Degree of Saturation of the Keswick Clay Within the Adelaide City Area Above the General Groundwater Table

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SUMMARY The available data on in-situ bulk density and moisture content, and the specific gravity of solids of the Keswick Clay within the Adelaide city area are examined. It is shown that for clay samples located at depths above the general water table the degree of saturation is typically greater than 95%, whereas these soils have been previously treated as unsaturated, and as a consequence, the in-situ effective stresses equated to the total stresses.

The paper also presents an evaluation of the sensitivity of the degree of saturation to the average value of specific gravity of the clay particles, using estimates from laboratory measurements and those based on crystal structure and mineral composition.

1. INTRODUCTION

Traditionally, the degree of saturation, S_r, is obtained from the measured moisture content, ω, and dry density, ρ_d, tabulated values of the density of water, ρ_w (usually assumed constant at 1000 kg/m^3) and the value of the specific gravity of the solids, G_s via the relationship shown in Equation (1), below.

$$S_r = \frac{\omega\, G_s\, \rho_d}{(G_s\, \rho_w) - \rho_d} \qquad (1)$$

For a soil mass, G_s varies over a small range; typically 2.60 to 2.80.

In coarse grained, and inert fine grained soils, the moisture in the voids has no influence on the size of the particles. In expansive clays, however, the size of the particles, and hence the volume of the soil mass, is dependent on its moisture content. For example, the clay mineral montmorillonite can increase its thickness many times due to the influence of moisture. The swelling nature of these clays makes it very difficult to perform accurate laboratory tests to determine G_s.

It has been recognised that the expansive clays found in the Adelaide city area exist with little or no air voids over a wide range of moisture contents.

This paper highlights the importance of the assumed value G_s on the computed S_r, and shows that when dealing with expansive clays, sensitivity analyses are a practical means of estimating S_r. In addition to this, a method is suggested for evaluating G_s based on the proportions of clay minerals present in the soil mass.

2. KESWICK CLAY WITHIN THE ADELAIDE CITY AREA

This paper, and its companion paper, Kaggwa and Jaksa (1992), will focus on a region of the city of Adelaide, described previously by others (eg. Cox, 1970 and Selby and Lindsay, 1982) as the *Adelaide city area*, which contains the central business district of Adelaide, as well as the suburb of North Adelaide.

The majority of this Adelaide city area, and a significant portion of the metropolitan area of Adelaide, is underlain by very expansive clays known as the Keswick and Hindmarsh clays. Until recently, the Keswick and Hindmarsh Clays were grouped into the one formation, namely the Hindmarsh Clay. This formation consisted of: an *upper clay layer* of high plasticity and extreme reactivity, (USC classification CH) which can be described as a heavily fissured, very stiff to hard, grey-green mottled clay; a *middle sand member*, a grey and brown dense, clayey coarse sand; and a *lower clay layer* similar in appearance and behaviour to the more recent upper clay layer. The formation is thought to have been deposited in the Pleistocene and is typically 10 to 25 metres in total thickness.

Sheard and Bowman (1987a,b) found that a disconformity exists between the upper clay layer and the underlying middle sand member. As a result, Sheard and Bowman renamed the upper clay layer; the *Keswick Clay*, and the middle sand member and the lower clay layer; the *Hindmarsh Clay.* The middle sand member marker bed is absent in some parts of the Adelaide city area and here the boundary between the Keswick and Hindmarsh Clays is difficult to establish. Figure 1 shows the distribution of these clays in the vicinity of the city of Adelaide.

Within the Adelaide city Area, the groundwater table generally occurs between 20 and 30 metres below the ground surface in the *Hallett Cove Sandstone*; a permeable formation which immediately underlies the Hindmarsh Clay. A perched water table has been encountered sporadically within the upper three metres of the Keswick Clay, and is thought to be due to drainage troughs associated with the formation of gilgai (Selby and Lindsay, 1982). Occasionally, a perched water table has been encountered in the sand member of the Hindmarsh Clay, but tends to affect only the upper few centimetres of the underlying clay (lower clay layer).

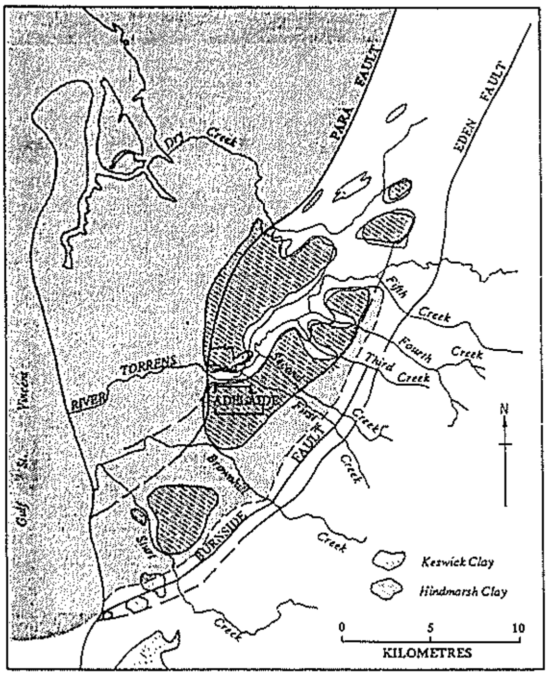


Figure 1. Distribution of the Keswick and Hindmarsh Clays in the Vicinity of the City of Adelaide.

A large data base of geotechnical properties of the Keswick and Hindmarsh Clays has been compiled by the authors from a number of consulting engineering firms and government institutions. These data included the majority of site investigations within the Adelaide city area, approximately 160 in all, since the mid 1960's. This paper makes use of this data base to investigate the degree of saturation of the Keswick Clay.

2.1 Review of Published Data

In his detailed and significant paper, Cox (1970) compiled geotechnical properties of the Keswick and Hindmarsh Clays from 20 site investigations within the Adelaide city area. He compared the properties of these clays, the Keswick Clay in particular, to the well known London Clay and found striking similarities between them. Among the many properties that Cox investigated, he presented a relationship between the dry density, ρ_d, of the Keswick Clay and its moisture content, ω. A unique relationship between ρ_d and ω can be obtained by assuming a constant specific gravity of solids, G_s. Cox's relationship, together with the results of experimentally determined values of ρ_d and ω, are reproduced in Figure 2. Cox assumed a constant value for G_s of 2.70, which was the mean of three laboratory tests carried out on samples of Keswick Clay. The results of these tests, however, were not published. As can be seen from Figure 2, the majority of test results lie between the 95% and 100% degree of saturation lines. He suggested that the 0% to 5% air which was measured could be attributed to air entering the fissure system during sampling and testing. Cox calculated that, for a fissure spacing of 25 mm, the fissures need open only 0.0025 mm to give a degree of saturation of 95%. Similar calculations carried out by the authors, suggest a fissure opening of 0.25 mm.

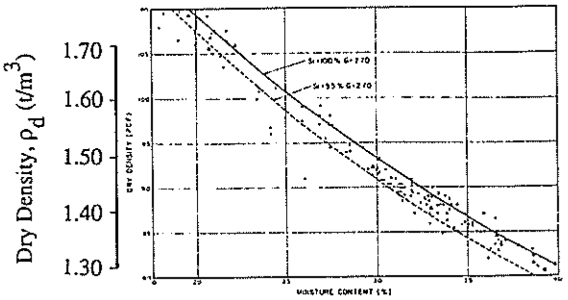


Figure 2. Relationship between Moisture Content, Dry Density and Degree of Saturation for Keswick Clay (after Cox, 1970)

3. SUMMARY OF IN-SITU DRY DENSITY AND MOISTURE CONTENT

Figure 3 shows the variations of the moisture content, ω, and dry density, ρ_d, of the Keswick Clay with depth below ground surface of 451 separate test results from the compiled data base. As is clearly evident, there appears to be no correlation between either of these measured quantities and depth.

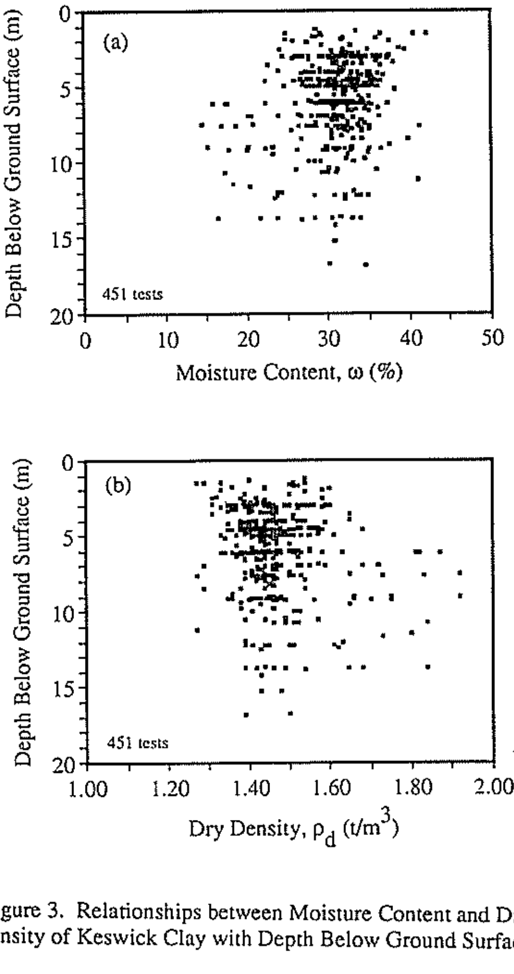


Figure 3. Relationships between Moisture Content and Dry Density of Keswick Clay with Depth Below Ground Surface.

The relationship between the measured values of dry density and moisture content is shown in Figure 4. Superimposed on this graph are the 80%, 90% and 100% degree of saturation lines based on a G_s of 2.70 as quoted by Cox(1970). As can be seen from Figure 4, there is a strong correlation to a constant degree of saturation. Many of the test results, however, plot above the 100% saturation line which is physically not possible. Two reasons are suggested for this. Firstly, the test results, obtained from many different testing laboratories, may not have been accurately determined. Secondly, and more likely, the specific gravity of solids, G_s, as published by Cox may be lower than the *true* mean of the soil particles. These two postulations will be treated in turn.

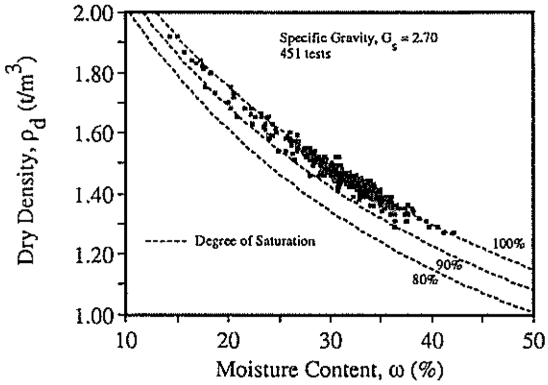


Figure 4. Relationship between ω, ρ_d and S_r for Keswick Clay for G_s = 2.70

4. SENSITIVITY OF S_r TO THE REPORTED ρ_d AND ω

It is possible to determine whether the accuracy of the laboratory tests contribute to the variation in S_r by comparing the reported test results to those determined by assuming S_r = 100% and substituting into Equation (1). Figure 5 shows the relationship between the reported moisture content, ω, and that evaluated by expression (1) and using S_r = 100%, G_s = 2.70 and the reported ρ_d. Figure 6 shows a similar relationship between the reported dry density, ρ_d, and that derived by assuming S_r = 100%. Superimposed on both of these figures is the line where the reported value equals that obtained by assuming saturation. The spread of results about these lines suggests that it is unlikely that the reported test results greatly contribute to the calculated S_r. As a result, it is likely that the G_s suggested by Cox(1970) is lower than the *true* mean G_s of the Keswick Clay. The sensitivity of G_s on the degree of saturation of the Keswick Clay will be treated in the following section.

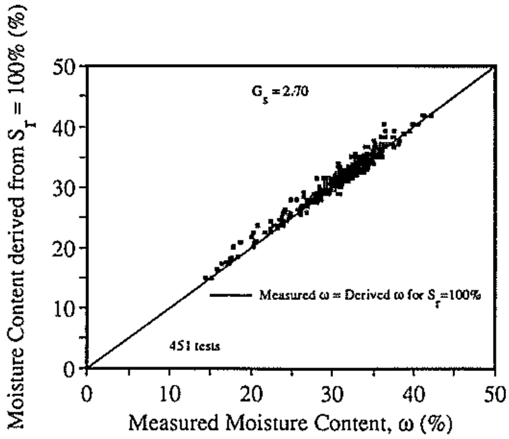


Figure 5. Relationship between Reported Moisture Content and the Moisture Content Calculated assuming Saturation.

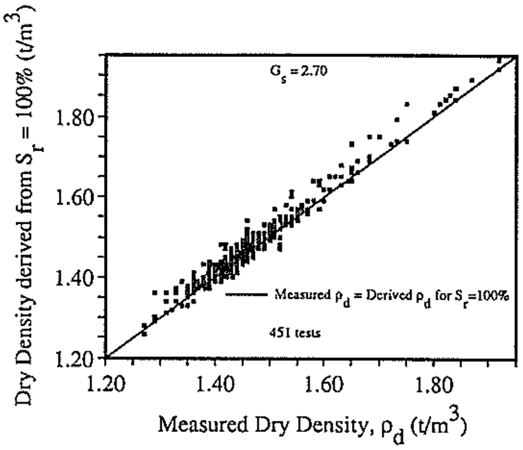
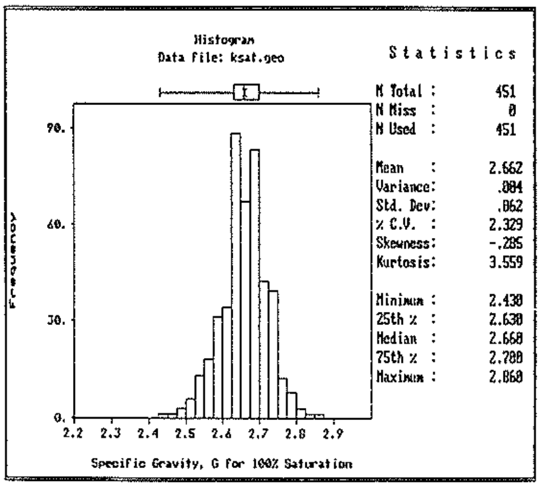


Figure 6. Relationship between Reported Dry Density and the Dry Density Calculated assuming Saturation.

5. SENSITIVITY OF S_r TO THE ASSUMED VALUE OF G_s

One could postulate, as Cox(1970) inferred, that the bulk of the Keswick Clay within the Adelaide city area is saturated. Should this be the case, the value of G_s can be back-calculated, from the expression (1), using the measured quantities of ρ_d and ω and setting S_r = 100%. Figure 7 presents the histogram and statistical parameters of the back-calculated values of G_s. The variation in G_s is due mainly to



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Statistics

N Total :      451
N Miss  :        0
N Used  :      451

Mean    :    2.662
Variance:     .004
Std. Dev:     .062
% C.V.  :    2.329
Skewness:    -.285
Kurtosis:    3.559

Minimum :    2.430
25th %  :    2.630
Median  :    2.660
75th %  :    2.700
Maximum :    2.860
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Figure 7. Histogram of Back-Calculated G_s of Keswick Clay assuming Saturation.

the fact that it is unlikely that all of the Keswick Clay is saturated and hence by assuming S_r = 100% the back-calculated G_s is under-estimating its *true* value. Secondly, while the Keswick Clay is relatively homogeneous throughout the Adelaide city area, there are regions where the clay becomes quite sandy, especially in the vicinity of the Hindmarsh Clay sand member and in the proximity of the River Torrens. This natural variability would also contribute to the variation of G_s.

Whilst this back-calculation of G_s for S_r = 100% is a useful technique for estimating the likely ranges of G_s, this procedure does not provide a true average of the specific gravity because of the likelihood that some of the Keswick Clay is not completely saturated.

One would expect, that due to the influence of variations in seasonal moisture ingress and egress caused by transpiration, rainfall, irrigation and evaporation, the degree of saturation for depths less than 3 to 5 metres below the ground surface to be less than 100%, and below this, to tend toward 100%. Figure 8 shows the variation of S_r with depth below the ground surface. It appears, from this figure, that no such conclusion can be drawn. Thus the use of a single value of G_s to represent the entire Keswick Clay is misleading. Since the Keswick Clay does not exhibit free moisture it is classified as being *quasi-saturated.*

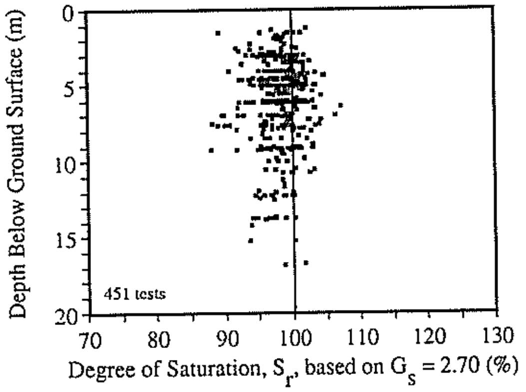

Figure 8. Relationship between Degree of Saturation for Keswick Clay and Depth Below Ground Surface.

Table I presents the results of a sensitivity analysis based on varying the assumed value of G_s from 2.70 to 2.80 so as to reduce the number of test results that have a calculated degree of saturation greater than 100% for the 451 test results obtained from the data base. The degree of saturation was evaluated using Equation (1). While an assumed G_s of 2.80 gives only two results with an S_r greater than 100%, it is unlikely that the mean value of G_s for Keswick Clay would be as high as this. Values of 2.73 - 2.77, on the other hand, give credible degrees of saturation. Figures 9, 10 and 11 show the relationship between ρ_d and ω with degree of saturation lines based on assumed values of G_s of 2.73, 2.75 and 2.77, respectively. These assumed values of G_s provide sensible degrees of saturation for the laboratory tested samples.

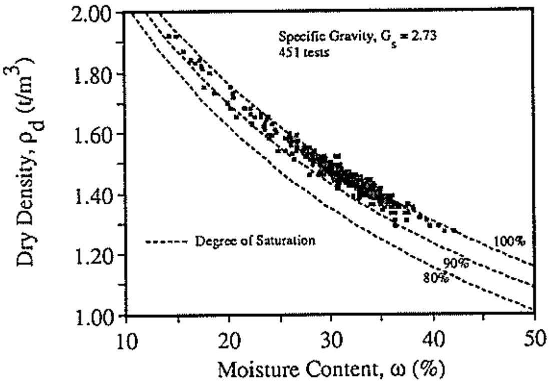

Figure 9. Relationship between ω, ρ_d and S_r for Keswick Clay for G_s = 2.73

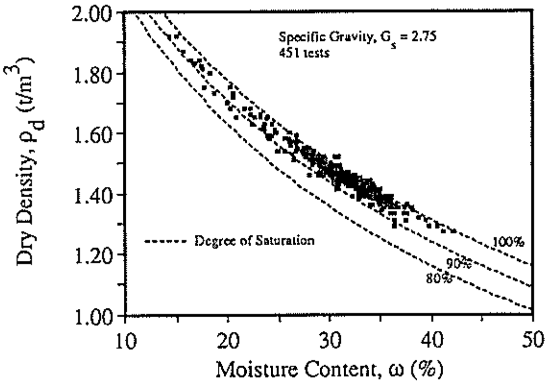

Figure 10. Relationship between ω, ρ_d and S_r for Keswick Clay for G_s = 2.75

TABLE I. RESULTS OF SENSITIVITY ANALYSIS OF DEGREE OF SATURATION FOR VARIOUS G_s

Specific Gravity, G_s	No. of values where S_r >100%	Mean (%)	Standard Deviation (%)	Minimum S_r (%)	Maximum S_r (%)
2.70	64 of 451 (14%)	98.24	2.84	88.83	107.12
2.73	25 of 451 (6%)	96.96	2.84	86.29	105.63
2.75	**13 of 451 (3%)**	**96.15**	**2.84**	**85.18**	**104.67**
2.77	6 of 451 (1%)	95.35	2.84	84.11	103.74
2.80	2 of 451 (0.5%)	94.59	2.84	83.10	102.85

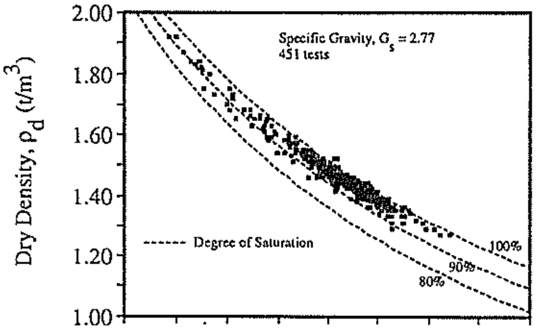

Figure 11. Relationship between ω, ρ_d and S_r for Keswick Clay for $G_s = 2.77$

6. ESTIMATION OF G_s BASED ON MINERALOGY OF CLAY PARTICLES

Few laboratory tests have been carried out to determine the G_s of the Keswick Clay. In the extensive data compilation carried out by the authors no such test results were found. It is likely that this is due to the fact the G_s published by Cox(1970) has been universally accepted throughout the geotechnical community in South Australia.

As discussed previously, it is difficult to determine the specific gravity of solids of a reactive clay. Table II shows the wide range of specific gravities of solids of reactive clay minerals as reported by a number of sources.

A more appropriate technique for estimating G_s is to use the mineralogy of the soil mass. Lambe and Whitman(1969) published a set of specific gravities of clay minerals based on theoretical calculations of the clay crystal structure. These are shown in Table II.

Cox reported that x-ray diffraction tests performed on the Keswick Clay from one site investigation within the Adelaide city area, found that the clay contained "greater than 50% illite, greater than 20% kaolinite, and generally less than 20% montmorillonite". These were found to be in similar proportions to that of the London Clay.

It is proposed, that to estimate G_s of a reactive clay, the following expression be adopted:

$$G_s^* = \sum_{i=1}^{n} p_i \, (G_s)_i \qquad (2)$$

where:

G_s^* is the average specific gravity of solids based on the mineralogy of the soil mass,

p_i is the proportion of the ith mineral present in the soil mass,

$(G_s)_i$ is the specific gravity of solids of the ith mineral, calculated from the crystal structure, and

n is the number of significant mineral types present in the soil mass.

Performing this calculation based on the proportions detailed above and the specific gravities shown in Table II, the estimated G_s is between 2.74 and 2.77, which compares well with the results obtained from the sensitivity analyses presented earlier.

7. IMPLICATIONS FOR ANALYSES

Keswick Clay is essentially saturated and hence effective stresses will differ from total stresses. High total suctions have been measured within the Keswick Clay, and as a result, effective stresses should be based on negative pore pressures and total stresses. Hence the calculated coefficient of earth pressure at rest, K_o, will be much lower than currently used. The evaluation of effective stresses and K_o is treated in detail in the companion paper Kaggwa and Jaksa (1992).

8. CONCLUSIONS

A large number of laboratory test results of dry density, ρ_d and moisture content, ω, have been examined, and their relationship presented. It has been found that the majority of the Keswick Clay is saturated or very close to being saturated.

The value of the specific gravity of solids, G_s, of the Keswick Clay has been re-examined. Using sensitivity analyses and statistical procedures, it is suggested that a more appropriate value of the mean of G_s for the Keswick Clay is 2.75 ± 0.02. This more precise evaluation of G_s will enable errors associated with geotechnical design, and their inherent probability of failure, to be reduced.

A technique for estimating the G_s of reactive clays, based on their mineralogical composition, has been proposed which provides a practical alternative to carrying out often difficult laboratory testing.

TABLE II. PUBLISHED SPECIFIC GRAVITIES OF CLAY MINERALS

	Specific Gravities, G_s				
Clay Mineral	Lambe & Whitman Crystal Structure	Lambe & Whitman Measured	Mitchell Measured	Sowers Measured	Bowles Measured
Illite	**2.84**	2.60 - 2.86	2.6 - 3.0	2.2 - 2.6	2.60
Kaolinite	**2.61**	2.62 - 2.66	2.60 - 2.68	2.2 - 2.6	2.60 - 2.63
Montmorillonite	**2.74**	2.75 - 2.78	2.35 - 2.7	2.2 - 2.6	2.40

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