Collapse potential and strength of calcareous clay soils

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ABSTRACT

Collapsible soils are very strong in the dry state but undergo a loss of their strength upon wetting. The bond between particles is reduced by water, leading to collapse of loose soils, particularly when loaded. Calcium carbonate is known to be a bonding agent in sands and in loess soils (Gao 1983). In this paper, the role of calcium carbonate is presented on the loss of strength and, ultimately, the collapse of clay soils. Calcareous soil samples from Adelaide were obtained, but it was found that the carbonate contents varied spatially over short distances. Some samples exhibited swell rather than collapse. The degrees of collapse varied from moderately severe to severe. Consequently artificial soils were produced with kaolinite and calcium carbonate to investigate the influence of carbonate content. Tests on samples of calcium carbonate showed that it had a base friction angle unaffected by wetting, however, the cohesion was lost with inundation. Oedometer tests conducted on the artificial soil samples indicated that the degree of collapse increased with the calcium carbonate content. The degree of collapse could not be adequately predicted by available criteria.

1 INTRODUCTION

The paper concerns the collapse of calcareous-rich clay soils associated with the pedoderm unit mapped by Sheard and Bowman (1996) in the Adelaide area. The thickness of this wind-blown calcareous deposit can vary from less than one metre to a few metres. The pedoderm consists predominantly of calcium carbonate which occurs in several forms: as loose, low density, earthy to powdery silt; as loose, powdery silt with secondary pisoliths, concretions and nodules; or as compact re-cemented blocks or sheets, often as a capping on other material (Sheard and Bowman 1996). The proportion of clay in the pedoderm is usually less than 30%.

The climate in Adelaide leads to unsaturated soils, which when wetted may result in swelling if the soils are rich in clay, but can lead to collapse if the material is of low density and of low plasticity. Usually collapse is associated with both wetting and loading of the soil. Partial saturation, resulting in capillary suction, can act as a weak, water-sensitive bond. Inundation resulting from a water leak can result in full collapse.

Collapsing soils are found most often in arid areas and have different characteristics to other soils, such as low in-situ dry density ($< 1.55\ t/m^3$), and low natural moisture content (Arnold, 1979). The major soil particles are bonded together in a loose matrix. The bonding agent must be susceptible to removal or weakening on immersion in water (Arnold 1979). Loss of the bonds can result in radical re-arrangement of the soil particles. Collapsing soils such as loess are usually silts, which have been loosely deposited with some clay. The clay forms weak bonds between the silt particles. Fine silty sands, rich in calcium carbonate can also collapse; the carbonate acts as the cement between soil grains (Arnold 1979, Cameron et al. 2005).

The Quaternary period in South Australia produced two mains types of collapsing soils (Selby, 1982), the dune sands of the coast and inland desert, and the Mallee soils; calcareous clays, silts and sandy silts. Large areas of the Adelaide plains are underlain by the Pooraka Formation, a red-brown, Pleistocene alluvial deposit, with weakly-developed calcareous horizons (Bourman et al 1997). The Pooraka Formation includes clays and silts of low to high plasticity, and uniform, poorly graded and gap-graded sands and gravel. The Pooraka Formation usually overlies the pedoderm unit in Adelaide, and highly expansive clays can underlie the pedoderm, so the collapsing soil in and around the pedoderm basically consists of clay and calcium carbonate. Therefore both collapse and swelling are possible.

Generally calcium carbonate is regarded as water-susceptible. Gao (1983) observed that water destroys or reduces the strength of the calcium carbonate bond in Chinese loess. However, Yang (1989) classified calcium carbonate as a water stable cementation in Chinese loess, "the strength of which does not obviously decrease when it comes into contact with water'. Indeed the solubility of calcium carbonate is low.

The insurance industry would like to be able to quantify collapse movement of the soils associated with the pedoderm unit. When the pedoderm unit is relatively small within a swelling soil profile, its influence on ground movement may be difficult to define. Therefore testing of the collapse potential of undisturbed soil samples was begun, to study the importance of the calcium carbonate content. It was soon discovered that carbonate contents varied widely over short spaces, and so thereafter the study focussed on artificial soils, prepared with kaolin and calcium carbonate.

1.1 Prediction of collapse

Some simple methods have been proposed to check if a soil may collapse or swell. Holtz and Gibbs (1967) set a boundary between soils which are collapsible and non-collapsible, based on the liquid limit, w_L, and dry density. The boundary was defined by a liquid limit of 85% and a dry density of 1.75 t/m^3.

Feda (1966) promoted a subsidence index, K_L, defined by the equation:

$$K_L = \frac{{}^{w}\!/_{S_o} - w_P}{w_L - w_P} \tag{1}$$

S_o is the degree of saturation, w is the moisture content, and w_P is the plastic limit. Feda regarded that collapse was probable when the subsidence index was greater then 0.85.

2 METHODOLOGY

Firstly, tests were conducted on natural soils taken from two sites in the Adelaide area. However the percentages of $CaCO_3$ were found to be highly variable. Subsequently, artificial soils with controlled $CaCO_3$ contents were prepared and tested.

2.1 The natural soil

Samples were taken from two sites in Enfield, about 10 km North East of Adelaide, in autumn (April-May 2006), when the topsoil was dry and cracked. The carbonate pedoderm at these sites was less than a metre thick. Three boreholes were drilled close together to collect Shelby tube samples. All samples were red brown to brown clay, which were rich in calcium carbonate. The calcium carbonate content was determined using procedure, D4373-96 (ASTM 1996). Results for Site 1 are shown in Figure 1, from tests on trimmings of the top and bottom of each thin-walled tube sample. Holes 1 and 2 were within a metre, but hole 3 was approximately 5 m away. At Site 2, the calcium carbonate contents were higher, ranging between 38 and 57% over the depth interval 0.5 to 1.0 m.

Grain size analyses revealed that the soil composition varied from 12% to 32% clay, 34% to 60% silt and 20% to 39% sand. Liquid limits ranged between 33% and 67% and plastic indices between 15% and 52%.

2.2 Artificial soils

Because collapsible soils usually have a dry density smaller than 1.5 t/m^3 and low water content, the soils were compacted statically to a target dry density of 1.3 t/m^3 and a moisture content of 12%.

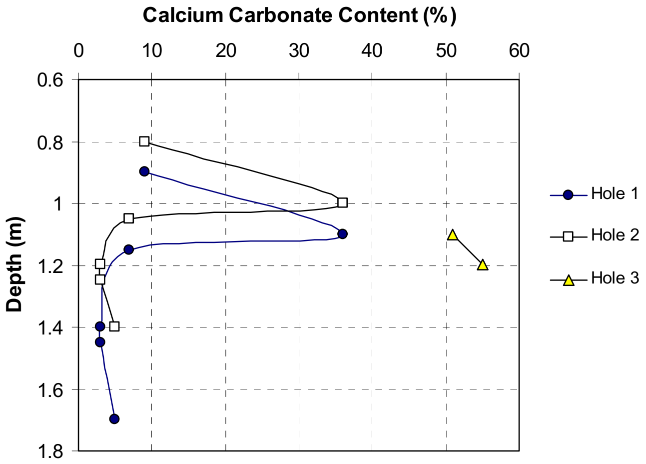

Figure 1: Variation of calcium carbonate contents at site 1

Three different soil compositions were made, using 0, 25 and 50% by dry mass of $CaCO_3$ to kaolinite. Some tests were also conducted on calcium carbonate, prepared as a paste in sampling rings. The $CaCO_3$ paste was oven dried at 70°C for 24 hours thereafter, to give a consistent starting point for the engineering tests. The initial dry density was consequently higher than 1.3 t/m^3 and the moisture content was very low.

2.3 Oedometer test

Both single and double oedometer tests were performed to ASTM (1992) to determine the "collapse index" of the soils. In the single oedometer tests, vertical stress was increased before inundation in stages from 12.5 to 200 kPa. After settlement had finished at the 200 kPa loading stage, the sample was inundated to find the collapse settlement and the collapse index, I_e,. The collapse index is defined by ASTM (1992) as the collapse settlement strain of the sample, relative to the sample height at the beginning of the stage. The degree of collapse is then rated against the collapse index as slight (0.1 to 2.0%), moderate (2.1 to 6.0%), moderately severe (6.1 to 10.0%) or severe (10.0%).

Double oedometer tests were performed following almost the same procedure. However, two companion samples were set up from the one soil core. One sample remains dry, while water is added to the second sample when it is under a small initial load. Collapse index is determined as the difference in strain between the two samples at 200 kPa.

2.4 Direct Shear Test

The direct shear test was chosen to compare the shear strengths of the dry and wet artificial soils. Samples were trimmed to fit a square cutter ring measuring 60 mm by 60 mm and 24.5 mm deep. The wet samples were loaded vertically, inundated and soaked for 24 hours before commencing shearing. All the nominally undrained tests were conducted at a rate of 1.2 mm per minute. Drained tests were conducted at a rate of 0.7 mm/hour or 0.011 mm/minute.

3 RESULTS

3.1 Natural soils

A summary of the engineering properties of the natural soils is given in Table 1. The initial water content, total soil suction and dry density are provided. Calcium carbonate contents were determined, before and after the oedometer testing. The carbonate checks were to indicate if the carbonate had become soluble after inundation, decreasing the carbonate content of the soil, but no such indication was evident. The samples were dry as indicated by the high total suctions. Densities were generally low except for two of the three CH soils from site 1 (samples 1-2 and 1-3).

Calcium carbonate content was least in sample 1-2. Accordingly, sample 1-2 did not collapse upon wetting and loading (zero collapse index). Moreover it was observed that many of the samples swelled rather than collapsed with wetting during the oedometer tests; sample 1-2 swelled approximately 2% during a single oedometer test under an applied pressure of 200 kPa. Surprisingly, sample 1-3 did collapse, despite a high dry density (> 1.7 t/m^3), high plasticity (LL ~ 60%) and high clay content.

Table 1: Properties of natural samples

Sample	$CaCO_3$ content (%)	Dry density (t/m^3)	Total suction (pF)	w (%)	w_L (%)	w_P (%)	USCS	Clay (%)	Silt (%)	I_e (%)
1-1 H5	20-65	1.55	4.6	17.5	70	18	CH	20	60	0*
1-2 H6	5-31	1.8	4.75	18	62.5	18	CH	20	52	0
1-3 H7	50-55	1.75	4.9	12.5	60.5	16.5	CH	32	36	6
2-1 F4	50-55	1.45	4.9	10.5	40.5	16.5	CI	32	34	7
2-2 F6	38-46	1.3	4.85	12.5	33.5	18.5	CI	24	37-40	12*

* from double oedometer tests

Table 2: Properties of artificial soils; single oedometer tests

Sample	Dry density (t/m^3)	w (%)	w_L (%)	w_P (%)	USCS	I_e (%)
K-100%	1.4	10.5	75	29.5	CH	4.5
K-75%	1.35	11	57.5	23.5	CH	7.5
K-50%	1.25	11	47.5	18.5	CI	13.5
$CaCO_3$	1.55	0.5				3.5

Table 3. Comparison of direct shear tests

Sample	"Undrained" Test Dry		"Undrained" Test Wet		Drained Test Wet		
	ϕ (°)	c_u (kPa)	ϕ (°)	c_u (kPa)	Total suction (pF)	ϕ' (°)	c' (kPa)
Kaolin	44.5	50	11	13			
K-75%	35	37.5	11	8.5	4.6 - 4.75	32.5	2.5
K-50%	34	30	13.5	1.5	4.3 - 4.65	37	5
$CaCO_3$	29	42.5	32.5	0			

3.2 Artificial soils

A summary of the engineering properties of the artificial soils is given in Table 2. Plasticity decreased with increasing carbonate content from CH to CI at 50% $CaCO_3$ content. All the artificial soils exhibited the collapse phenomenon after inundation at 200 kPa pressure in the single oedometer test. Collapse settlement decreased with clay content. The purely calcareous sample exhibited modest collapse (I_e = 3.5%), despite the relatively high initial dry density of 1.55 t/m^3.

3.3 Direct shear tests on artificial soils

When the calcium carbonate is dry, it has a reasonably high apparent undrained cohesion (~ 40 kPa) and a high friction angle (about 30°). However, when wet, and tested undrained, the carbonate has almost no cohesion; its friction angle is unaffected by wetting however. The artificial soil samples had even greater apparent angles of friction when tested dry, with values increasing with clay content. When tested after inundation, the angle of friction was much diminished to only 10 to 15°, well below that of the wet carbonate sample. It may be concluded that the softened clay smears the carbonate particles to reduce the internal friction. Apparent cohesion was also reduced, the least affected sample being the 100% kaolin soil, with the cohesion falling from 50 to 13 kPa.

The initial consolidation and dissipation of pore water pressures during drained shearing led to a largely frictional response with friction angles similar to the levels obtained from undrained testing on equivalent dry samples. Apparent cohesion was 5 kPa or less.

4 ANALYSIS AND DISCUSSION

4.1 Prediction of collapse

The degrees of collapse (ASTM, 1992) for all the soils tested are shown in Table 4, along with degrees of saturation, S_o, and subsidence indices, K_L (equation 1). The degree of saturation was based on an assumed particle density of 2.65 t/m^3.

The criteria of Holtz and Gibbs (1967) failed to predict collapse for all but one soil sample, the natural soil sample, 2-2. Feda's (1966) subsidence index criterion concurred with the Hotz and Gibbs criteria; it indicated that collapse could occur only for sample, 2-2, for which the subsidence index exceeded 0.85. Five other collapsing samples were unable to be predicted correctly. The two methods of prediction cited would seem to be inadequate for relatively high plasticity soils and the ASTM collapse criterion, particularly the high collapse load of 200 kPa applied in the test.

Collapse index has been plotted against subsidence index in Figure 2. Although the data are limited, there would seem to be an almost linear relationship between I_e and K_L for each dataset (artificial and natural soil samples). Such a correlation, if further proven, would have great application in dealing with collapsing clay soils.

Table 4: Prediction of collapse

Nature of soil	Sample	ASTM, 1992 degree of collapse	S_o	K_L	I_e (%)
natural	1-1	none	0.65	0.15	0
	1-2	none	1.0	-0.02	0
	1-3	≤ moderately severe	0.64	0.06	6
	2-1	moderately severe	0.33	0.62	7
	2-2	severe	0.32	1.37	12
artificial	K-100%	moderate	0.32	0.08	4.5
	K-75%	moderately severe	0.30	0.39	7.5
	K-50%	severe	0.27	0.79	13.5

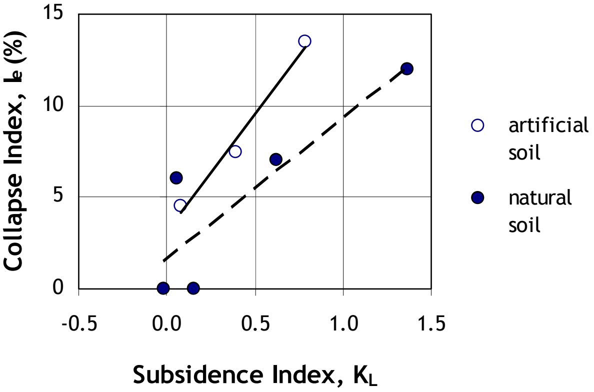

Figure 2: Collapse index as a function subsidence index

4.2 Shear strength of collapsing soils

The loss of apparent cohesion measured between undrained pore water shear tests on dry and wet samples is linked directly to the composition of the samples. The greater the calcium carbonate content, the greater the loss of apparent undrained cohesion upon wetting. The angle of friction was found also to drop markedly, but seemed to be independent of the carbonate content.

Drained tests indicated a more frictional response, however such tests reflect the remaining shear capacity of the soil after inundation and collapse, and may not be relevant to the building industry. A leaking water pipe under a heavy building would be more likely lead to shear failure of the soil in the short term, as evidenced by the low levels of shear strengths from the undrained shear tests.

5 CONCLUSIONS

The aim of the study was to investigate the role of calcium carbonate on the collapse process. Calcium carbonate can act as a cementing agent in clay soils, which is susceptible to softening upon wetting. If the soil has high carbonate content, an initially low dry density and moisture content, it is likely to suffer collapse upon wetting while under load. Calcium carbonate links the particles together. When dry, that link is strong, providing the soil with a moderately high cohesion and a high friction angle. However upon wetting, that link is weakened and the apparent cohesion may be destroyed completely. Initial evidence from this study suggests also that wet clay may interfere with the frictional capacity of the carbonate in undrained loading, making the overall soil response weaker.

The study has shown that one dimensional collapse may be predicted on the basis of water content, dry density and Atterberg Limits, or Feda’s subsidence index, K_L. Further verification is needed from tests on a wider range of natural and artificial soil samples.

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