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Design of Foundations Built on a Shallow Depth (Less than 4 m) of Egyptian Macro-Porous Collapsible Soils

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ABSTRACT

It is nowadays well reported that collapsible soils spread in many countries, including United States, Russia, China, South America (e.g. Brazil), South and North Africa (e.g. Egypt, Algeria), Middle East (e.g. Saudi Arabia) and many countries in Eastern Europe. In general, collapsible soils are located in arid and semi-arid regions around the world. This special type of soil is characterized by abrupt reduction in strength, excessive and sudden settlement when it becomes wet leading to failure of the structure. Construction on such a kind of soil is one of the prominent problems in geotechnical engineering. The main objectives of this study are reporting geological and geotechnical zonation maps for potentially collapsible soils in inhabited areas in Egypt. Furthermore, a design technique for foundations built on a shallow depth of Egyptian macro-porous collapsible soils (less than 4 m) is developed. The design method includes a design chart for soil collapse field classification in terms of the most governing parameters, a method for foundation settlement estimation based on a correlation between the wetting-induced collapse strain and the applied pressure, and a design practice to guide practicing engineers to select the appropriate foundation system to construct on such soil with a great degree of confidence and safety.

Keywords: Collapsible Soils; Design Method; Foundations; Shallow Depth; Settlement

1. Introduction

Soil collapse forms a major hazard in many parts of the world. Human activities continue to increase in regions underlain by collapsible soils, so that the hazards posed, and the economic impacts are increasing in both relative and absolute terms. In Egypt, recent extensions of urban communities towards the desert have exposed the Egyptian engineer to relatively new geotechnical challenges, among which is the collapsible soils.

Construction of foundations on collapsible soil is considered one of the outstanding problems in geotechnical engineering. It could be difficult, costly or sometimes even impossible to modify the design of railway tracks, highways or power supply lines in order to avoid the area where such a soil is found. On the other hand, construction on collapsible soil in its natural state without special precautions may cause dramatic and undesired results.

Man's activities are definitely the prime cause of most of soil collapse. These activities include watering grass and shrubs, failing to recognize and or to repair damaged water lines in utility trenches, impounding water, blocking drainages by highways, loading excessively on collapsible soils, and any activity which increases subsurface moisture in soils prone to collapse.

Selection of foundation design alternatives depends on several factors including whether the soil is susceptible to wetting or not, the type of structure, the type and nature of collapsible deposit, the depth of collapsible soil (either shallow or deep), the probable sources of wetting, and the extent and degree of wetting. The simplest solution is either to replace the collapse soil with granular soils, subject to the cost associate and the nature of the project; or to carry the foundation loads to deeper strata through piles or encapsulated stone columns [1]; or treating the collapsible soils with additives [2].

The lack of knowledge in the construction industry about the identification, behavior and treatment of collapsing soils is believed to have had led to many cases of either foundation problems or unnecessary treatment measures. In literature, little or no attempts were made to develop a rational soil classification technique based on the most governing parameters of soil collapse behavior.

Furthermore, no work was found dealing with a guideline to assist engineers to select the appropriate remedial measures to build on such soil with a high degree of confidence and safety.

In view of the above considerations, the present study has been conducted with broad objectives of reporting geological and geotechnical zonation maps for potentially collapsible soils in inhabited areas in Egypt. Moreover, a procedure is proposed for the design and construction of foundation on shallow macroporous collapsible soils (less than 4 m). The design method includes: 1) A design chart for soil collapse field classification in terms of the relative density, liquidity index and the equivalent diameter; 2) An expression for soil settlement estimation based on a correlation between the wetting-induced collapse strain and the applied pressure; and 3) A design procedure is presented to assist engineers to select the appropriate treatment method to build on such soil with a high degree of confidence and safety.

2. Zonation Map for Potentially Collapsible Soils in Egypt

Typical formations of collapsible deposits such as loess are not often encountered in the geological or geotechnical literature on Egypt. Nevertheless, the Egyptian geotechnical engineers have always suspected the structural stability of desert dry sand formations that contain appreciable amounts of fines to be potentially collapsible [3]. The literature, however, recognizes Aeolian fluvial and highly saline soils (sabkha) as naturally occurring collapsible soils. Aeolian deposits, which are mainly in the form of sand dunes, are located south of Siwa Oasis. Fluvial deposits extend from the southwest region of Egypt to the north of Sudan. Sabkhas are located in northern delta, along the Red Sea coastal Plan, northwestern coast of Egypt, coastal regions of Sinai Peninsula, and Qattara and Siwa depressions [4].

Geotechnical zonation maps for potentially collapsible soils in inhabited areas in Egypt currently exist [3]. These zonation maps were developed based on boreholes executed in already inhabited areas, and considering dry cemented sandy formations with variable fines content to be potentially collapsing soils. Furthermore, Several laboratory and field studies on collapsible soils have been performed for new urban developments such as 6th of October, New Amereya, El-Suff, New Maady, 10th of Ramadan, Nasr City, New Borg El Arab, and El-Obbor (**Figure 1**). Collapse potential reported for these different cities based on field and laboratory tests ranged from 0.2% to 17% [4].

Figure 1. Locations of new urban cities where detailed studies on collapsible soils were performed [3].

Detailed geological and geomorphologic reconnaissance for different area in Egypt is still needed for further define loessial deposits and/or other formations that are considered potentially collapsible.

3. Design Method of Foundations on Collapsible Soils

A guideline for designing shallow foundations on collapsible soils (≤4.0 m) is developed in this investigation. The design method proposed is mainly based on the experimental results obtained by [2,3]. These experimental works are summarized in the following points:

1) The soil gradation range of the different soils tested is shown in **Figure 2**.

2) The tests were performed using pedometers and Rowe cells.

3) The testing procedure is described in details in [6].

4) The testing program and the obtained results are grouped in **Tables 1** and **2**.

The design method proposed in this investigation for foundations on Egyptian collapsible soils is composed mainly by three steps, namely identification of soil collapse, determination of settlement expected under given applied load, and soil foundation treatment considerations, as follows:

1) Identification of soil collapse: Quite often, designers require fast assessment of soil samples to collapse based on easy to obtain soil parameters. A design chart (**Figure 3**) was proposed for this purpose based on the experimental results reported by [5]. The most important parameters that are found to govern soil collapse behavior were soil equivalent diameter, relative density and the maniability index, which is defined as $I_m = \frac{w_L - w_o}{IP}$ [6]. An earlier attempt was performed with the liquidity index but the results were not representative.

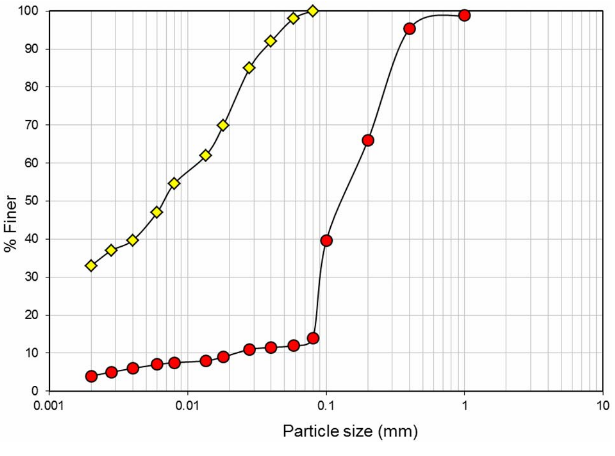

Figure 2. Soil gradation range of the different soils tested [5].

Table 1. (a) Measured values of wetting-induced collapse strain for soils S1 to S5 & S11 [5]; (b) Measured values of wetting-induced collapse strain for soils S6 to S10 [5].

(a)

Sols	R_D (%)	w_o (%)	e_o (%)	S_r (%)	ε_o (%)
S1	10	2	73.40	7.08	1.22
		4	73.29	14.09	1.01
		6	73.25	21.29	0.95
	30	2	67.24	7.73	0.97
		4	67.12	15.49	0.86
		6	67.06	23.26	0.67
	50	2	61.11	8.50	0.43
		4	60.96	17.06	0.395
		6	60.87	25.62	0.22
S2	10	2	73.95	6.95	3.45
		4	73.91	13.90	2.12
		6	73.84	20.88	1.51
	30	2	67.59	7.60	1.97
		4	67.17	15.30	1.91
		6	67.11	22.97	1.16
	50	2	61.21	8.43	1.67
		4	61.14	16.87	1.21
		6	61.05	25.34	1.07
S3	10	2	77.44	6.63	9.97
		4	77.37	13.28	4.85
		6	77.28	19.95	2.78
	30	2	70.14	7.32	8.44
		4	70.08	14.66	3.35
		6	69.79	22.09	1.38
	50	2	62.54	8.21	6.30
		4	62.40	16.47	2.39
		6	62.24	24.77	1.25
S4	10	2	78.49	6.54	10.54
		4	78.38	13.11	4.95
		6	78.24	19.57	2.82
	30	2	70.29	7.34	10.04
		4	70.17	14.70	3.62
		6	70.05	22.09	1.74
	50	2	62.60	8.34	9.74
		4	62.48	16.70	2.79
		6	62.32	25.11	1.37
S5	10	2	80.02	6.34	12.55
		4	79.94	12.70	5.73
		6	79.86	18.84	3.63
	30	2	71.12	7.14	12.28
		4	71.01	14.30	3.95
		6	70.92	21.48	2.08
	50	2	62.66	8.16	11.14
		4	62.59	16.33	2.92
		6	62.46	24.73	1.52
S11	10	2	134.88	3.74	0.82
		4	136.11	7.30	0.79
		6	136.79	10.92	0.21
	30	2	111.98	4.52	0.56
		4	111.65	9.08	0.47
		6	111.44	13.64	0.13
	50	2	89.12	5.71	0.16
		4	89.04	11.50	0.13
		6	88.98	17.33	0.05

(b)

Sols	R_D (%)	w_o (%)	e_o (%)	S_r (%)	ε_o (%)
S6	10	2	85.92	5.96	7.59
		4	85.80	11.93	2.36
		6	85.74	17.62	1.55
	30	2	75.60	6.78	6.60
		4	75.52	13.58	1.45
		6	75.44	20.39	0.71
	50	2	65.20	7.87	2.91
		4	65.12	15.78	0.675
		6	65.04	23.69	0.360
S7	10	2	89.50	5.72	7.01
		4	89.42	11.46	2.13
		6	89.46	16.95	1.26
	30	2	78.20	6.57	5.17
		4	78.08	13.17	1.36
		6	77.98	19.78	0.67
	50	2	66.64	7.72	2.76
		4	66.58	15.47	0.47
		6	66.49	23.23	0.21
S8	10	2	93.92	5.35	5.74
		4	93.86	10.73	2.05
		6	93.78	15.78	1.03
	30	2	81.40	6.20	3.57
		4	81.34	12.43	1.28
		6	81.26	18.70	0.52
	50	2	68.42	7.39	2.61
		4	68.34	14.79	0.34
		6	68.24	22.29	0.17
S9	10	2	96.30	5.23	4.35
		4	96.22	10.48	1.68
		6	96.18	15.70	0.93
	30	2	82.62	6.10	3.12
		4	82.56	12.24	0.89
		6	82.49	18.41	0.47
	50	2	68.76	7.35	2.47
		4	68.70	14.73	0.29
		6	68.65	22.16	0.15
S10	10	2	109.28	4.61	2.86
		4	109.19	9.25	1.23
		6	109.12	13.90	0.61
	30	2	92.24	5.47	1.73
		4	92.18	10.97	0.72
		6	92.10	16.51	0.36
	50	2	75.20	6.73	0.63
		4	75.14	13.52	0.19
		6	75.06	20.36	0.11

R_D = relative density; w_o = initial water content; e_o = initial void ratio; S_r = initial degree of saturation; ε_o = wetting induced collapse strain.

2) Determination of wetting induced collapse strain (*i.e.* soil settlement under given applied pressure): a regression analysis was applied on the data of [5] in order to evaluate possible relationships between some physical parameters of soil (relative density, liquidity index, and the soil equivalent diameter) and the applied pressure versus wetting induced collapse strain. Statistical analysis indicated that the equation used for predicting wetting induced collapse strain, ε_o (*i.e.* soil settlement) was in the form of:

- When $D_e > 0.02$ mm:

$$\varepsilon_c = \left(\frac{17.5}{\left(R_D\right)^{0.4} + \left(w_o\right)^{1.3}}\right) \times P - 0.52 \times IP - 250 \times D_e + 17.5 \tag{1}$$

- When $D_e < 0.02$ mm:

$$\varepsilon_c = \left(\frac{17.5}{\left(R_D\right)^{0.4} + \left(w_o\right)^{1.3}}\right) \times P - 3.3 \times \left(IP\right)^2 + 48.8IP + 0.01 \times e^{160D_e} - 192.7 \tag{2}$$

where,

D_e = equivalent diameter [7]

R_D = relative density

IP = plasticity index

w_o = initial water content

P = applied pressure

3) Design consideration of foundation: When the soil is classified in point #1 as collapsible, a practical measure should be considered in order to construct on it with safety. If the collapsible soil layer is not too thick (less than 4.0 m), it is often recommended to replace it with a suitable well compacted soil. Nevertheless, borrowing well graded soils and the process of compaction at the optimum moisture content may be expensive and lengthy, especially if the site was situated in arid or semi-arid regions. However, it was established that the soil can be excavated and re-used after treating it with additives. Furthermore, it was reported that with cement and lime as additives, the compacting water content was about half of the optimum moisture content of the treated soil [2]. For given amplitude of soil collapse (*i.e.* wetting induced collapse strain, ε_o), the minimum amount of additives necessary to produce a non-subsiding soil with higher shear strength characteristics can be determined by the following equation (**Figures 4** and **5**):

$$\varepsilon_c = \varepsilon_o \times e^{-k \cdot A} \tag{3}$$

or

$$A = \frac{1}{k} \log\left(\frac{\varepsilon_o}{\varepsilon_c}\right) \tag{4}$$

where,

ε_o = wetting induced collapse strain determined in point #2 (it includes the effect of the initial water content, the initial unit weight, the applied pressure, etc.),

A = type of additives (cement or lime in %),

k = coefficient representing the slope of the exponential curve (it was averaged to k = 0.53 for cement and 0.44 for lime).

Finally, it is imperative to indicate that the design method proposed in this investigation (*i.e.* relationships given in Equations (1) to (4) are only valid for soils having

Table 2. Measured values of wetting-induced collapse strain for treated soil [2].

Type of additive	**Level of additive** (%)	**Water content** (%)	**Compacting effort** (number of blows)					
			10	20	25	40	60	80
Untreated soil	0	2	18.6	17.4	15.1	12.8	11.2	9.5
		4	17.3	15.9	13.1	11.1	10.2	8.4
		6	15.1	10.2	8.2	6.4	3.5	2.2
		8	6.3	4.2	3.0	1.2	1.12	0.85
Ciment	1	4		13.4		9.92	9	
		6		4.93		1.11	0.7	
		8		1.04		0.66	0.61	
	3	4		8.4		4.31	1.52	
		6		0.72		0.46	0.27	
		8		0.02		0.02	0.01	
	5	4		5.17		1.61	1.05	
		6		0.72		0.4	0.22	
		8		0.05		0.05	0.01	
Lime	1	2	14.1		11.8	10.1		
		4	8.4		4.2	1.6		
		6	5.6		2.7	0.9		
	3	2	9.2		7.9	6.3		
		4	4.6		2.3	0.8		
		6	3.2		0.5	0.3		
	5	2	6.3		3.7	2.4		
		4	2.9		1.05	0.6		
		6	2.0		0.3	0.2		

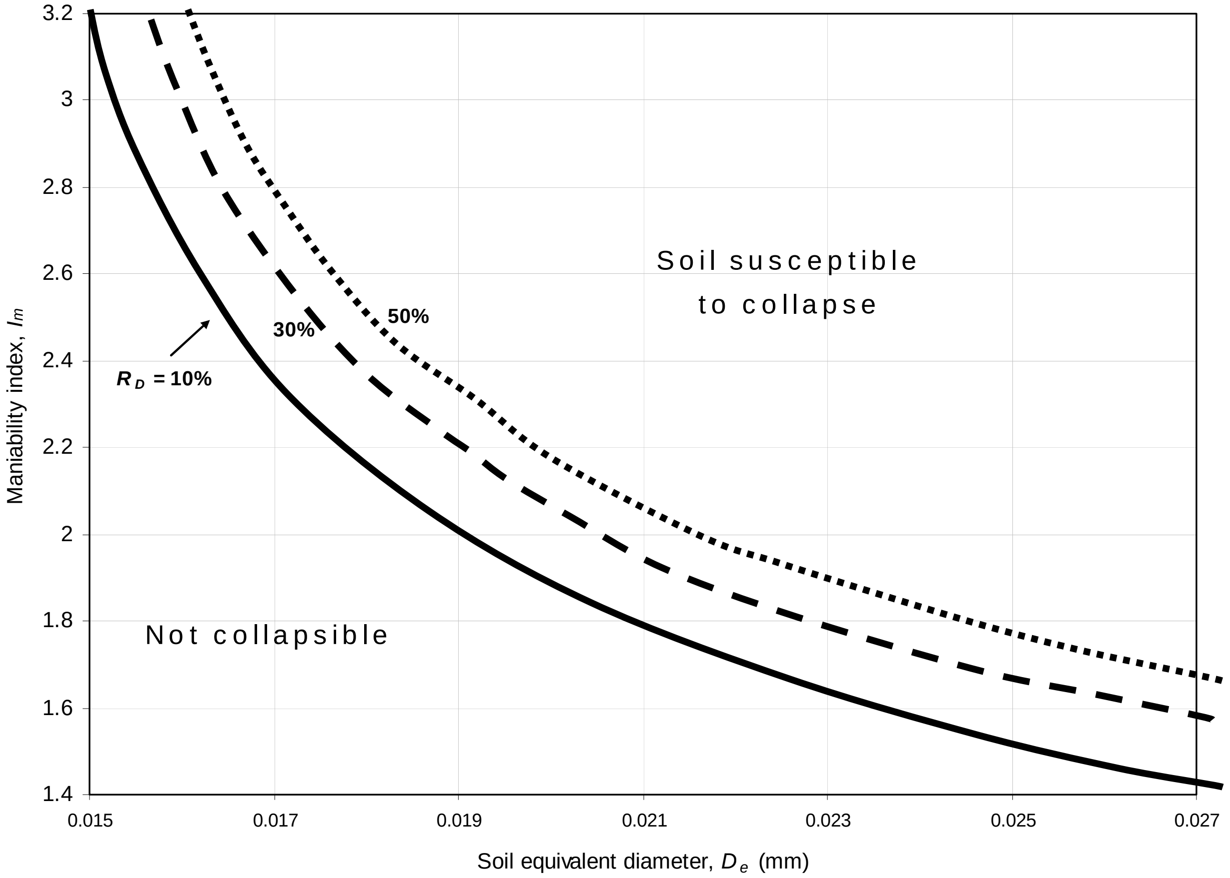

Figure 3. Design chart for identification of soil collapse behaviour.

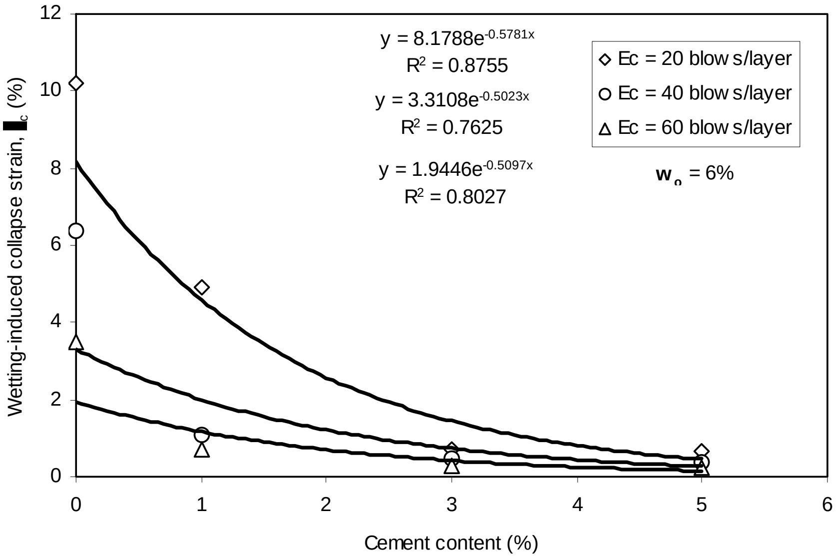

Figure 4. Variation of wetting-induced collapse strain against ciment content [2].

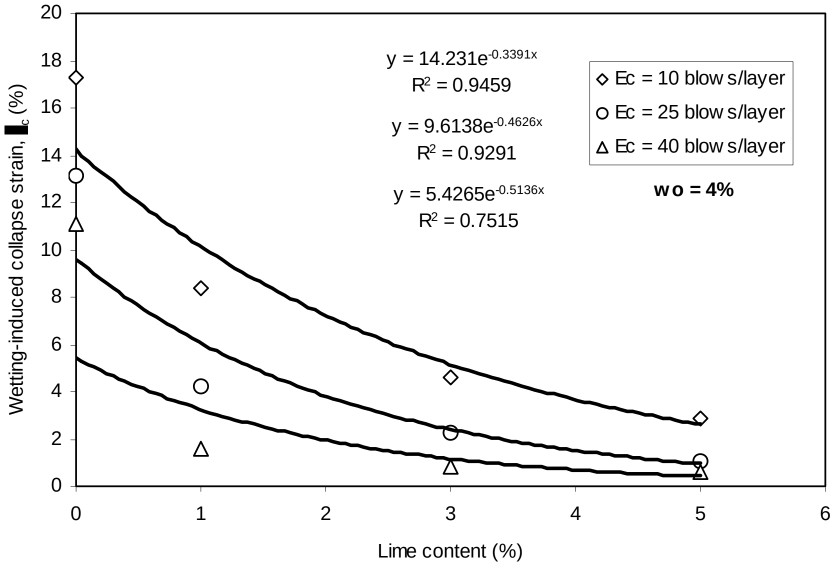

Figure 5. Variation of wetting-induced collapse strain against lime content [2].

particle size distribution in the range shown in **Figure 2** (*i.e* for clayey and/or silty sand and/or sandy silt).

4. Design Procedure

The following procedure is recommended to design foundations of a facility built on a shallow depth (less than 4.0 m) of Egyptian macro-porous collapsible soils:

1) Identify the different elements of the projected facility, notably geometry and type of the foundation system, and the transmitted loads to the ground.

2) Identify the soil foundation of the construction site, such as: depth and soil classification (*i.e.* particle size distribution and Atterberg limit, if any).

3) If the soil foundation is classified as clayey sand, silty sand or sandy silt (*i.e.* the particle size distribution of the soil is in the range of **Figure 2**), an assessment process of soil collapsibility should be conducted.

4) For the construction site, the designer might first use the chart of **Figure 3** to assess the collapsibility of the soil investigated (*i.e.* the soil foundation).

5) Then, knowing the projected load which will be applied on foundations, the settlement of the soil under such load can be estimated using either Equations (1) or (2).

6) Following that, if the soil is identified as collapsible and if the depth of the site is less than 4 m, the soil can be excavated and re-used after treating it by cement or lime.

7) The amount of cement or lime required depends mainly on the wetting induced collapse strain of the untreated soil (ε_o) and the level of soil settlement tolerated for the project, ε_c (Equations (3) and (4)). It is worthy to note that the compacting water content expected is about half of w_{opt}.

5. Conclusions

A procedure is proposed for the design and construction of foundations on sites of shallow macroporous collapsible (less than 4.0 m). Based on the results of this study, the following conclusions can be drawn:

- Typical formations of collapsible deposits such as loess are not often encountered in the geological or geotechnical literature in Egypt. The literature, however, recognizes Aeolian fluvial and highly saline soils (sabkha) as naturally occurring collapsible soils.
- A design chart was proposed for fast assessment of soil collapse behaviour based on easy to obtain soil parameters (**Figure 3**).
- Based on a regression analysis, a relationship between the physical parameters of soil (relative density, liquidity index, and the soil equivalent diameter) and the applied pressure versus wetting induced collapse strain was developed (Equations (1) and (2)).
- For a given wetting induced collapse strain, ε_o, the minimum amount of additives necessary to produce a non-subsiding soil with higher shear strength characteristics can be determined by Equations (3) and (4).
- A guideline for the design of shallow foundations on collapsible soils with limited depth (≤4.0 m) is presented.

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