = T_{EW}$ = 0, w = 4.3 kPa;
Rectangle 2: $W_W = W_E$ = 3.1 kN/m, $W_N = W_S$ = 4.0 kN/m, $T_{NS} = T_{EW}$ = 0, w = 4.3 kPa.

By AS2870 4.4(d) use E_c = 15000 MPa, and by AS2870 F4(c) use k = 1000 kPa/m
For Rectangle 1 in the long direction,

L = 25 m, B = 16 m, n_L = 5 beams, n_B = 7 beams,
From Equation **(3),** m = (1.5x25)/(2.32-0) = 16.2
By AS 2870 Table 4.1 for clad frame, Δ = L/300 = 83 mm > 40 mm, i.e use 40 mm.
Program SLOG gives M_{CH} = 25 kNm/beam, required EI_{CH} = 3.2 MNm^2/beam,
M_{EH} = 26 kNm/beam, required EI_{EH} = 3.2 MNm^2/beam,

For Rectangle 1 in the short direction,

L =16 m, B =25 m, n_L = 7 beams, n_B = 5 beams, Δ = L/300 = 53 mm, i.e. use 40 mm.
From Equation **(3),** m = (1.5x16)/(2.32-0) = 10.3
Program SLOG gives M_{CH} = 32 kNm/beam, required EI_{CH} = 3.6 MNm^2/beam.
M_{EH} = 22 kNm/beam, required EI_{EH} = 3.6 MNm^2/beam.

For Rectangle 2: In the long direction,

L = 25 m, B = 8 m, n_L = 3 beams, n_B = 7 beams,
Δ = L/300 = 83 mm > 40 mm, i.e use 40 mm.
From Equation **(3),** m = (1.5x25)/(2.32-0) = 16.2
Program SLOG gives M_{CH} = 21 kNm/beam, required EI_{CH} = 2.7 MNm^2/beam.

M_{EH} = 21 kNm/beam, required EI_{EH} = 2.7 MNm^2/beam.

For Rectangle 2: In the short direction,

L = 8 m, B = 25 m, n_L = 7 beams, n_B = 3 beams,
Δ = L/300 = 26.6 mm, i.e. use 26.6 mm.
From Equation **(3),** m = (1.5x8)/(2.32-0) = 5.2
Program SLOG gives M_{CH} = 46 kNm/beam, required EI_{CH} = 9.8 MNm^2/beam.
M_{EH} = 22 kNm/beam, required EI_{EH} = 3.6 MNm^2/beam.

For these bending moments and stiffnesses, a sub-beam 300 mm wide x 300 mm deep, reinforced with 2-N12 bars top and bottom, W6 ligatures at 1000 mm spacing, cast integrally with a 100 mm floor slab reinforced with SL72 fabric top face and concrete 20 MPa will meet the design requirements. The footing layout comprises 5 sub-beams in the long direction and 7 sub-beams in the short direction for Rectangle 1, and 3 sub-beams in the long direction and 7 sub-beams in the short direction for Rectangle 2, with extra tie-beams to cater for the re-entrant corners in the actual complex layout shown in Figure 23. The specification for construction will include details of drainage requirements and the provision of flexible plumbing to cater for a soil movement of ±70 mm.

10 CONCLUSIONS

The parameters (Δu_s and H_s) required for the design of footings on expansive (or reactive) soil by AS2870-1996 for arid regions of Australia (TMI < -40) are derived theoretically from established relationships based on experiences in the more temperate climates. Current recommendations for arid climates have a range Δu_s = 1.2pF to 1.8pF, and H_s =3.7 m to 6.0 m.

The relationships between the Thornthwaite Moisture Index, the average annual cycle of wet/dry months, the magnitude of wet and dry surface soil suction values, and H_s, were determined for several locations in the more temperate climates of Victoria. These enabled the diffusion equation to be solved to obtain the relationship between TMI and the diffusion coefficient.

Solving the diffusion equation using a value for the diffusion coefficient for a soil profile in an arid climate that was extrapolated from the determined relationship between the TMI and diffusion coefficient for the more temperate climates, it was found that for an arid climate, Δu_s =1.8pF and H_s =2.5 m.

This finding was supported by a case history of a building in the Jackson oil-field, south west Queensland that had been distorted by the effects of an expansive soil profile. Three worked examples, using Δu_s =1.8pF and H_s =2.5 m for the design of a footing for a residential type building on an expansive soil in an arid area, are given.

11 ACKOWLEDGEMENTS

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12 NOTATION

B	Breadth of rectangular building footprint
D_e	Depth of embedment of the footing edge beam from finished ground level
D_{cr}	Critical depth of soil suction by Equation (4) used to determine the mound exponent in Equation (3)
E_c	Young's modulus of concrete
E_p	Potential Evapo-transpiration by Thornthwaite (1948) method
EI_{CH}	Stiffness of footing in centre heave
EI_{EH}	Stiffness of footing in edge heave
H_s	Depth of design soil suction change
h	Depth
I_{pt}	Instability Index (ratio of vertical strain to change in log suction)
k	Mound stiffness

L	Length of rectangular building footprint
M_{CH}	Bending moment in centre heave
M_{EH}	Bending moment in edge heave
m	Mound exponent by Equation (3)
n_L	Number of sub-beams in the direction of L
n_B	Number of sub-beams in the direction of B
T	Central line loads in building (eg T_{NS} represents line load in north-south direction of rectangular building footprint etc)
TMI	Thornthwaite Moisture Index
t	Time
u	Logarithm of soil suction in measurements of pF (Δu = change in soil suction in pF)
u(h,t)	Soil suction in pF as a function of depth and time
u_s	Surface soil suction in pF (Δu_s = change in surface soil suction in pF)
u_{eq}	Equilibrium soil suction in pF
W	Building edge loads including footing self weight (eg W_N represents edge load on northern side of rectangular building footprint etc)
w	Uniformly distributed load over building footprint, excluding W and T
y_s	Characteristic surface movement by Equation (1)
α	Diffusion coefficient in Equation (2)
Δ	Maximum design differential movement by AS 2870-1996 Table 4.1

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APPENDIX A: NUMERICAL SOLUTION OF THE DIFFUSION EQUATION

The Diffusion Equation (Equation **A1**) can be solved analytically as given by Mitchell (1979, 1980, 1984). The numerical method of solution used in this paper follows the 'explicit method' described by Kreyszig (2006) for the solution of the heat equation.

$$\frac{\partial^2 u}{\partial h^2} = \frac{1}{\alpha}\frac{\partial u}{\partial t} \qquad \textbf{(A1)}$$

Writing Equation (A1) in finite difference form, with *I* being the number of the depth increment (Δh) and *J* being the number of the time step (Δt) in Figure A1, then rearranging Equation A1 gives Equation A2.

$$u_{I,J+1} = (1 - \frac{2\alpha\Delta t}{(\Delta h)^2})u_{I,J} + \frac{\alpha\Delta t}{(\Delta h)^2}(u_{I+1,J} + u_{I-1,J}) \qquad \textbf{(A2)}$$

The boundary conditions are shown in Figure A2. The suction changes at the soil surface are defined, i.e. u(0,t) is known. In this paper, u(o,t) takes the form shown in Figure 14(b), with the magnitudes and durations of dry and wet surface soil suctions, and the magnitude of u_{eq}, varying with climate by Table 1.

By making a sensible initial estimate for u(h,0), i.e. the soil suction profile at t = 0, convergence to a solution of Equation A2 occurs provided $\alpha\Delta t/(\Delta h)^2 \leq 0.5$, i.e. when the coefficient of u_{IJ} in Equation A2 is positive.

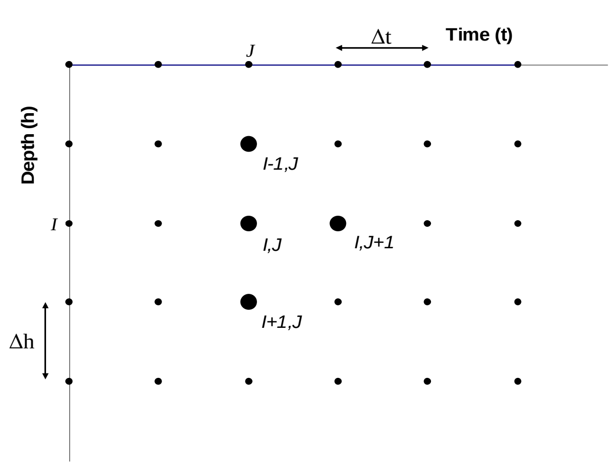


Figure A1: Grid and mesh points for Equation A2.

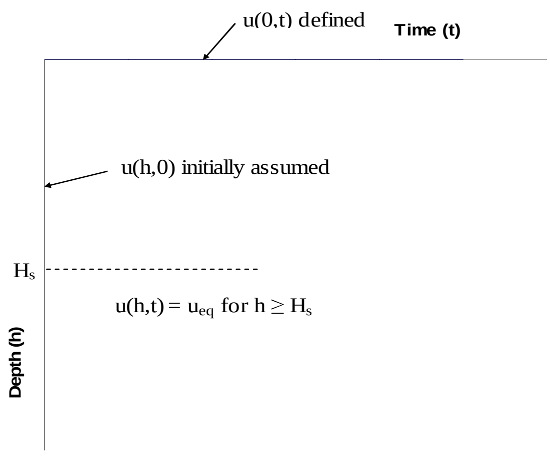


Figure A2: Boundary conditions for Equation A1.

APPENDIX B: DETERMINATION OF DIFFUSION COEFFICIENT FOR VICTORIAN SITES

The following outlines the determination of the value of the diffusion coefficient (α) so that the calculated H_s for Wilsons Promontory, Hamilton, Horsham and Mildura matched the AS 2870-1996 value of H_s for the locality.

The moisture curves for Wilsons Promontory (TMI = +51) are shown in Figure B1(a). The ratio of wet/dry months is 8/4. By Figure 2, $u_{eq} \approx 4.1$, and AS 2870-1996 gives $\Delta u_s = 1.2$ for Wilsons Promontory so that the dry surface suction = 4.9, and the wet surface suction = 3.7 since [(4x4.9)+(8x3.7)]/12 = 4.1. Figure B1(b) shows the idealised surface suction changes [u(o,t) in Appendix A] for the solution of the Diffusion Equation (2). Figure B2 shows the solution of the Diffusion Equation **(2)** for the surface suction changes of Figure B1(b) for a value of diffusion coefficient $\alpha = 0.0002$ cm^2/sec. Figure B2 indicates soil suction changes to about 1.5 m. AS 2870-1996 specifies $H_s = 1.5$ m for Wilsons Promontory, so that $\alpha = 0.0002$ cm^2/sec for the diffusion coefficient is appropriate for Wilsons Promontory.

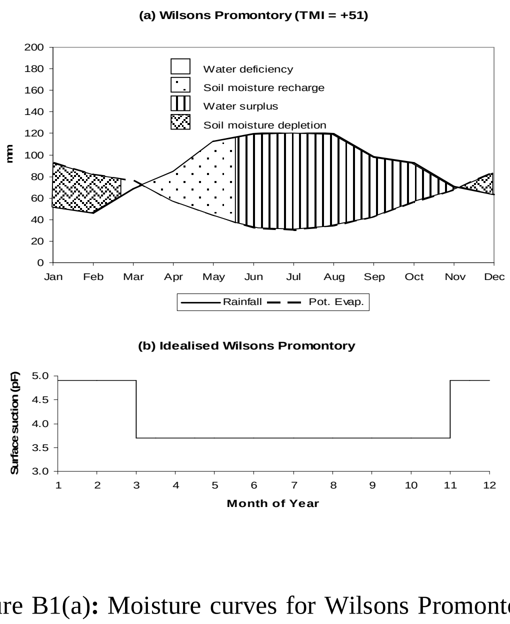


Figure B1(a)**:** Moisture curves for Wilsons Promontory: and B1(b) Idealised surface suction changes for Wilsons Promontory

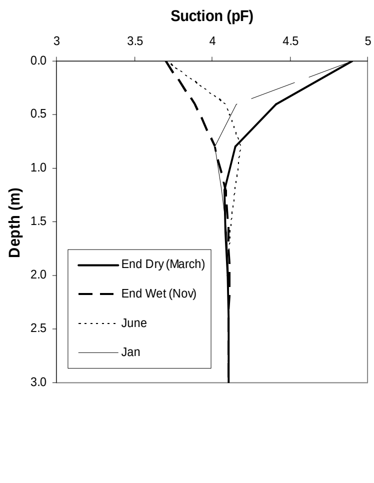
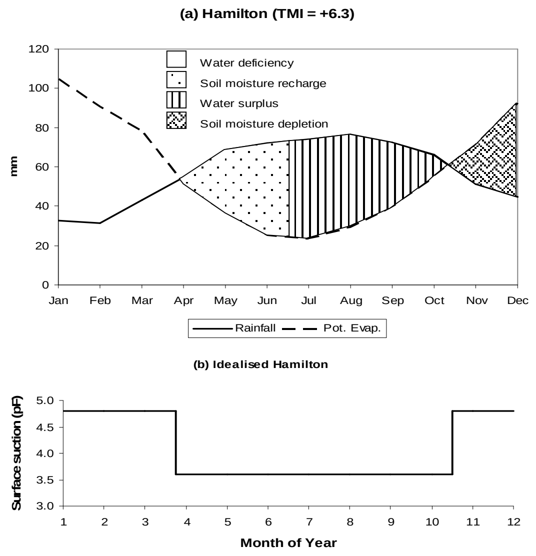


Figure B2: Calculated soil suction changes with depth for surface suction changes in Figure B1(b) for $\alpha = 0.0002$ cm^2/sec.



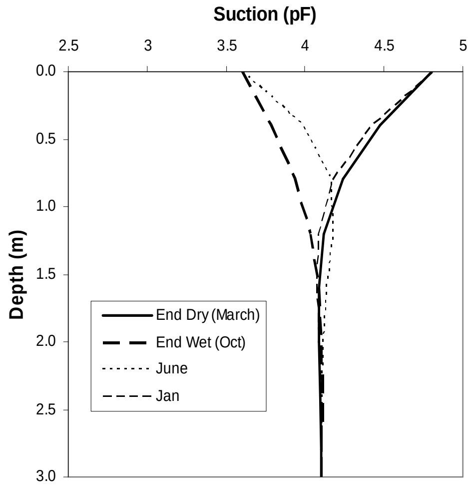
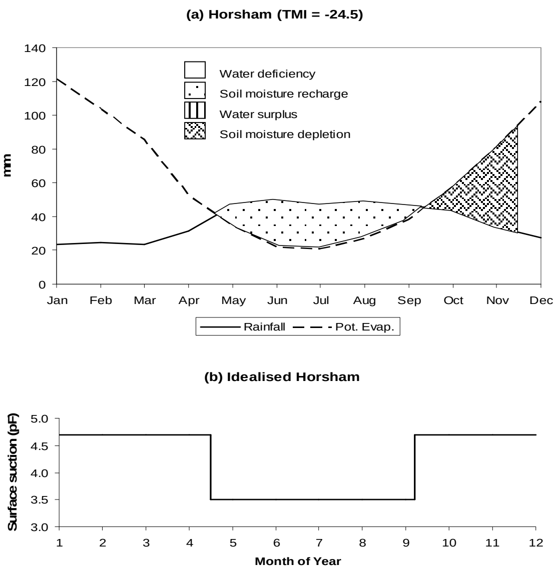


Figure B3(a)**:** Moisture curves for Hamilton, and **B3**(b) Idealised surface suction changes for Hamilton.

Figure B4**:** Calculated soil suction changes with depth for surface suction changes in Figure B3(b) for α = 0.0003 cm^2/sec.

The moisture curves for Hamilton (TMI = +6.3) are shown in Figure B3(a). The ratio of wet/dry months is 7/5. By Figure 2, $u_{eq} \approx 4.1$, and AS 2870-1996 gives $\Delta u_s = 1.2$ for Hamilton so that the dry surface suction = 4.8, and the wet surface suction = 3.6 since [(5x4.8)+(7x3.6)]/12 = 4.1. Figure B3(b) shows the idealised surface suction changes [u(o,t) in Appendix A] for the solution of the Diffusion Equation (2). Figure B4 shows the solution of the Diffusion Equation **(2)** for the surface suction changes of Figure B3(b) for a value of diffusion coefficient α = 0.0003 cm^2/sec. Figure B4 indicates suction changes to about 1.8 m. AS 2870-1996 specifies H_s = 1.8 m for Hamilton, so that α = 0.0003 cm^2/sec for the diffusion coefficient is appropriate for Hamilton.



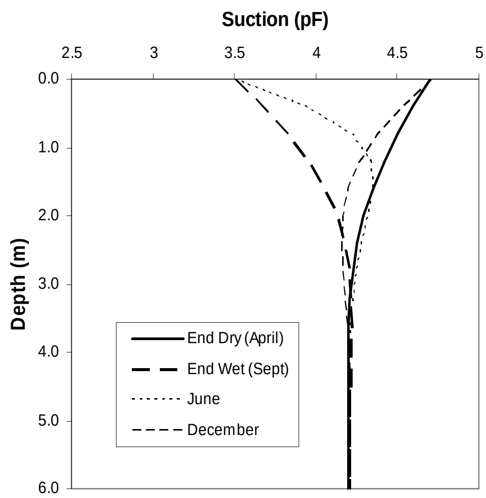


Figure B5(a)**:** Moisture curves for Horsham: and **B5**(b) Idealised surface suction changes for Horsham.

Figure B6: Calculated soil suction changes with depth for surface suction changes in Figure B5(b) for α = 0.0010 cm^2/sec.

The moisture curves for Horsham (TMI = -24.5) are shown in Figure B5(a). The ratio of wet/dry months is 5/7. By Figure 2, $u_{eq} \approx 4.2$, and AS 2870-1996 gives $\Delta u_s = 1.2$ for Horsham so that the dry surface suction = 4.7, and the wet surface suction = 3.5 since [(7x4.7)+(5x3.5)]/12 = 4.2. Figure B5(b) shows the idealised surface suction changes [u(o,t) in Appendix A] for the solution of the Diffusion Equation **(2).** Figure B6 shows the solution of the Diffusion Equation **(2)** for the surface suction changes of Figure B5(b) for a value of diffusion coefficient $\alpha = 0.001$ cm^2/sec. Figure B6 indicates suction changes to about 3.0 m. AS 2870-1996 specifies $H_s = 3.0$ m for Horsham, so that $\alpha = 0.001$ cm^2/sec for the diffusion coefficient is appropriate for Horsham.

The moisture curves for Mildura (TMI = -41) are shown in Figure B7(a). The ratio of wet/dry months is 2½/9½. By Figure 2, $u_{eq} \approx 4.5$, and AS 2870-1996 gives $\Delta u_s = 1.2$ for Mildura so that the dry surface suction = 4.75, and the wet surface suction = 3.55 since [(9.5x4.75)+(2.5x3.55)]/12 = 4.5. Figure B7(b) shows the idealised surface suction changes [u(o,t) in Appendix A] for the solution of the Diffusion Equation **(2).** Figure B8 shows the solution of the Diffusion Equation **(2)** for the surface suction changes of Figure B7(b) for a value of diffusion coefficient $\alpha = 0.0025$ cm^2/sec. Figure B8 indicates suction changes to about 4.0 m. AS 2870-1996 specifies $H_s = 4.0$ m for Mildura, so that $\alpha = 0.0025$ cm^2/sec for the diffusion coefficient is appropriate for Mildura.

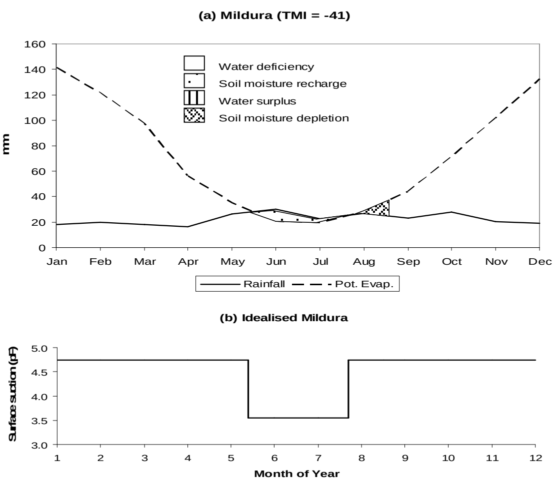


Figure B7(a) Moisture curves for Mildura, and Figure **B7**(b): Idealised surface suction changes for Mildura.

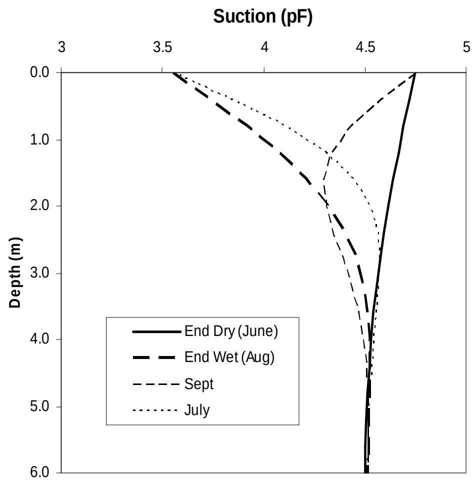


Figure B8: Calculated soil suction changes with depth for surface suction changes in Figure B7(b) for $\alpha = 0.0025$ cm^2/sec.

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