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PREDICTION OF COLLAPSIBLE SOILS BY CONE PENETROMETER AND ULTRASONIC TESTS

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Abstract: Collapsible soils type are in nature unsaturated soils, which are characterized by a metastable structure and undergo an abrupt collapse when they are flooded (with or without loading), which causes important damage. Based on the structural composition of these soils, we reconstituted the samples made up of sand and fine particles occurring in various proportions. The first phase of the work consists in the experimental determination of the geotechnical characteristics of these samples. It is thereafter proposed a test program based primarily on the use of the cone penetrometer and the ultrasonic apparatus allowing the factors which influence collapse to be predicted. The results obtained clearly show the influence of certain parameters such as water content and the energy of compaction on the collapse potential and the ultrasonic speed.

LIST OF SYMBOLS

γ_d – dry density,
$\gamma_{d\max}$ – maximum dry density,
CP – collapse potential,
c_u – coefficient of uniformity,
E – number of blows,
e_0 – initial void ratio,
G_S – specific density of grains,
I_L – liquid index,
I_P – plastic index,
I_C – consistence index,
I_W – manageability index,
$P_{\lim}$ – limit penetration,
V – ultrasonic speed,
w_0 – initial moisture content,
w_L – liquid limit,

w_P – plastic limit,
w_{opt} – optimum moisture content.

1. INTRODUCTION

The collapsible soils are metastable soils of loose open structure, unsaturated nature, occurring in the form of deposits. In the dry state, a natural cementing between the grains is responsible for an important inter-granular connection and can support very high loads. However, the saturation, even without additional loading, causes the disintegration of the connections, giving a denser structure followed by a sudden collapse of the soil particles. Among the causes of saturation there is the groundwater rise, water infiltration by the top and canalization leaks. Because of the important collapse potentials and serious consequences which can arise in the construction, this type of soil is considered unstable as foundations settle. These soils are primarily localized in the arid and semi-arid regions. They occur in a significant number of countries, in particular those of the northern hemisphere located between the 30th and 55th parallels as well as in the countries of South America [3]. The cycles of prolonged dryness which have repeated last years on several occasions and in several regions of the world modify the parameters governing the behaviour of the soil and give rise to new collapsible soil zones. The following soils are considered as collapsible: the alluvial and eolian deposits, mud flows, residual grounds, volcanoes rejections, loesses, and embankments slightly compacted or compacted in the dry slope of the compaction curve.

The collapse of Cheria in 2009 in the eastern of Algeria provides a good example of a great collapse, in which tens of constructions were inserted more than two meters and half in the ground. While waiting for the measurements of a technical expertise, the preliminary report relate this catastrophe to the movement in the ground water. A geotechnical study made by LNHC Batna [19] within the scope of the realization of a natural gas station in Hassi Messaoud shows that the site is composed of two layers of collapsible nature, thus the adopted solution is to substitute the first layer and to take measures which allow us to avoid the infiltration of water to the second layer. In addition, degradations that several residence buildings underwent in Biskra were due to the water infiltrations [8]. A building of three floors in Xining, Qinghai, was destroyed beyond repair because of collapse [23]. This problem occurs because the loess beneath the foundations undergoes a structural collapse when flooded. Experimental and theoretical studies being aimed at understanding the great number of uncertainties over the phenomenon of collapse are currently undertaken. The literature revealed that the majority of research was devoted to the collapse mechanisms and the identification methods of the treatment and prediction.

DUDLEY [11] qualitatively describes the collapse of cemented structures and concludes that it does not depend on dampness, but occurs only when the cementing connections are broken by mechanical constraints. On the contrary, if the ground is a mixture of grains and fine particles which induce important connections due to suction or cementing, dampness leads to the cancellation of suction which decreases cohesion and supports collapse. This result was confirmed by CUI and MAGNAN [10]. MORGENSTERN and De MATOS [22], GANESHAN [14] affirmed that the cause of collapse lies in a low water content. BOOTH [7], TING [24] and GANESHAN [14] explain that collapse depends on the initial dry density, the void ratio and the degree of saturation. MARKIN [21] proposes an interval of degree of saturation between 60% and 65% beyond which collapse does not appear any more. The same result is confirmed by GANESHAN [14]. BOOTH [7] and LAWTON [18] observed that for a given dry density the overload which causes collapse is inversely proportional to the natural moisture content of the soil. The destruction of the capillary forces can explain the sudden collapse by flooding the ground [4]. The suctions developed in the clay connections can be different from those developed between the silt grains. Up to now, there is no means to measure these differences [13]. The examination of the macroscopic and microscopic aspects of the sudden collapse is recommended [12]. Abrupt collapse occurs when the dry density and the initial moisture content are low [9]–[20]. If the relative density is higher than 0.65% and the moisture content is close to the optimum of Proctor there is no risk of collapse [2]. In spite of having a high-tech ultrasonic equipment and a great use of this process in various fields, the literature reveals that, except geotechnical marine applications and some other applications, little attention was devoted to this technique in the soil mechanics. This experimental work presents the results of three series of tests. In addition to the compression tests, a series of tests using the cone penetrometer and for the first time the original experimental curves of the non-destructive tests with the ultrasounds are put in parallel, in the objective to propose a predicting method for the collapsible soils based on ultrasonic tests.

2. CHARACTERISTICS OF MATERIALS

The tests were carried out on six reconstructed soils made up of sands and of kaolin in various proportions for which the application of the various criteria of collapse, reported by AYADAT and BELLILI [5], shows that those are collapsible.

Two types of sands, less than 2 mm in diameter, are used for the soils' reconstruction; sand of the dunes of Oum Ali region and sand of stream extracted from the Melag stream of El Aouinet region were washed and dried at 105 °C during 24 hours. In view of a small percentage of fine particles that they contain, these two types of sands are used for the concretes' making. The kaolin used (< 80 μm) is extracted from the Hamame Debagh Mine of Guelma region. It is white in colour and generally used in the manufacture of the fine porcelain, pottery and ceramic products. The soils S1, S2 and S3 are reconstructed with sands of dunes and kaolin, while the soils S4, S5 and S6 are reconstructed with sands of stream and kaolin. The geotechnical characteristics of sands, kaolin and reconstructed soils are presented in table 1. The gradation curves of the reconstructed soils are presented in figures 1 and 2.

Table 1

Characteristics of materials

Materials	Characteristics					
Sand of dunes	Sand equivalent: 73.26% Grain size distribution (0.08 and 2 mm) with 1.36% of particles < 80 μm Coefficient of uniformity: 3.91 and coefficient of curvature: 1.33					
Sand of stream	Sand equivalent: 68.69% Grain size distribution (0.08 and 2 mm) with 3.01% of particles < 80 μm Coefficient of uniformity: 2.19 and coefficient of curvature: 0.94					
Kaolin	%< 2 μm 43% Liquid limit: 65.83% Plastic limit: 39.64% Specific density of grains $G_S = 2.42$					
Reconstructed soils	Label	S1	S2	S3	S4	S5	S6
	% Kaolin	15	35	50	20	30	40
	% Sands of dunes	85	65	50	–	–	–
	% Sands of stream	–	–	–	80	70	60
	G_S	2.65	2.59	2.46	2.62	2.56	2.48
	w_L %	16.47	26.63	35.37	18.47	28.97	33.42
	w_P %	11.03	5.37	20.87	11.95	14.77	19.03
	$\gamma_{d\max}$ (g/cm^3)	2.04	1.95	1.84	1.95	1.82	1.75
	w_{opt} %	8.62	9.43	13.88	12.82	14.67	17.82
	%<2 μm	4.91	1.73	16.74	7.03	9.84	14.12

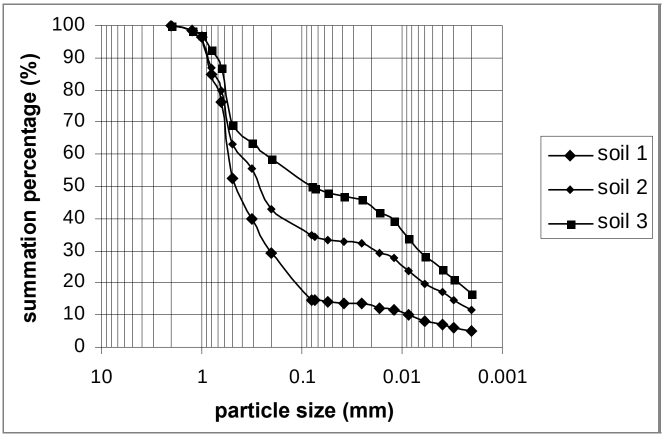

Fig. 1. Grains size distribution curves (soils 1, 2, and 3)

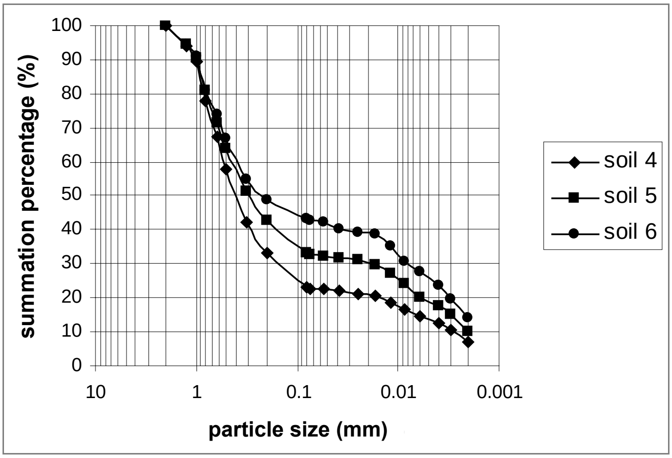

Fig. 2. Grains size distribution curves (soils 4, 5, and 6)

2.1. CHARACTERISTICS OF CONSISTENCY OF THE SOILS

The literature revealed that a soil is expected to collapse if at least one of the following criteria is met [6]: $A_C < 1$, $I_L < 0$, $I_P \leq 20$, $I_C > 1$, $I_W \leq 1$. The results presented in table 2 show that these soils are expected to collapse and that the characteristics of consistency of the reconstructed soils depend basically on the initial moisture content.

Table 2

Characteristics of consistency of soils

Soil	w_0	A_C	I_P	I_L	I_C	I_W	Soil	w_0	A_C	I_P	I_L	I_C	I_W
Soil 1	2	1.11	5.44	–1.66	2.66	0.37	Soil 4	2	0.93	6.52	–1.53	2.53	0.31
	4			–1.29	2.29	0.73		4			–1.22	2.22	0.61
	6			–0.92	1.92	1.10		6			–0.91	1.91	0.92
	8			–0.56	1.56	1.47		8			–0.61	1.61	1.23
Soil 2	2	0.96	11.26	–1.19	2.19	0.18	Soil 5	2	1.44	14.2	–0.90	1.90	0.14
	4			–1.01	2.01	0.35		4			–0.76	1.76	0.28
	6			–0.83	1.83	0.53		6			–0.62	1.62	0.42
	8			–0.65	1.65	0.71		8			–0.48	1.48	0.56
Soil 3	2	0.87	14.5	–1.30	2.30	0.14	Soil 6	2	1.02	14.39	–1.18	2.18	0.14
	4			–1.16	2.16	0.27		4			–1.04	2.04	0.28
	6			–1.02	2.02	0.41		6			–0.90	1.90	0.42
	8			–0.89	1.89	0.55		8			–0.77	1.77	0.55

3. THE MATERIALS USED

3.1. OEDOMETRIC TESTS

The oedometer whose essential elements are an oedometer mould, 50.4 mm in diameter and 20 mm in height, a frame of consolidation of lever arm of 1/10, and a set of weight.

The compaction tamper (figure 3) is designed especially at the laboratory for the compaction of the soil in the oedometer ring. Entirely manufactured of steel, it consists of a base, 48.42 mm in diameter and 3 mm thick, attached to a column of guidance of 280 mm length, through which a piston slips. A stopper sliding along the rod makes it possible to adjust drop height of the hammer. A hammer is circular in shape, with a dish of 84.42-mm diameter and 8.40-mm thickness. Its weight is 121 g and it has a centre drilling of 8.45-mm diameter.

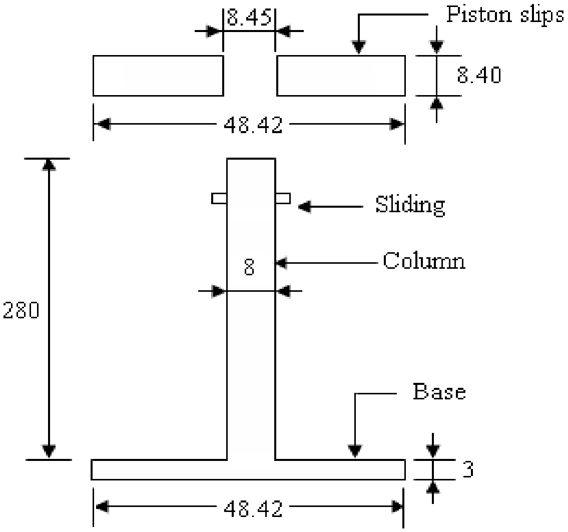

Fig. 3. Compaction tamper

3.2. PENETRATION TESTS

The manual cone penetrometer (figure 4) is made up of a stainless steel, 30 degrees of opening, surmounting a rod. The weight of the mobile system is of 80 g, a comparator of 36 mm/0.01 mm, and a metal dish of 53-mm diameter and 36.4-mm height. Its mass is about 56.2 g.

Fig. 4. Cone penetrometer

3.3. ULTRASONIC TESTS

The equipment (figure 5) includes an analyzer for measuring the velocity of ultrasonic waves, a calibration bar, a set of two transducers of 54 kHz with cables, acting differently as transmitter or receiver, and a paste pot of contact.

Fig. 5. Ultrasonic analyzer

4. PROGRAM OF TESTS

Three series of principal tests were carried out on six reconstructed soils; table 3 illustrates the program of these tests.

Table 3

Test program

Test type	Selected parameters	Test #	Observation
Oedometric tests	Moisture contents: 2%, 4%, 6% and 8% Compaction degrees: 10, 25, 40 and 60 blows	96	Made according to Jennings' and Knight's procedure
Penetration tests	Moisture contents: 2%, 4%, 6%, 8%, 10%, 12%, 14% Compaction degrees: 10, 25, 40 and 60 blows	168	Made with the cone penetrometer
Ultrasonic tests	Moisture contents: 2%, 4%, 6% and 8% Compaction degrees: 10, 25, 40 and 60 blows	96	Supplied to the ultrasonic analyzer

5. TEST PROCEDURE AND REALIZATION

5.1. OEDOMETRIC TESTS

The soil tested consists of sand and kaolin in the proportions mentioned above. The soil is brought to the required moisture content by the addition of distilled water; the soil–water mixture must be well homogenized in a porcelain mortar. Then it is poured into the mould of the oedometer and compacted using the compaction tamper. The compaction of the soil consists in dropping the hammer which slides along the rod of the tamper (a height $H = 15$ cm), which will strike the dish that transmits the shock to the specimen. To make it perfectly plane, the higher face of the sample must be levelled using a rigid blade.

The compression tests with the oedometer are made according to JENNINGS' and KNIGHT's procedure [16] which consists in the application of the following loads: 25, 50, 100, and 200 kPa. Then, the sample is flooded and a new settlement value recorded, afterwards the loading is increased up to 400 kPa. During the test the settlements are recorded after 15 s, 30 s, 1 min, 2 min, 5 min, 10 min and 24 h.

5.2. PENETRATION TESTS

The tests are performed with a cone penetrometer provided with a metal dish. The soil reconstruction, the mix filling and the compaction in the dish are carried out in same manner as that in the compression tests. The cone with its rod comes into the contact with the upper face of the soil sample. The cone penetration into the soil is measured with the comparator. The Δh penetrations of the cone are carried forward, relating to the selected parameters.

5.3. ULTRASONIC TESTS

This series of tests starts with the calibration of the analyzer, by measuring the transmission speed of the wave through the calibration bar. There is measured the velocity of an ultrasonic wave train, which crosses soil specimens, produced in the oedometric mould, according to the procedure of the compression tests. To guarantee a good transmission of the waves in the body of the specimen and before adjusting the system of measurement, thin layers of contact grease are applied to the two faces of the transducers (transmitter and receiver). On the screen of the analyzer there is represented the transit time or the speed of the wave, that according to the configuration of the analyzer.

6. RESULTS AND INTERPRETATION OF TESTS

The results of this experimental work are presented in two parts; the first concerns the standard tests (tables 1 and 2) (the characteristics of materials and the characteristics of consistency) necessary for the geotechnical identification of the materials used and the soils reconstructed. The second is distributed as follows:

6.1. OEDOMETRIC TESTS

6.1.1. DEPICTION OF SOIL COLLAPSE

The variations of the moisture content and the energies of compaction allow us to check whether these soils have the properties of collapsible soils. The variations of moisture content and energies of compaction make it also possible to control the collapse potential. The curves obtained are similar to those of KNIGHT’s and JENNINGS’ [17] as shown in figures 6 and 7.

The collapse potential CP (%) is calculated from the relation:

$$CP = \frac{\Delta e_c}{1+e_0} \times 100\% , \tag{1}$$

where: $\Delta e_c = e_1$ (200 kPa) – e_2 (200 kPa, flooded), and e_0 is the initial void ratio.

The results of these tests show that the collapse potential CP varies for

- Soil S1: from 0.52% to 7.54%.
- Soil S2: from 0.59% to 8.34%.
- Soil S3: from 0.83% to 8.92%.
- Soil S4: from 0.66% to 7.61%.

- Soil S5: from 0.74% to 7.84%.
- Soil S6: from 0.77% to 7.90%.

According to the classification suggested by JENNINGS and KNIGHT [14] (table 4), these results correspond to the headings from “no risk” to “troubles”.

Table 4

Classification of collapse potential

CP	Degree of problem
0% to 1%	No risk
1% to 5%	Moderate trouble
5% to 10%	Trouble
10% to 20%	Severe trouble
>20%	Very severe trouble

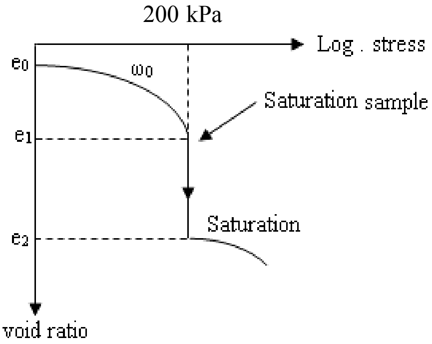

Fig. 6. Typical oedometric curve of a collapsing soil (KNIGHT and JENNINGS [16])

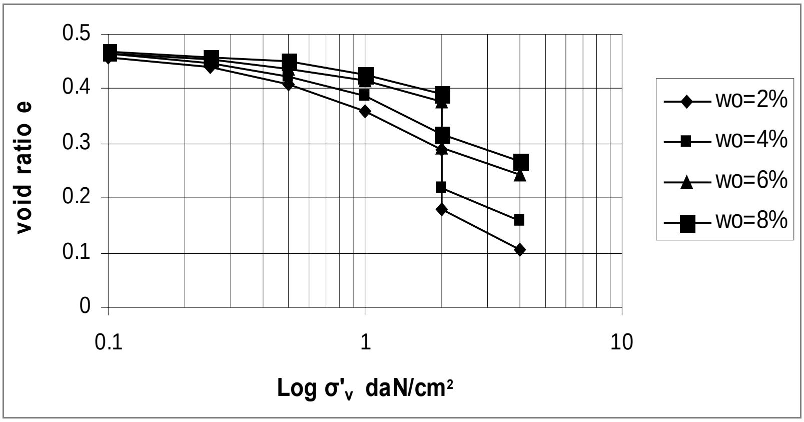

Fig. 7. Oedometric curve of soil 1 (*E* = 10 blows)

6.1.2. INFLUENCE OF WATER CONTENT AND ENERGY OF COMPACTION ON SOIL COLLAPSE

The high collapse potentials are recorded for low initial moisture contents. For a given initial water content the collapse potential is decreasing with an increase in the energy of compaction (figure 8). A decrease in collapse is more obvious than the moisture content increase (figure 9). Under the same conditions of compactness and moisture content, the soil containing the greatest percent of kaolin exhibits the greatest collapse potential. These results agree with those of AYADAT et al. [6] and confirm the observations of ABBECHE et al. [1]. One can conclude that the soils reconstructed at the laboratory display the behaviours similar to those met in situ, therefore suitable for the series of the tests suggested.

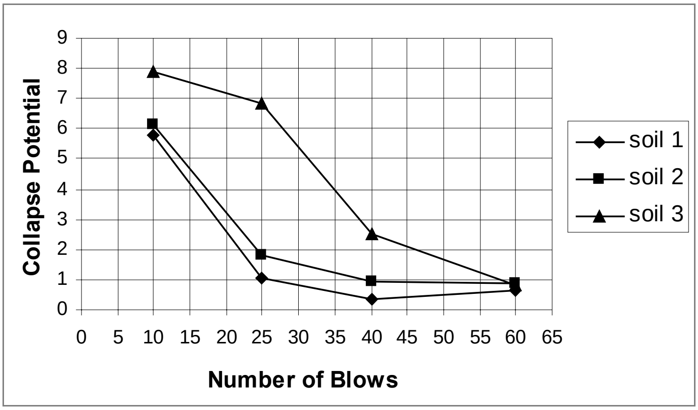

Fig. 8. Collapse potential versus number of blows ($\omega_0 = 6\%$)

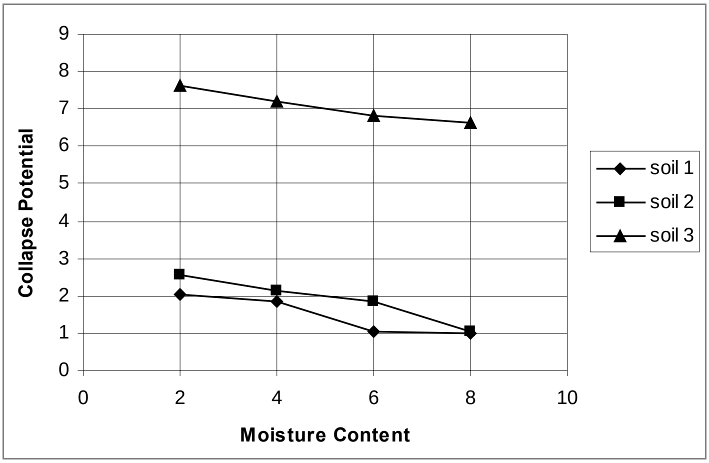

Fig. 9. Variation of collapse potential with moisture content (E = 25 blows)

6.2. PENETRATION TESTS

6.2.1. INTERPRETATION OF PENETRATION VERSUS INITIAL MOISTURE CONTENT w_0

The moisture content between $w = 2\%$ and $w = 8\%$ does not give any clear idea on the behaviour of the soils studied; thus the water content is increased up to 14%. Each curve obtained can be divided into two parts based on its slopes (figure 10). In the first part, the collapse decreases gradually with an increase in the moisture content until a lower limit when the moisture content approaches the Proctor optimum. In the second part, one observes an opposite behaviour – the collapse increases with the growth of the moisture content. Considering the speed of compaction and its convenience compared to the Proctor test, it can be more practical for the compaction projects of the collapsible soils to use the test of the cone penetrometer for the determination of the limit penetration and the corresponding moisture content which divide the penetration curves into two parts of different slopes, the first is "dry" and the second is "wet". This is an analogue of the Proctor test that the optimum separates also the curves into two slopes, "dry" and "wet". A similar performance is measured for all the soils tested. One can deduce that for collapsible soils there exists an inverse relationship between the penetration test and the Proctor test, the first being used to determine the limit penetration, and the second – the maximum dry density.

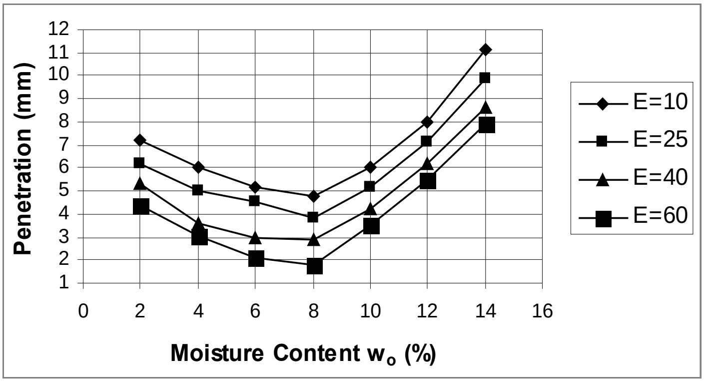

Fig. 10. Variation of penetration with moisture content (Soil 1)

6.2.2. INTERPRETATION OF PENETRATION VERSUS w_{opt}/w_0

Collapsible soils are characterized by the condition $w_{opt}/w_0 > 1$, HOLTZ and GHILF [15]. The analysis of the penetration curves versus the w_{opt}/w_0 ratio (figure 11) confirms the existence of two distinct behaviours being separated by the line $w_{opt}/w_0 = 1$. On the left of this line, the penetration gradually decreases, then it grows in a roughly regular way as one moves away from the limit separating the collapsible soils ($w_{opt}/w_0 > 1$)

from the noncollapsible soils. This limit corresponds to the limit penetration indicated by P_{lim}.

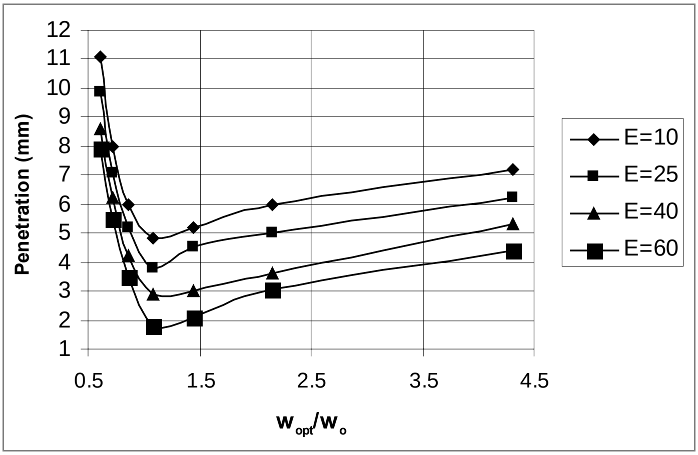

Fig. 11. Variation of penetration with w_{opt}/w_0 (Soil 1)

6.2.3. INTERPRETATION OF PENETRATION VERSUS γ_d/γ_s

The same statement is visualized in the representation of the penetration against the ratio of density γ_d/γ_s (figure 12). We observe a gradual decrease of the penetration depth up to a limit value corresponding to the straight line separating the two states of soils. Then a phase of a progressive increase with the growth of this ratio is visible. The similarity of the previous curves illustrates the existence of a similar behaviour of the collapsible soils with respect to the penetration and also shows that a limit characteristic value separates the collapsible soils from the noncollapsible soils.

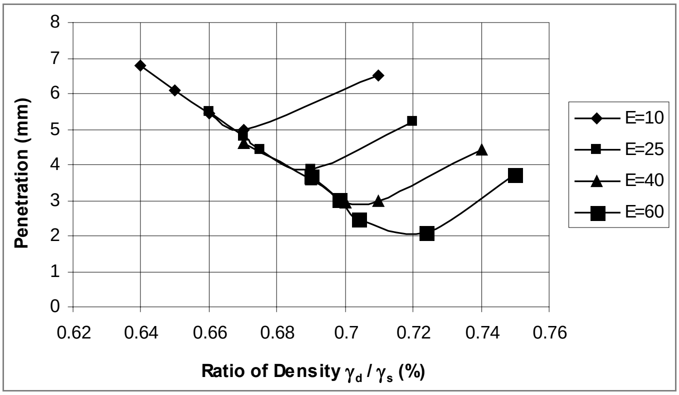

Fig. 12. Variation of penetration with γ_d/γ_s (Soil 5)

6.3. ULTRASONIC TESTS

6.3.1. INFLUENCE OF MOISTURE CONTENT AND ENERGY OF COMPACTION ON SOIL COLLAPSIBILITY

The results of the ultrasonic tests show that ultrasonic speed varies, depending on the variation of the energy of compaction and/or moisture content (figures 13 and 14). For the same value of the energy of compaction, whatever the soil, the ultrasonic speed is increasing with the growth of the moisture content.

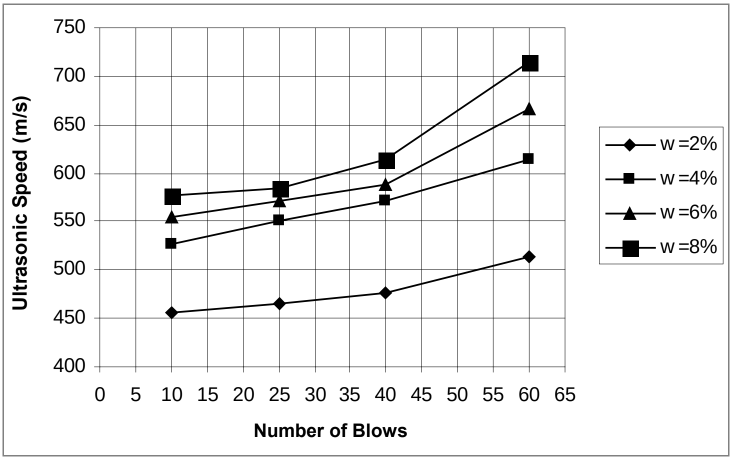

Fig. 13. Variation of ultrasonic speed with number of blows (Soil 4)

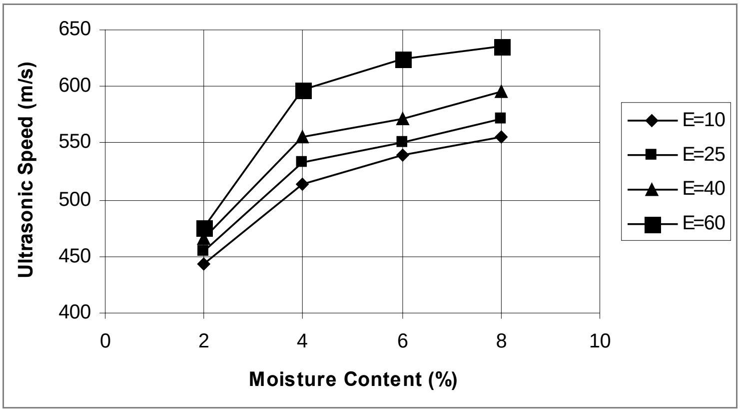

Fig. 14. Variation of ultrasonic speed with moisture content (Soil 1)

The growth of compaction contributes to the increase of speeds, especially if the moisture content comes close to the Proctor optimum. Let us note that the curves corresponding to 60 blows present more important speed values compared to other energies of compaction, especially with the increase in the moisture content. This proves a good state of compactness due to the humidification and the rearrangement of the grains; it is the case of noncollapsible soils.

6.3.2. PREDICTION OF COLLAPSE BY ULTRASONIC TEST

Figures 15 and 16 show a vital relationship between ultrasonic speed and potential collapse; the decrease in one of them is synchronized with the increase in the other. In figure 15, the curves assume the same shapes. They pass through three phases: At the beginning parallel straight lines represent an important fall of the *CP* with very close speed values. Then, two successive slopes of the curves are noted; in the first, a reduction of *CP* corresponds to an increase in speeds; in the second, the stabilization of collapse is explained by the great values of speed and very close collapse potentials.

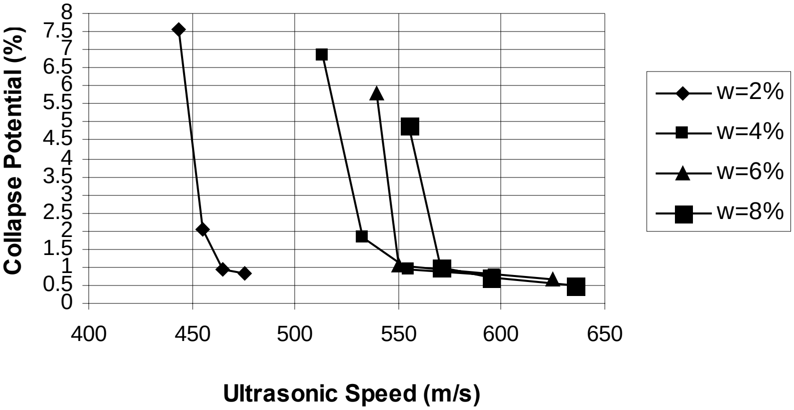

Fig. 15. Variation of collapse potential with ultrasonic speed for *w* (%) (Soil 1)

The curves of collapse potential, depending on the speed, show that the compaction and the water content take part in the reduction of collapse and the increase in ultrasonic speeds. Figure 16 shows that the energy of compaction contributes more effectively than the water content to the reduction of collapse. At a higher energy of compaction, responsible for the noncollapsibility of soils, the variation in the state of soil compactness is low, which is valid for various proportions of water content, while speed variation proves more important.

Based on these observations, the values of ultrasonic speeds are compared against various water content and compaction energy. Since the soils tested can collapse when they are loose, it is possible to propose the method for predicting collapsible soils based on ultrasonic tests (nondestroyed) fast and easy to realize.

The values of ultrasonic speed are limited as follows:

- $V \leq 400$ m/s → collapse appears.
- 400 m/s $< V <$ 1000 m/s → collapse can occur.
- $V >$1000 m/s → no risk of collapse.

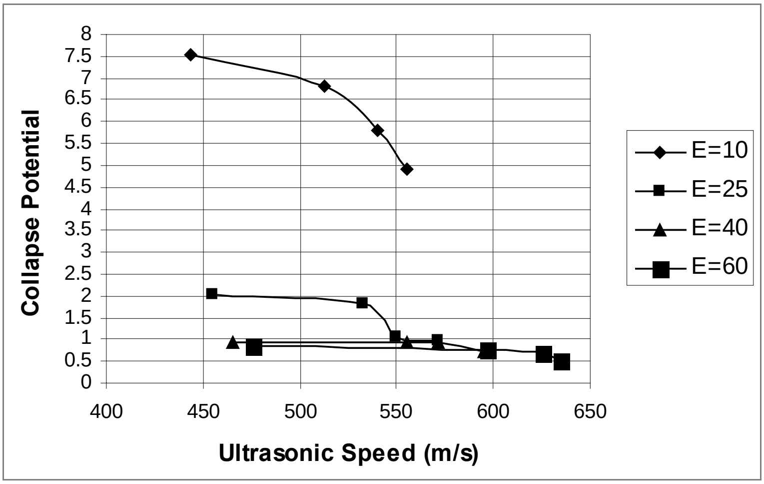

Fig. 16. Variation of collapse potential with ultrasonic speed for *E* (Soil 1)

In the second case, the soil susceptibility to collapse depends on the water content and the compactness of soil. This procedure can be applied to the restructured or intact soil, at the laboratory and even on site. Considering its advantages, the results of the ultrasonic examination can be applied to various types of collapsible soils such as loesses and other unsaturated soils.

6.3.3. LIMIT PENETRATION VERSUS ULTRASONIC SPEED

The results of the compression tests using the oedometer show that the energy of compaction which corresponds to 60 blows makes the soils noncollapsible, independently of the percentage of fine particles and water content. This agrees with the representation of the limit penetrations versus ultrasonic speeds (figure 17), which shows that the reduction of limit penetrations is increasing with the increase of ultrasonic speeds. For the energies of compaction varying between 10 and 40 blows, the soils remain likely to collapse and the curves have almost the same slope and are represented by the same tendency equations. A remarkable slope of these curves is visualized by applying the energy of compaction equal to 60 blows, which explains a similar behaviour specific to the collapsible soils and which differs from the behaviour of the noncollapsible soils.

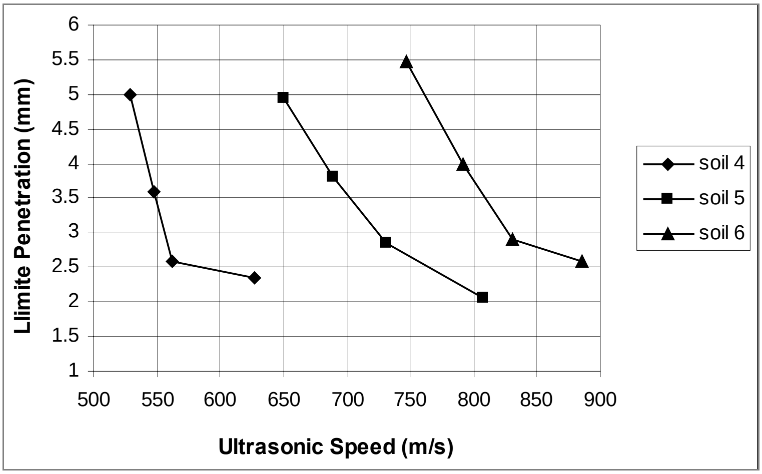

Fig. 17. Variation of limit penetration with ultrasonic speed

7. CONCLUSION

The principal conclusions which one can draw from this study are summarized as follows:

1. The experimental program allows the behaviour of the collapsible soils to be characterized in a satisfactory manner.

2. Collapsible soils can be reconstructed in the laboratory by mixing, in various proportions, kaolin with fine particles of sand, which makes the water content lower than the optimum of Proctor and the energies of compaction moderate.

3. The results obtained clearly show the influence of certain parameters such as kaolin content, water content and energy of compaction on the collapse potential, the limit penetration and the ultrasonic speed.

4. The collapse potential can be excessive if the initial water content is low. For water content lower than the optimum of Proctor, there exists the energy of compaction beyond which collapse does not occur.

5. The possibility of using the cone penetrometer as identification means of the collapsible soils makes it possible to follow the evolution of collapse and to propose a limit penetration, separating the collapsible soils from the noncollapsible soils.

6. A new experimental approach to the prediction of collapsible soils based on ultrasonic tests, easy and fast, is proposed. The results obtained depend on grain-size distribution, compactness of soil and water content. Ultrasonic speeds are limited as follows:

- $V \leq 400$ m/s, collapse appears.
- $V > 1000$ m/s, no risk of collapse.

- Between these two limits collapse can occur, it depends on water content and compactness.

7. The ultrasonic test can be carried out in a laboratory or in situ, on intact or altered samples of an unspecified form.

8. The ultrasonic speed of metastable soils gives an idea of the state of compactness; it is in inverse proportion to the potential of depression.

REFERENCES

[1] ABBECHE K., MOKRANI L., BOUMEKIK A., *Contribution à l'identification des sols effondrables* [J], Revue Française de Géotechnique, 2005, 110, 85–90.

[2] ABBECHE K., HAMMOUD F., AYADAT T., *Influence of Relative Density and Clay Fraction on Soils Collapse. Experimental Unsaturated Soil Mechanics* [C], Springer Proceedings in Physics, 2007, 112, 3–9.

[3] ABELEV M.Y., *Loess and its Engineering Problems in the USSR*, Proc. of the Int. Conf. Engineering Problems of Regional Soils, Beijing, China, 1988.

[4] ALONSO E. et al., General report, Proc. 9th Conf. Soil Mech., Dublin, 1987, 3, 1087–1146.

[5] AYADAT T., BELLILI F., *Sols susceptibles d'affaissement: Identification mécanique et traitement*, Revue Algérie Equipment, 1995, No. 20, 18–23.

[6] AYADAT T., OUALI S., *Identification des sols affaissables basée sur les limites d'Atterberg*, Note Technique, Revue française de géotechnique, 1999.

[7] BOOTH A.R., *The Factors Influencing Collapse Settlement in Compacted Soils*, [in:] Proceedings of the 6th Regional Conference for Africa on Soil Mechanics and Foundation Engineering [C], Dublin, South Africa, 1975, 57–63.

[8] CTC BSKRA., *Intervention du directeur du CTC de Biskra*, 2eme Colloque Maghrébin de Génie Civil, Biskra, Algérie, 10, 11 December 2002.

[9] CUI Y.J., DELAGE P., SCHLOSSER F., WONAROWCZ M., *Etude du comportement volumique d'un lœss du nord de la France*, Xlléme congrès Européen de Mécanique des sols et de Géotechnique, Amsterdam, 1999, Vol. 1, 337–342.

[10] CUI Y.J., MAGNAN J.P., *Affaissement locaux dus à l'infiltration d'eau en géomécanique environnementale*, Chapitre n°6 « Risques naturels et patrimoine », Ed. Hermes, 2000, 139–164.

[11] DUDLEY J.H., *Review of Collapsing Soils* [J], Journal of Soil Mechanics and foundation div ASCE, 1970, 96, n° SM3, 925–947.

[12] FEDA J., *Mechanisms of collapse of soil structure*, [in:] E. Derbyshire (ed.), *Genesis and properties of collapsible soils*, NATO Series C. Mathematical and Physical Sciences, 1994, Vol. 468, 149–172.

[13] FREDLUND D.G., RAHARDJO H., *Soil Mechanics for Unsaturated Soils*, New York, John Wiley and Sons, inc, 1993.

[14] GANESHAN V., *Strength and Collapse Characteristics of Compacted Residual Soils*, Thesis (M.E), Asian Institute of Technology, Bangkok, Thailand, 1982.

[15] HOLTZ W., GHILF J.W., *Settlement of Soil Foundation due to Saturation*, [in:] Proceeding 5th International Conference on Soil Mechanics and Foundation Engineering, 1961, Vol. 3, 673–679.

[16] JENNINGS J.E., KNIGHT K., *The Additional Settlement of Foundation due to Collapse of Sandy Soils on Wetting*, [in:] Proceeding 4th International Conference on Soil Mechanics and Foundation Engineering, 1975, 316–319.

[17] KNIGHT K., JENNINGS J.E., *A guide to construction on or with materials exhibiting additional settlement due to collapse of grain-structure*, Proc. 6th Regional Conf. for Africa on SMFE, Durban, South Africa, 1975, 99–105.

[18] LAWTON E.C., FRAGASZI R.J., JAMES H.H., *Collapse of Compacted Clayey Sand* [J], Journal of Geotech. Eng. ASCE, 1989, Vol. 155, No. 9, 1252–1267.

[19] LNHC, Projet Extension des Gazoducs à Hassi Messaoud, Rapport de reconnaissance de sol, Laboratoire National de l'Habitat et de la Construction de Batna, Algérie, 2000.

[20] LOISEAU C., CUI Y.J., De LAURE E., *Etude du comportement des loess sur le tracé du TGV Est*, rapport de recherche TERRASOL, 2001.

[21] MARKIN B.P., *Discussion on standard criteria of Sag in Loess soils*, Soil Mechanics and Foundations Engineering, 1969, No. 2, 137.

[22] MORGENSTERN N., De MATOS M.M., *Stability of slopes in residual soils*, Proc. 5th. Pan American Conf. on Soil Mech. and Found Eng., Buenos Aires, Argentina, 1975, 3, 367–383.

[23] QIAN H.J., LIN Z.G., *Loess and its Engineering Problems in China*, [in:] Proceeding of the International Conference Engineering Problems of Regional Soils, Beijing, China, 1988, 136–153.

[24] TING W.A., *Consolidation of a partially saturated residual soil*, Proc. 6th Asian Reg. Conf. on Soil Mech. and Found. Eng., Singapore, 1979, Vol. 1, 95–98.