ASSESSEMENT OF SOIL COLLAPSE PREDICTION METHODS

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Abstract Expansive and collapsible soils are some of the most widely distributed and costly of geologic hazards. These soils are subjected to change in volume and settlement in response to wetting and drying, often resulted in severe damage to structures. Collapsing soils are generally characterized by sudden and large volume decrease at constant stress when inundated with water. A geotechnical engineer needs to be able to identify readily the soils that could collapse and to determine the amount of collapse that may occur. Various methods of predicting collapse from simple and rapidly-performed index have been suggested by several workers in the field. In this investigation, most of the well known collapses identifying criteria are reviewed and evaluated. New method and interpretations let rapid and safe prediction of collapse are further discussed in this paper.

Keywords Collapsing soils; Assessment; Prediction; New method; Geotechnical engineering.

چکیده تمایل خاک به انبساط و فروریختن از شایع ترین و پر هزینه ترین مخاطرات زمین شناسی محسوب میگردد. این خاک‌ها در پاسخ به رطوبت و خشکی در معرض تغییرات حجمی و زیستگاهی قرار دارند که اغلب منجر به آسیب شدید به ساختمان انها میگردد. عموما، فروپاشی خاک‌ها زمانیکه با آب اشباع میگردند، با کاهش حجم ناگهانی و بزرگی در فشار ثابت توصیف می‌شود. یک مهندس ژئوتکنیک باید قادر به شناسایی آمادگی خاک برای فروپاشی بوده و همچنین بتواند مقدار ممکن فروپاشی را تعیین نماید. روش‌های مختلفی برای پیش بینی فروپاشی با استفاده از شاخص ساده و سریع توسط چند کارگر در این زمینه پیشنهاد شده است. در این تحقیق، بسیاری از معیارهای معروف شناسایی فروپاشی بررسی و ارزیابی شده است. تفاسیر جدید و روشی نوین که امکان پیش بینی سریع و ایمن فروپاشی را فراهم میسازد نیز مطرح شده است.

1. INTRODUCTION

The decrease in total volume of a soil resulting from wetting-induced breakdown of its structure at essentially unchanging total vertical stress is commonly referred to "collapse". It was reported that, any type of desired compacted dry soil may develop a collapsible fabric or metastable structure at low densities [1].

In the past much attention was not paid to detailed studies and investigation of soils susceptible to collapse. Also erected structure tended to be inexpensive and of small size. Besides this, water consumption patterns were quite different from those of today. With rapid advancement of civilization and increasing use of water for irrigation, industrial and domestic purposes near the structures caused severe damage to a founded structure on collapsible soil. Also developments in all aspects of life have resulted in the construction of modern cities and large structures in areas of collapsible soil. This clearly establishes the need for an in depth study of the subject of subsidence in collapsible soils. A safe, reliable and economic method for predicting areas of likely soil subsidence is considerably important.

An extensive amount of work has been performed in the past toward quantifying parameters that qualify settlements associated with metastability particularly that concerned with an increase in soil water content. These include laboratory tests such as single oedometer test [2, 3], double-odometer test [3- 6], triaxial and double-triaxial tests [7, 8], shear tests [9] and in-situ field tests of various types [5, 10- 12].

Generally speaking, combination of factors such as: soil type i.e. mineralogy and gradation, level of applied stress, degree of partial saturation, in situ or as compacted density, nature of cementing agents, pore fluid chemistry and the amount of wetting up under stress (due to rise of ground water table, infiltration of rain water etc.,) control collapse potential of soils. Most of the works that have been carried out to study the parameters governing collapse have concentrated on initial dry density, moisture content (degree of saturation), grain size and overburden pressure [13].

A geotechnical engineer needs to be able to identify readily the soils that could collapse and to determine the amount of collapse that may occur. This paper attempts to review the literature predicting collapse for soils from a variety of depositional environments. In addition, new method and interpretations permit rapid, reliable and safe prediction of collapse were discussed.

2. EVALUATION OF EXISTING METHODS

The methods available in the literature (Tables 1*a* and 1*b*) are mostly inter-related since many of the parameters involved are interdependent. The presented criteria grouped into four categories:

1. Methods based on voids ratio, density and water content relationship [11, 14- 20];
2. Methods based on water content and Atterberg limits relationship [21- 23]
3. Methods based on density and Atterberg limits [15, 25- 26]
4. Methods based on particle size distribution of soils [27, 28].

Methods of the first three categories do not take into account the influence of soil particle distribution. It was observed that soil grading has an important role in controlling collapse behavior [28]. Furthermore, it has been established that the phenomenon of suffusion (grain-movement in a ground layer from one horizon to another during wetting up) is one of the main causes of collapse [2].

Although a great deal has been written in past on the properties and origins of collapsible soils, their recognition and the prediction of their collapse, there has been comparatively little literature on the comparison of prediction criteria. Tables 2a and 2b represent a quantitative evaluation of these existing methods using available experimental data in the literature. In these tables, application of collapse criteria reviewed here is listed for several soils of different depositional histories. The tables include soils encountered by the authors and others reported data in the literature. It was noted that in most cases no single criterion has predicted accurately the collapsibility of a particular soil. For example, for the criterion of Denisov [14], where the coefficient of susceptibility to soil collapse given by the corresponding expression should be less than 1, only 5 soils have been identified as collapsible over 16 reported. Furthermore:

1. The percentage of soils predicted to be collapsible by the Clevenger and Handy criteria do not exceed 50%.
2. The number of soils classified by the expressions of Gibbs, Anderson and Krastilov essentially depends on the collapse ratio (R) chosen to predict the collapse. For example,
    - ❑ If collapse is considered to occur when R>1% ([4] classification), the percentage of soil predicted to be collapsible by Gibbs criterion is approximately 45%.
    - ❑ If R is increased to 2% [37], the percentage of soil predicted to be collapsible dramatically decrease.
3. The criterion of Salas et al. [18] (not presented in the table) only applies to soils that contain a certain amount of gypsum).
4. Feda’s [22] and Priklonskij’s [21] criteria does not appear sufficiently sensitive to accurately predict collapse in certain cases.
5. Not all the models appear to predict susceptibility to soil collapse for important cases. This is believed to be due to the linearity considered between the collapse potential and the uniformity coefficient.
6. Some expression proposed predicted high values of collapse potential (CP) for relative high values of uniformity coefficient, C_u (Tables 2*a* and 2*b*).

TABLE 1*a*. Existing criteria for soil collapse prediction

Expression	Reference	Remarks
$K = \frac{e_L}{e_0}$	Denisov [14]	K = 0.5 – 0.75 highly collapsing soils K = 1.0 non collapsible loams K = 1.5 – 2.0 non collapsible soils
$w_L \Big/ \left(\frac{\gamma_w}{\gamma_d} - \frac{1}{G_s} \right)$	Gibbs and Bara [26]	< 1.0 collapse occur
$\alpha = (e_0 - e_L)/(1+e_0)$	Markin [15]	α < - 0.3 prone to swelling α > - 0.1 and S_0 < 60% susceptible to collapse
$\alpha = (e_0 - e_L)/(1+e_0)$	Minheev (1969)	S_0 < 0.6 and α > - 0.1 susceptible to collapse (this criterion is known as the new soviet building code)
$K_d = w_L - w_0 / I_p$	Priklonskij [21]	K_d < 0 highly collapsing soils, K_d > 0.5 non collapsing soils, K_d > 1.0 swelling soils
$K_L = \left(\frac{w_0}{S_0} - w_p \right) \Big/ I_p$	Feda [22]	For S_0 < 60% K_L > 0.85 collapsible soils
$R = \frac{w_S}{w_L} = \left(\frac{\gamma_w}{\gamma_d} - \frac{1}{G_S} \right) \Big/ w_L$	Gibbs [25]	R ≥ 1% collapse susceptible This was also put into graph form
$\alpha = \gamma_{0_d} / \gamma_{L_d}$	Markin [15]	α > 1.3 prone to swelling α < 1.1 prone to collapse
$\gamma_{0_d} < 1.28$ g/cm^3 , $\gamma_{0_d} > 1.44$ g/cm^3	Clevenger [11]	Settlement will be large, Settlement will be small
$R = 5.5 - 3.82 \log \frac{w_L}{w_p} - 1.63 \log w_p - 1.24 \log C_u -$ $0.918 \log P_{10} - 0.303 P_{200} + 0.465 \log \frac{D_{60}}{D_{40}} - 0.45 \log \frac{D_{99}}{D_{50}}$	Anderson [27]	

TABLE 1*b*. Existing criteria for soil collapse prediction (continued)

Expression	Reference	Remarks
$\delta(5,3) = 0.166 (S_0)^2 + 0.665 I_P$ $+ 0.078 e_0 - 0.165 S_0 - 0.85 I_P S_0$	Krastilov [23]	
$\delta_{np,3} = K(n_0 - 40)(30 - w_0)$	Minkov et al.[17]	K = 0.02 for loess sand, K = 0.03 for sandy loess K = 0.05 for typical loess, K = 0.08 for clayey loess K = 0.09 for loess like clay
$I'_P = 14.6 \frac{S}{9}$	Salas et al. [18]	Gypsum soils of low I_P are in many respect similar to loess soils, although they exhibit greater collapse and compressibility
$n_0 > 40\%$	Feda [19]	Soil is susceptible to collapse
Lowa loess with clay < 0.002 mm contents	Handy [20]	< 16% high probability of collapse, 16 to 24 % probably collapsible , 24 to 32 % less than 50% probability > 32% usually safe from collapse
Cu ≤ 4% 4 < Cu < 12 Cu ≥ 12	Ayadat and Belouahri [28]	Safe from collapse Transition interval (collapse may occur) Soil is collapsible
Graphical method based on the work of Kenney and Lau (1985)	Ayadat et al. [2]	Collapse occur if the equivalent grain size curve of the soil is situated above or cut the line H = 1.3 F
I_P < 20, 15 < w_L < 35	Ayadat and Ouali (1999)	Collapse is susceptible
$CP = a(\gamma_d - 15.27) + b w_0 + 17$ $a = -0.036 C_u - 1.379$ $b = 0.0006 C_u^2 - 0.089 C_u + 1.3$	Ayadat and Hanna [44]	CP < 1 collapse will not take place CP > 1 collapse is susceptible

TABLE 2*a*. Evaluation of existing criteria for soil collapse identification

References of soils tested	Soil type (reported collapsible)	**Existing criteria for soil collapse identification**											
		Denisov [14]	Markin [15] Miheev [16]	Priklonskij [21]	Feda [22]	Gibbs [25]	Markin [15]	Clevenger [11]	Anderson [27]	Minkov et al. [17]	Feda [19]	Handy [20]	Criterion 3
Ayadat and Hanna [44]	Soil C	1.1	0.12	1.33	1.03	1.11	0.99	1.414	3.35	4 43	43	15	0.61
	Soil D	1.03	0.16	1.78	0.97	0.85	1.05	1.378	4.12	4 44	44	20	0.64
	Soil E	0.98	0.09	1.52	0.88	1.14	1.06	1.55	4.72	6 41	41	22	0.58
Ferriera et al [33]	Sandy soil	1.08	- 0.03	1.5	0.8	0.92	1.03	1.65	2.54	10 38	38	25	0.68
Grigorian [7]	Loess	0.83	0.08	1.37	1.5	1.2	0.91	1.32	1.06	11.5 50.7	50.7	20	0.55
Charles [30]	Cohesive fill	1.28	- 0.105	0. 59	0.63	0.77	1.106	1.70	5.36	18 37	37	19	0.74
Ayadat and Gharabli [29]	Clayey sand	0.63	0.155	2.9	0.9	0.3	0.84	1.523	4.77	4 42.5	42.5	5	0.59
Maswoswe [38]	Clay sand	1.00	0.00	1.07	0.99	0.99	1.00	1.59	-1.33	11.05 40.6	40.6	17	0.67
Lutenegger et al. [37]	Loess	0.96	0.018	3.13	1.13	1.04	0.98	1.41	5.73	1.7 48	48	15	0.53
Ting [41]	Residual soil	1.13	- 0.07	1.83	0.7	0.88	1.07	1.28	3.72	15 54	54	16	0.52
Zaretsky et al. [42]	loess	0.66	0.16	2.36	2.98	1.51	0.84	1.40	3.28	8.9 48	48	13	0.57
Zur et al. [43]	loess	1.09	-0.04	1.06	0.82	0.91	1.04	1.54	9.71	15 44	44	7	0.64
Feda [19]	silt	1.04	0.05	0.92	0.93								
Denness [31]	Pyroclastic silt	1.06	-0.03	0.89	0.87								
Holtz and Hilf [10]	Alluvial silt	1.01	0.00	0.02	0.96								
Fookes et al [34]	Silty Loess	1.01	-0.01	2.7	0..99								
Conditions of susceptibility to soil collapse		< 1	> -0.1	< 0.5	> 0.85		< 1.1	< 1.44		< 30 % > 40 %	> 40 %	< 16 %	< 0.78

3. NEW INTERPRETATIONS

It seems to be imperative that, some modifications and new interpretations should be introduced to different investigated criteria (Tables1*a* and 1*b*) in order to be more reliable in predicting soil collapse behavior. Moreover, some of these relationships are grouped together in new criteria as follows:

3.1. Criterion 1 Markin [15] stated that, a soil is susceptible to collapse if:

$$\frac{\gamma_{0_d}}{\gamma_{L_d}} < 1.1 \quad \text{i.e.} \quad \left(\frac{\gamma_S}{1+e_0}\right) \Big/ \left(\frac{\gamma_S}{1+e_L}\right) < 1.1$$

so, $$\frac{1+e_L}{1+e_0} < 1.1$$

This last expression can be rewritten as follows:

$$\frac{e_L}{e_0} < \left(\frac{0.1}{e_0} + 1.1\right) \tag{1}$$

Meanwhile, a soil is considered as collapsible, using Feda [19] criterion, if its void ratio is greater than 0.66 (i.e. $n_0 > 40\%$).

$$e_0 > 0.66 \text{ so } \left(1.1 + \frac{0.1}{e_0}\right) < \left(1.1 + \frac{0.1}{0.66}\right) = 1.25 \tag{2}$$

TABLE 2*b*. Evaluation of existing criteria for soil collapse identification (Continue)

References of soils tested	Types of soils **Tested** (reported as collapsible)	Existing criteria for soil collapse identification					
		Krastilov [23]	Sabry (1987)	Shalaby (1991)	Basma and Turner (1992)	Ayadat & Belouahri [28]	Ayadat & Ouali (1999)
Ayadat and Hanna [44]	*Soil B ($wo=4\%$ $\gamma_d=15.4\ kN/m^3$)*	0.07	5.21	6.58	10.51	33.5	7.3 18.3/11.0
	Soil C ($wo=8\%$ $\gamma_d=17.9\ kN/m^3$)	0.1	426	0.87	3.24	45	9.2 22.5/13.3
	Soil D ($w_o=8\%$ $\gamma d=16.85\ kN/m^3$	0.08	4.68	3.31	8.1	57	10.6 26.7/16.1
	Soil E ($w_o=6\%$ $\gamma d=17.19 kN/m^3$	0.06	7.52	5.66	11.07	78	11.4 30.3/18.9
Ferriera et al [33]	Sandy soil	0.03	2.1	1.1	4.54	40	8 21
Grigorian [7]	Loess	0.10	11.3	10.96	18.98	74	15 32
Charles [30]	Cohesive fill	0.016	-2.89	-3.53	-2.5	24	11 28
Ayadat & Gharabli. [29]	Clay silty sand	0.08	8.14	7.14	14.84	70	5 18.4
Maswoswe [38]	Clay sand	0.04	3.08	2.58	5.88	37	13 25
Lutenegger et al. [37]	Loess	0.127	9.87	8.54	15.79	30	NP 33
Ting [41]	Residual soil	0.12	6.78	6.33	14.82	35	35 11
Zaretsky et al. [42]	Loess like loam	0.065	13.54	12.58	18.16	82	5.5 22.5
Zur et al. [43]	Undist-erbed loess	0.05	0.99	0.98	6.65	45	15 31
Conditions of susceptibility to soil collapse			> 1	> 1	> 1	>12	< 20 15/35

By comparing Equations (1) and (2), we deduce:

$$\frac{e_L}{e_0} < 1.25 \qquad (3)$$

Consequently, the criteria of Markin [15] and Feda [19] can be replaced by the relation given by Equation 3 (noted as criterion 1). The limit of Denisov [14] criterion should also be modified. In addition, the expressions of Markin [15] and Miheev [16] should be substituted by this criterion (criterion 1) because they are identical and give similar results to that computed by Markin [15] criterion:

$$\frac{\gamma_{0_d}}{\gamma_{L_d}} < 1.1 \quad \text{i.e.:} \quad \left(\frac{\gamma_S}{1+e_0}\right) \Big/ \left(\frac{\gamma_S}{1+e_L}\right) < 1.1$$

Therefore:

$$e_L - e_0 < 0.1(1+e_0) \quad \text{so} \quad \frac{e_0 - e_L}{1+e_0} > -0.1$$

where,

γ_{0d}: initial dry unit weight of soil

γ_{Ld}: unit weight the soil at liquid limit

γ_S: specific soil unit weight

e_o: initial void ratio

e_L: void ratio at liquid limit

n_o: initial porosity

3.2. Criterion 2 According to Minkov et al. [17], the relative settlement (collapse ratio), can be obtained by using the following relation:

$\delta_{np,3} = K(n_0 - 40)(30 - w_0)$ (K was previously defined)

$\delta_{np,3}$ is always greater than zero. Therefore, a soil is considered to be collapsible, using this criterion if $n_0 > 40\%$ and $w_0 < 30\%$. The other possibility has been discarded because a soil is more susceptible to collapse when it is loose and having a low degree of saturation. This finding, namely criterion 2, was used to replace the relation given by Minkov et al. [17] and modify Feda's criterion which was introduced into implemented condition. The modified condition includes the limitation of the initial water content (i.e. $w_0 < 30\%$).

where,

K: coefficient of collapse prediction

$\delta_{np,3}$: collapse ratio of soil

w_o: initial water content

n_o: initial porosity

3.3. Criterion 3 Based on criterion 2, the limit of the other criterion of Feda [22] must be changed. The value of 0.85 is surestimated, and soils with a prediction coefficient of K_L slightly lower than this value may show a collapsible behavior.

According to the modified Denisov criterion:

$$\frac{e_L}{e_0} < 1.25 \quad \text{so} \quad \frac{w_0}{S_0} > 0.8 w_L \tag{4}$$

collapse to occur.

According to Feda [22]:

$$\left(\frac{w_0}{S_0} - w_p\right) \Big/ I_p > 0.85 \quad \text{so:} \quad \frac{w_0}{S_0} > (0.85 w_L + 0.15 w_P)$$

i.e.:
$$\frac{w_0}{S_0} > 0.8 w_L + (0.15 w_P + 0.05 w_L) \tag{5}$$

collapse to occur.

where,

w_o: initial water content

e_o: initial void ratio

e_L: void ratio at liquid limit

S_o: initial degree of saturation

w_L: liquid limit of soil

w_p: plastic limit of soil

I_p = plasticity index

By comparing Equations (4) and (5) we deduce that, the term between brackets decreases the interval of collapsible soils which can be predicted by Feda's criterion. This solution shows that, in the expression of Feda, a significant interval which may contain some collapsible soils was neglected.

4. DEVELOPMENT OF A NEW PREDICTING METHOD

Previous equation (Equation (2)) can be adapted to develop another one. It can be rearranged to include only values for the bulk unit weight (γ) and the unit weight of soil constituents (γ_S), as follows:

$$n_0 > 40\% \quad \text{and} \quad w_0 < 30\%$$

Or:
$$e_0 > 66\% \quad \text{and} \quad w_0 < 30\%$$

$$\frac{\gamma_S}{1+e_0} < \frac{\gamma_S}{1+0.66} \quad \text{and} \quad w_0 < 30\%$$

But,
$$\frac{\gamma_S}{1+e_0} = \gamma_d$$

Therefore,
$$\gamma_d < 0.6\gamma_s \quad \text{and} \quad w_0 < 30\% \tag{6}$$

Also:
$$\gamma_d = \frac{\gamma}{1+w_0}$$

This imply (by substitution in 6) that:

$$\gamma < 0.6\gamma_S\left(1+w_0\right)$$

Since:
$$w_0 < 30\%$$

So:
$$\gamma < 0.6\gamma_S\left(1+0.3\right)$$

i.e.:
$$\gamma < 0.78\gamma_S \tag{7}$$

for collapse to be likely.

where,

γ: bulk unit weight of soil

γ_d: dry unit weight the soil at liquid limit

γ_S: specific soil unit weight

w_o: initial water content

e_o: initial void ratio

n_o: initial porosity

This expression can be presented on a chart of bulk unit weight against unit weight of soil constituents. This chart (Figure 1) is used to predict the susceptibility of soil to collapse directly by knowing its bulk and soil constituents unit weight. The plotted soil unit weights under the line shown in Figure1 are termed collapsible. It is worthwhile to note that the expressions of Feda [19] and Minkov et al. [17] can also be replaced by this method.

Validation of the different reported criteria in literature and discussed herein, including the proposed method is shown in Tables 2*a* and 2*b*.

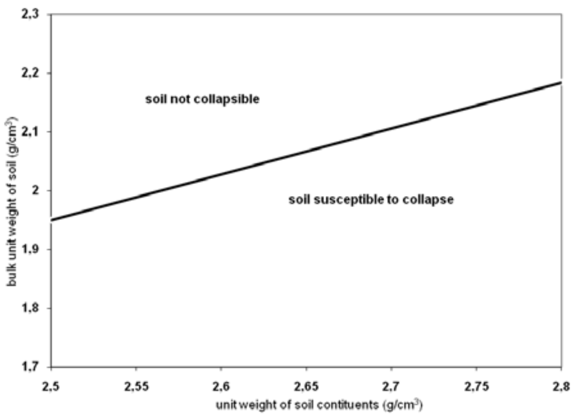

Figure 1. A proposed chart for soil collapse identification

5. CONCLUSION

An evaluation and new interpretations have been carried out on the existing collapse prediction criteria. This includes the modification of the form and the limit conditions of some of these criteria and also the introduction of new method. The criteria of Feda [19], Markin [15], and Miheev [16] can be replaced by Equation (1). Furthermore, the limit of Denisov [14] equation should also be modified. Equation (2) can be used to replace Feda [19] and Minkov et al. [17] equations. The limit of the other criterion of Feda [22] must be changed. Equation 7 or the chart of Figure1 can be used to predict the susceptibility of a soil to collapse directly by knowing its bulk and soil constituents unit weight. It is considered that the proposed equations (1 to 3) and the developed method are sufficiently sensitive to cover virtually all soil encountered. The other criteria on the other hand do not appear sufficiently sensitive to predict collapse in certain important cases. However, it should be noted that these methods are very useful tools in preliminary investigations; but the actual collapsibility of soils should be determined by means of laboratory and field tests for confirmation.

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