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Prediction of the Strength Behaviour of the Sandy Soil by using Collapse Potential in the Kintele Site-Congo

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Abstract

This work aims to evaluate the water effect on the soils collapse potential. The laboratory tests based on the soils samples preparation determined the soils properties. Parameters such as water content, dry unit weight, degree of saturation, voids ratio and particles size distribution were determined. The collapse potential was analysed indirectly according to various researchers criteria. The results confirmed the high vulnerability of the study area to collapse. The oedometer tests determined the values of the collapse potential showing the conventional relationship between the collapse potential and the water content. It is noted that increasing water content leads to decrease soils strength to collapse, and the increasing progress of collapse poses a risk to constructions on silty sand. The collapse potential decreases with the increase in the relative density keeping the water content constant. This collapse potential caused by soil water content variation can be reduced from compaction.

Keywords: Collapsible soils, Collapse potential, Collapsibility, Saturated soil, Unsaturated soil, Sandy soil, Water content.

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Contents

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Contribution of this paper to the literature
This work contributes to solve and to make clear problems related to constructions which are exposed to the risk of collapse.

1. Introduction

In geology and geotechnical engineering, soil collapse phenomena with a significant percentage of fines induce differential settlements, leading to damage of infrastructures (building, foundations and retaining structures). Sudden collapse potential is occurred many times on unsaturated soils with potential deformations and radical rearrangement of grains after wetting. These soils with loose structures are often made of grains ranging from clay to fine sand. They are particularly located in areas with a complex relief. These regions have become vital today, in view of the demographic and technological evolution of the man who exploits his wealth. The occupation of these areas necessarily leads to the modification of their original properties. This favours the ideal environment for soil collapse and consequently the ruin of constructions [1].

Many existing researches noticed many unsaturated soil problems confronted by engineers, related to collapsible and expansive soils under wet conditions. From the volume changes, the soils can remain problematic in construction engineering due to their expansion, collapsibility, dispersion, and sometimes excessive settlement with a loss of strength. Certain soils behaviours can be referred to their mineralogy, the pore liquids nature, or their particles arrangement. Collapsible soils have tendency to collapse as a closely packed, with a significant reduction of their volume. The collapsible soils have a non-significant inter-particle link strength which is destroyed by either soil filling, saturation of soil or a mixture of both conducting to soil collapse occurrence [2]. Constructions on collapsible soils are often suffered of unexpected settlements, with tendency to produce awful failure. In general, an inundation of the soils in metastable state causes collapse in loess soil and engorgement for some clayey soils. Then, in geotechnical engineering the collapsible soils instability is associated to the effect of water when the soil is under wetting conditions. These types of soils lead to high defies in foundations engineering [3].

Collapsible soils have become a grave engineering problem and a geotechnical challenge all over the world. These soils can be formed naturally or by man activity and sometimes represent a natural risk for a man and his property [4]. Unexpected collapse happens once wetting or surcharge surpass the yield of the material resistance [5]. Collapsible soils are largely formed by silt and fine sandy soils, sometimes with low clay content. The soil can be affected by wetting, such as rainfalls and groundwater level growth, or by man activities. Though, collapsible soils are conquered for man activities. Many factors can describe the collapse behaviour of soils such as the collapse prediction related to any type of unsaturated soils, the compacted soils with perfect water content; the capillary action in the soils which yields shear stresses; the increasing compressibility that causes a shear strength reduction of soils leading them to failure [6].

Studies based on soils collapsibility behaviour consider the collapse potential as an essential monitor for foundations design [6]. The evaluation of soils collapsibility from many criteria has been well-defined by several investigators. Research works related to soils collapsibility could be find in existing literatures [7-14].

Collapse potential was firstly revealed by Jennings and Knight [6] and repetitive tests were advanced to measure soil collapse. Schwartz [15] systematically revised these works in the art paper state. Foundations for collapsible soils have tendency to be predictable when they are built on a collapsible soil layer, excavation and re-compaction of the material with drainage safety to avoid inundation process.

The works based on the collapsible soils properties deal with the identification, laboratory tests and engineering properties of collapsible soils [16]. Collapsible soils could mostly be recognised by using laboratory tests of particles size, Atterberg limits, dry density, saturation degree which are able to predict collapse. Oedometric or triaxial laboratory tests could determine the collapse potential with some plain restrictions for disturbed soils samples as revealed by Houston, et al. [17]. Fredlund and Gan [18] moved off the collapse relationships by using a similar method to consolidation principle and including suction stresses. Lin [19] proposed instructive test outcomes for unsaturated soils highlighting the effect of overload stresses, suction stresses and saturation degree. Schwartz [15] evoked that the degree of saturation remained important in evaluating collapse potential, being a degree of saturation at a critical level during the collapse occurrence. Inopportunely this perception can be essentially disregarded in practice, while McKnight [20] replicated the Schwartz data and additional information, thus made a convenient illustration of an overall relationship among critical saturation degree and percentage of fines. Schwartz [15] also considered the effective pressure in the design of any construction structures.

Compilation delivered by Rogers [2] produced the meanings of collapsible soils from many studies such as a soil with a considerable volume variations by wetting, loading, or a mixture of both. Any unsaturated soil with particles rearrangement can show significant loss of volume by wetting with or without further loading [14]. There are additional settlements caused by unsaturated soils, without some increase in practical stresses. Some existing works are focused on the wetting state of unsaturated soils under consolidation which is associated to apparent cohesion of unsaturated soils. Residual soils sometimes involve minerals decomposition from rocks leading the soils willing to collapse. Residual soils have greatest high spatial changes, therefore their potential collapse becomes difficult to predict. Aeolian Soils include dunes and loess found as sandy silt covering abundant of the earth's surface where alluvial soils and colluvial soils are moved by water or by gravity and may be extremely collapsible [5, 6].

Sandy soils cover the northern part of Congo Republic including the study area. An amount of problems related to these sands were emphasised by existing works [21]. The major geological and geotechnical problem was observed to be the great collapse potential of these sands under different conditions.

In this work is founded on soil sampling with laboratory tests to evaluate the collapse phenomena in the study area. Then, the selected site represents the northern area of Ignie department, Congo republic as shown in Figure 1.

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2. Materials and Methods

2.1. Study Area

Information about the climate, relief and geology of the study area is vital for the soils engineering properties and it is a pre-requisite for the design of foundations. The study area is located in the Northern part of Kintele, in Southern part of Ignie Department as can be seen in Figure 1.

Morphologically the study has a flat relief, valleys and hilly areas. The years 80's were less warm than the years 90's. Two periods plainly characterize the recent evolution of temperatures in Congo before 1970 and after. Brazzaville presents a net variation of temperature from 1932 to 2010 showing an increase of +0.5°C to 1°C as average temperatures in the preceding two decades. But it is noticed the maximum and minimum average temperatures in the 1990s with an increase for the two recent decades. The maximum and minimum altitudes are 1100 m and 360 m respectively. The climate is tropical with a rainy season from October to May, and dry seasons between January-February and June-September. The annual rainfall oscillates among 1250 mm and 1350 mm/year [22]. The hydrogeological group is part of the Bateke's water table, with an area of 270 km². The aquifer components are sandstone with a weak contribution to the groundwater mineralogy. But two zones are identified using the Ca2+/Mg2+ ratio. The first zone determines the calcium minerals showing weathering process and the second one with ratio higher of Ca2+/Mg2+ which shows the dissolution of magnesium [23]. The soils are settled on different materials of three sedimentary series from the base to the top, made of the sandstone series of Inkisi, the sandstone series of the Stanley Pool and the series of Bateke's plateau. The soils are ferrallitic and hydromorphic. In general, these soils have very low clay content [24]. The Central Basin, involves the intracratonic depression of Central Africa with accumulation of sediments, tectonic activity and erosion process during a long history. Then the geological background consists of a Precambrian to Paleozoic age formation supporting a Mesozoic to Cenozoic sedimentary cover that rests unconformably on a Precambrian basement. Thus, the Precambrian to Paleozoic basement which appears downstream from the Stanley Pool and the sedimentary cover is formed by essentially sandy materials which outcrop upstream from the Stanley Pool series [25].

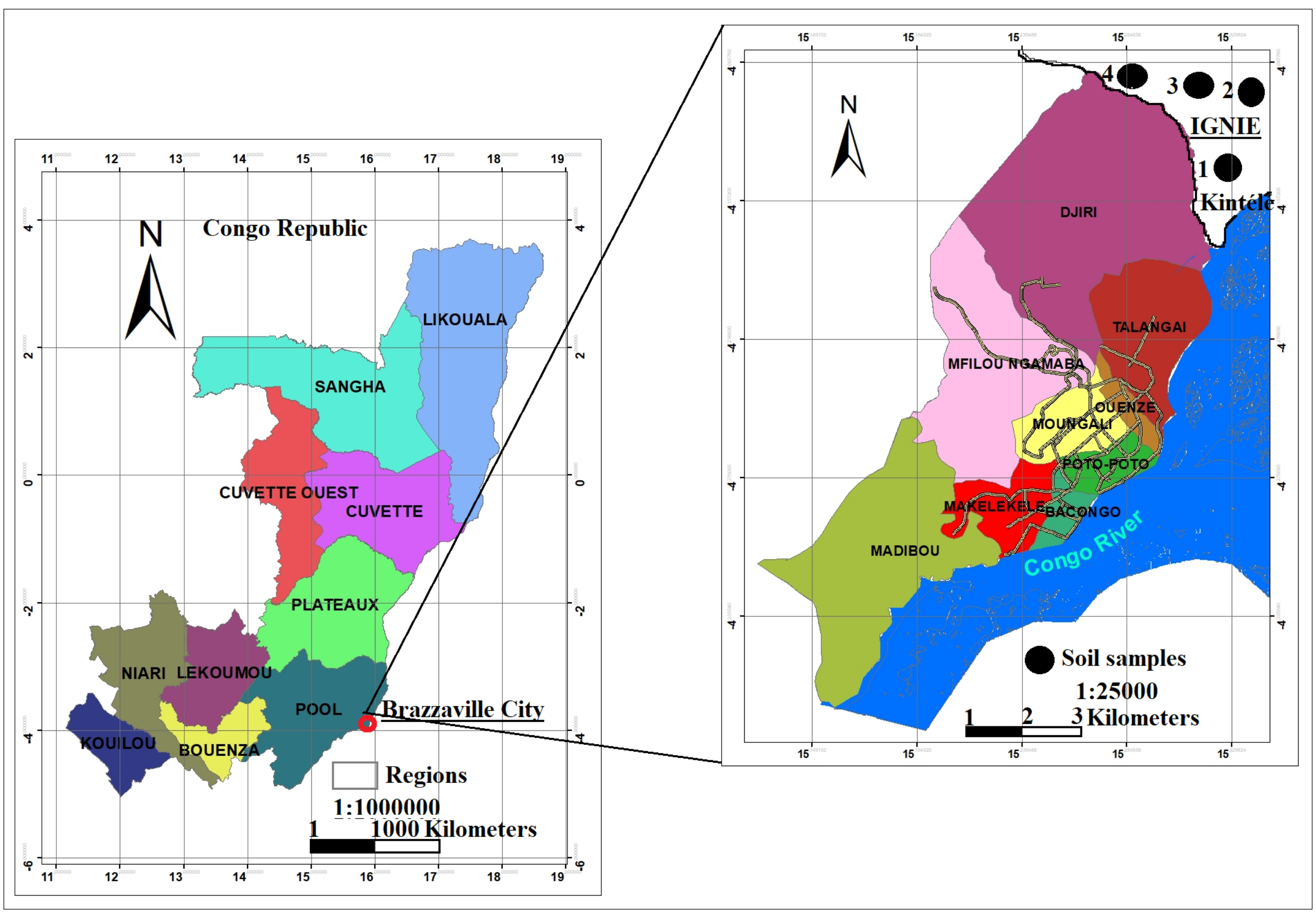

Figure 1. Study area.

2.2. Methodology

The study used terrain data related to geography, geology, superficial water and ground water to pick out soil specimens. The method of pits was selected for this study with four pits excavated followed by soils samples collection where, different laboratory tests were performed. The collected information was used to determine the collapsible soils localities in the study area. Founding on the field study; there was no important variation in soil visual observation, therefore four pits were selected to perform laboratory experiments.

2.2.1. Sampling Techniques

Founded on the pits locations, disturbed soil samples from four sites were taken at 1.4 m depth. The soil is considered non-cohesive and difficult to obtain undisturbed soils samples. And also, the undisturbed samples have tendency to be affected through transportation due to the large distance from the study area to the Laboratory site. Therefore disturbed samples were taken for laboratory tests and soil samples preparation, considering the scarce investigation in the study area, and the analogous and continuous soil layers observed using visual description of the soil from the pits.

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2.2.2. Experimental Study

The tests performed are: Determination of water content in natural state, particles size determination, Atterberg Limit, density, Proctor test, Specific gravity, consolidation tests. After different tests performed, the soils classification was carried out according to AASHTO and USCS systems.

2.2.2.1. Preparation of soils specimens

Using a 1.4 m depth for each soil sample, the soil samples were kept in plastic bags and brought to the laboratory. The preparation of samples followed the AASHTO T87-86 standard.

2.3. Laboratory tests

The laboratory tests considered at first the preparation of the soils specimens submitted to experiments to determine the soils properties. The tests included the distribution of grains size, proctor test for the maximum dry density and the optimum water content, Atterberg limits, specific gravity, and to end the oedometer test to determine the collapse potential of the soil. Soil samples collected for various laboratory tests are important to determine the sectors where collapsible soils are met in the study area. The majority of the laboratory tests were performed founded on the AASHTO manual in the case of soil testing, and the use of ASTM manual for certain laboratory tests.

2.3.1. Oedometer Tests

The tests were performed with a standard front loaded odometer, carefully following standard trials [6]. For the double odometer tests, dry soil samples were loaded in phases to σ_v = 200 kPa for the residual water content and inundated soil samples. For the single odometer tests, dry samples received a load in phases to σv = 100 kPa before being inundated just after loading to σv = 200 kPa. The swamping of samples just once loading in the 12 and 200 kPa is a deviation after usual practice [6], in which swamping is made next a full unsaturated soil samples by loading phase. Though, the the results of the oedometer tests including the data repeatability recommend that values of collapse potential are comparable to those found by using normal practice. All soil samples were discharged in phases to σv = 12 kPa. For the stages with pressures of 12 and 200 kPa, there were successions of tests at w_n = 6%, during the unloading phase.

2.4. Collapse Potential Assessment

The collapse potential recognition by international criteria is used from data provided by the Genesis and collapsible soils properties being a large variety of dry densities for collapsible soils [16]. Soil properties identification involves diverse mechanisms as a vital procedure. Collapsible soils can be studied by using indirect and direct approaches.

2.4.1. Direct Methods

These methods are based on values measurement by using single and doble oedometer tests in the laboratory considering the resultant stresses. Then the results can predict the settlement potential including the evaluation of the collapse potential by using the ASTM D *5333* method in the laboratory. This method is based on the determination of the collapse potential ratio that will occur for a certain vertical pressure and an index for assessing the collapse potential. This method can be used for soil samples in different consevation states.

2.4.2. Indirect Methods

In general, there are diverse approaches to study the susceptibility of soil to collapse, founded on the Coefficient of subsidence (K) and KD values as shown in Table 1 [26, 27].

Table 1. Criteria reported for the identification of soils susceptibility to collapse.

Authors	Year	Criterion
Denisov	1951	Coefficient of saturation k = (Saturated void index)/(Natural void index) k = 0.5-0.75: highly collapsible soils k = 1.0: loamy clay soils not collapsible k = 1.5-2.00: non-collapsible soils
Priklonski	1952	K= (Natural Water Ccontent - Liquid Limit)/(Plasticity Index) *KD < 0: soils with high collapsibility* KD > 0: non-collapsible soils KD > 0: swelling soils
Soviet Bulding Code	1962	L =(e_0-e_l)/(1 + e) e_0 e_0: natural voids index L: saturated voids index When a saturation degree is 60%, if L> -0.1: collapsible soils
Feda	1964	kL= w_o/sr-Ip/LL *w_o: natural water content* s_r: natural degree of sturation *Ip: Plasticity index* LL: Liquiquity limit *When s_r <100%, kL > 0.85: collapsible soil*

Table 2 shows a summary of several authors' proposals to determine the potential collapse.

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Table 2. Potential collapse classification for constructions [6].

Cp (%)	Severity of the problem
From 0 to 1	None
From 1 to 5	Moderate
From 5 to 10	Problematic soils
From 10 to 20	Serious
> 20	Very serious

While the oedometric tests are the most widely used in the laboratory to assess the possibility of collapse occurrence. Although there are embodiments of oedometric tests, then for the present work the double odometric test was used under the conditions of natural water content and under saturated condition for the same sample. The methods for evaluating collapse potential in this research are summarized in the Table 2. The validation of these methods presented in Table 2 was carried out by comparison with the collapse potential, considering the following equations [6]:

$$I=(\Delta_{ec})/[1+(e_{nat}/e_{onat})e_{omean}] \quad (1)$$

$$\Delta_{ec}=[(e_{nat}/e_{onat}) - (esat/e_{osat})e_{omean}] \quad (2)$$

$$e_{omean}=[(e_{onat}+ e_{osat})/2] \quad (3)$$

Where; $e_{ona}t$ and e_{osat} are initial void ratios in the natural and saturated conditions, respectively. These parameters are obtained following the completion of the oedometric tests. The criteria for categorizing the collapse potential can be found in Table 2.

Table 3. Particles size.

Particles size (µm)	Type of soil	Percentage
< 2	Clay	6%
2 - 63	Silt	18%
> 63	Sand	77.9%

Table 4. Soil density.

Specimens	M_0	M_S	M_1	M_2	γs (g/cm³)	Average
1	69	100	195	176	3	
2	68	106	199	175	3	3
3	68	102	197	175	3	
4	69	102	195	177	3	

Table 5. Results of Atterberg limits.

Parameters	Specimen 1	Specimen 2	Specimen 3	Specimen 4
Coefficient of uniformity (Cu)	3.1	4.2	2.6	3.2
Coefficient of Curvature (Cc)	1.5	1.7	1.6	1.8
Liquidity limit, WL	17	16	19	18
Plastic limit, Wp	14	12	13	12
Plasticity Index, (P)	5.0	5.0	5.0	5.0

Table 6. Classification of settling soils according to collapse potential values [6].

Collapse Potential (Cp), %	Problem gravity
0 - 1	Non-collapsible soil
1 - 5	Moderately collapsible soil
5 - 10	Problematic soil
10 - 20	Very collapsible soil
> 20	Very severe collapsible soil

Table 7. Soil properties.

Ec	20	40	60	20	40	60	20	40	60
W_o (%)	2	2	2	4	4	4	6	6	6
e_o	0.881	0.853	0.822	0.756	0.715	0.675	0.681	0.641	0.611
γ_d	14.18	14.46	14.59	15.18	15.90	16.10	15.86	16.24	1.655
Cp (%)	14.88	12.30	12.40	15.56	13.72	12.79	16.88	14.07	13.98

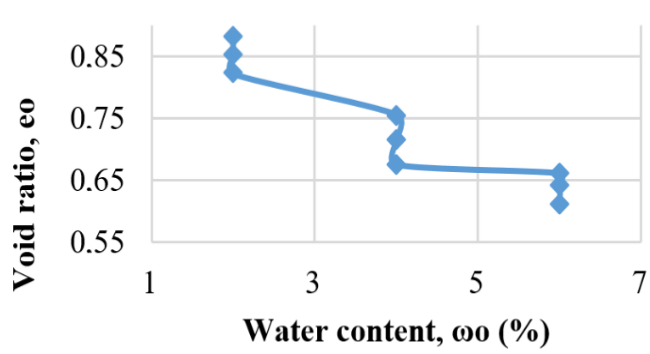

Figure 2. Water content vs Void ratio.

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Table 8. Values of collapse potential in the study area.

Sample	Locality	Authors			
		Denisov	Priklonski	Soviet Building Code	Feda
		Parameter (K)	Parameter (k_D)	Parameter (L)	Parameter (k_L)
1	Kintélé	0.65	-0.87	-0.08	0.98
2	Lifoula	0.58	-0.67	-0.06	0.88
3	Mandiélé	0.61	-0.31	-0.02	0.91
4	Ignie	0.55	-0.29	-0.05	0.89

3. Results

Cu = 3.3 and Cc = 1.8 and the soil is well graduated. Based on the methylene blue test, the soil is classified as a silty sand (0.2 - 1.5). Particles densities are shown in Table 4. Then the soil is collapsible [6]. Indeed, for the different pressures (σ) as well as the different energies of compaction (Ec), the collapse potential (Cp) differs from 12.40% to 14.88% (for an initial water content; w = 2%), from 12.79% to 15.56% for an initial water content w = 4%, and from 13.98 to 16.88% for an initial water content w = 6%). The void ratio reduction considered as one of the collapse index can be observed in Figure 2.

Values obtained correspond to the category of very collapsible soil as shown in Table 6. The collapse potential (Cp) decreases when the energy of compaction (Ec) increases. This can be noticed that the collapse is exalted by the action of water which easily eliminates the inter-granular bonds produced by capillary action and links formed by low clay content [28, 29]. These soils remained stable in wet conditions and become vulnerable to collapse after water infiltration. These types of soils have particular features with contribution to collapse such as metastable structure which results in great void ratio, young deposit, significant sensitivity, and weak inter-particles attachment.

Some compacted soil at optimum and small dry density can experience a metastable structure which is governed by shear strength, being bonds with a high dependence on capillary action. Then the bonds can lose strength when an increase in water content can cause the collapse of soil structure at critical saturation degree. The collapse occurrence is often due to an increase in surcharge or water content and sometimes a combined action of these two parameters. In addition, the capillary effects between aggregates and granular particles decrease. This makes it easier to break the bonds among the particles and therefore collapse occurs. Collapse behaviours are often seen in fine soils in which the fine particles are shown as connectors or sometimes as the blanket of granular particles [14]. It is noted the increase in the subsidence potential for an energy of compaction corresponding to 20 strokes for soils with a loose structure and many voids, causing the displacement of fine particles in different directions. Conversely, in the case of compaction with 60 strokes once the soil becomes relatively dense the destruction of inter-granular bonds and the movement of fine particles are reduced, yet the subsidence potential still remains high. Jennings and Knight [6] gave a classification of soils according to the severity of the problem and the values of the subsidence potential from following equations:

Initial void index $(e_0) = (\gamma s/\gamma d) - 1$ (4)

CP (Subsidence coefficient or Collapse potential) $= \Delta h/h_0 = \Delta e/(1 + e_0)$ (5)

This classification is shown in the Table 6. Considering as an indication, we can consider that a soil is not very compressible when Cc < 0.2, compressible when 0.2 < Cc <0.7, very compressible when 0.7 < Cc. Others results related to soil mechanical properties can be seen in Table 7.

The susceptibility of soils to collapse is founded on the geotechnical properties of soils and the collapse potential obtained from laboratory tests, considering the soils under dry condition. The LL and PI played also a vital role for collapsible soils classification. From Table 6, the results of collapse potential notice that all soil samples used showed high sensitivity to collapse. Commonly the soils under study showed a certain similarities about collapsibility analysis.

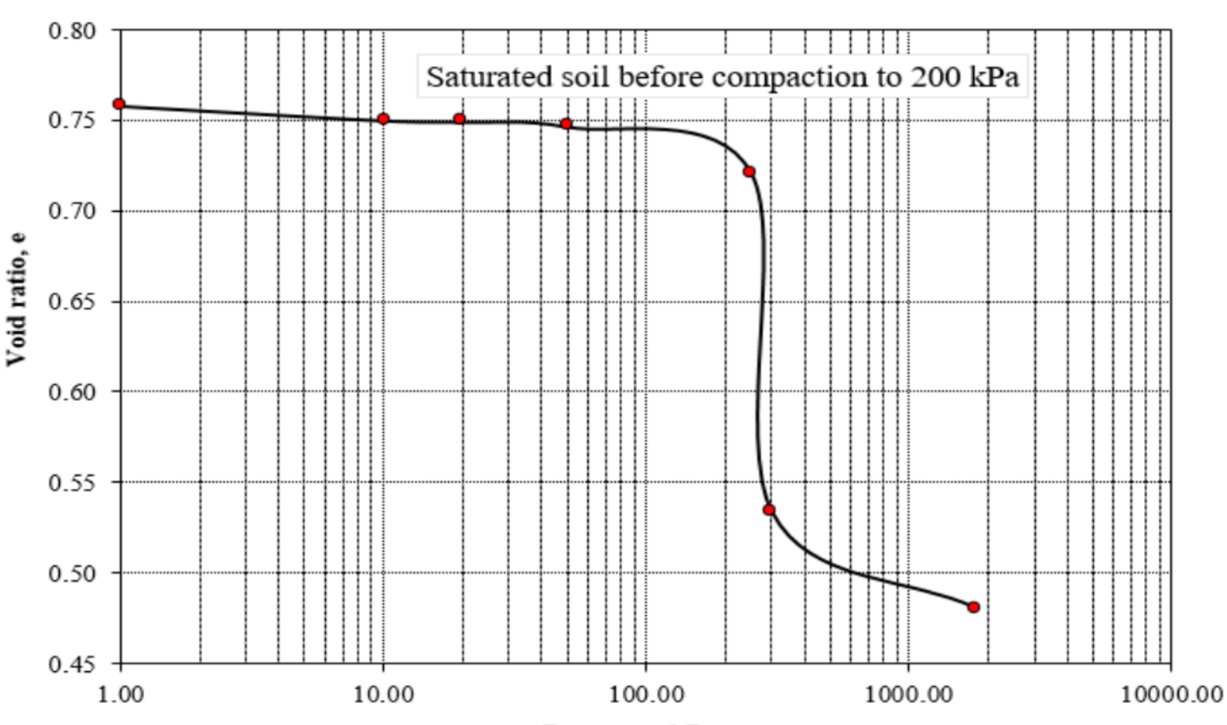

Figure 3. Soil curve before compaction.

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The Figures 3, 4 and 5 show the soil conditions under oedometric tests. In Figure 5, it is shown the curves for the dry and saturated conditions, respectively. These curves show that the collapse occurrence depends on the water content. Then, it is noticed that once the water content increases in the soil, it becomes unstable causing a sudden collapse with the decrease in the shear strength [1].

Due to the non-cohesive nature of the soil samples, the difficulty of collecting undisturbed samples was pronounced. Therefore, the tests of single oedometer considered soil samples prepared according to ASTM D 5333 procedures. Also, the loading conditions indicated in ASTM D 5333, supplementary oedometer tests were performed on remoulded samples swamped at the real loading conditions after final samples preparation. Then the collapse potential for remoulded samples and considering the natural densities based on the severity of collapse is minor to reasonable as shown in Figure 3.

In addition, the collapse potential for soil samples with maximum dry densities is met within the very slight severity of collapse (Figure 4 and Table 6).

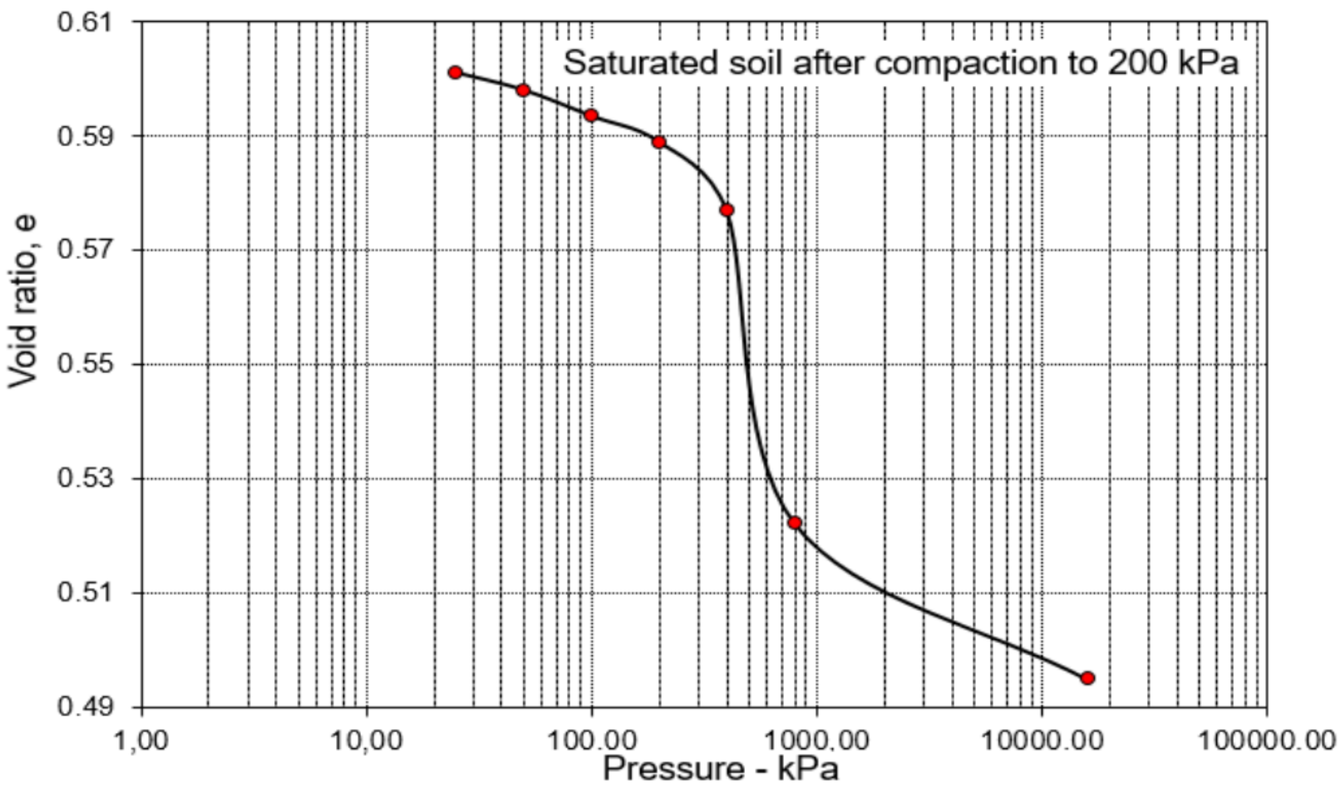

Figure 4. Soil curve after compaction.

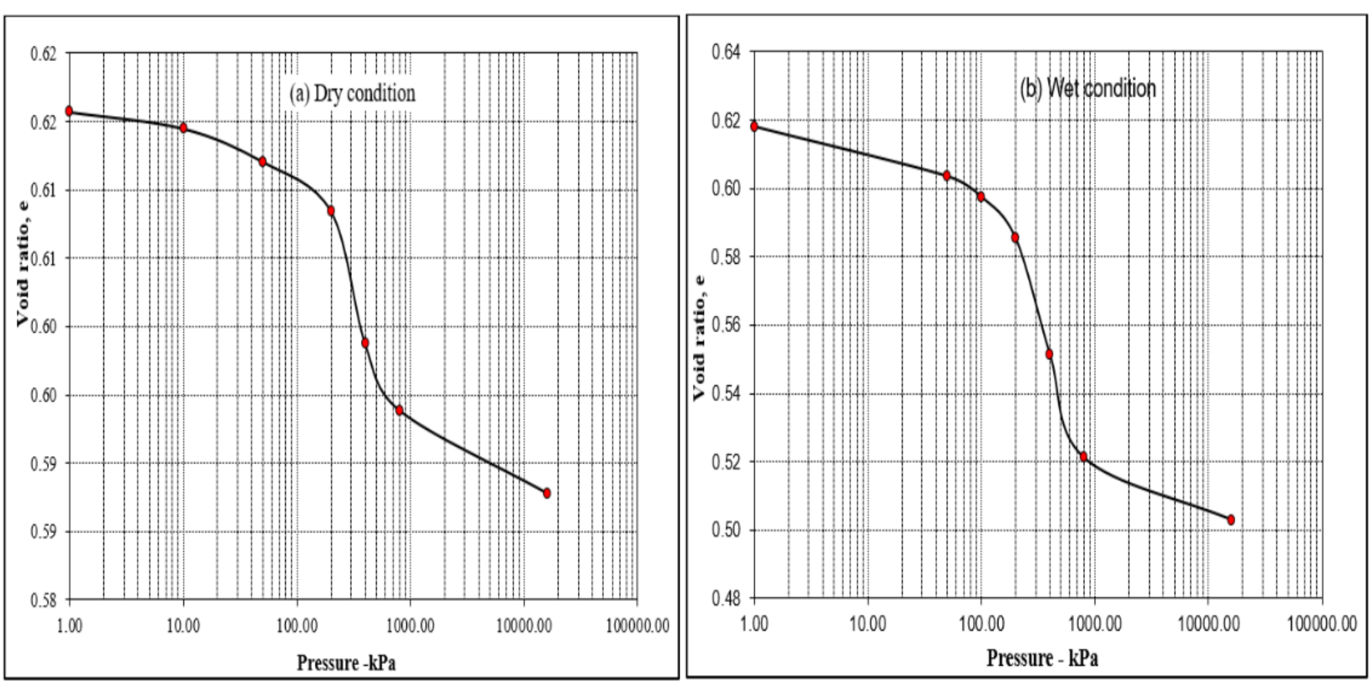

Figure 5. Double oedometer test curve.

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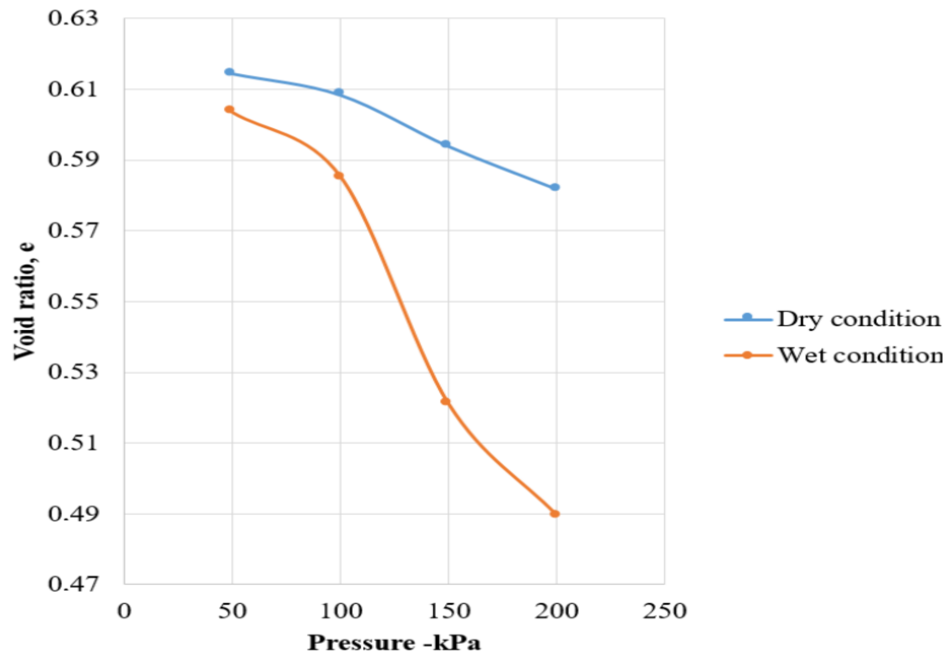

Figure 6. Soils behaviour using the double oedometer test.

From the Figure 6 it is observed that the soil remains collapsible and its collapse potential can be considerably reduced by compaction. This compaction has tendency to reduce the soil void index and makes it denser to resist against collapse phenomena.

In general, founded on the results obtained from the field and laboratory tests; one may assess the collapse potential in accordance with different criteria. The collapse potential evaluation by using the soils physical properties as an indirect method is based on the values of the collapse potential.

4. Discussion

Different collapse criteria were suggested to determine the soil responsibility face to collapse. Priklonski's criterion, is based on the liquidity index for soil collapse expectations, where the soil is collapsible when the liquidity index is lesser than zero [26]. Therefore, using the Priklonski's criterion the soil in the study area is collapsible by compaction. The results showed that all soil samples showed moderate to high collapse. Generally some similarities found on the collapsible soils met in the study area refer to geological and environmental conditions. From Tables 5, 6, 7 and 8, comparison can be made among the properties of collapsible soils for a good acknowledge about the collapse phenomenon in the study area.

Even though Clevenger [30] criterion was not used in the current study, but comparing results obtained from this criterion with those obtained in this study, this method stated by using the natural dry density. Then it is noticed that, when the natural density is inferior to 12.6 kN/m^3, an important settlement can be produced whereas once it is larger than 14.1 kN/m^3, slight settlement can be produced [31]. This criterion using clay percentage indicates that once the clay content is among 16.0 % and 24.0 % the soil is collapsible and it becomes highly collapsible when the clay percentage is inferior to 16.0 %. Then, the soil met in the study area is highly collapsible with a clay content lesser than 16% Table 3.

The soils parameters provide the soils susceptibility to collapse potential. It is noted that keeping the water content constant, it is observed a decrease in the collapse intensity with the increase of relative density [32]. It is also defined the maximum value of the collapse potential (Cp) at 200 Kpa pressure. This result can be explained by the intensity of the collapse which increases up to a certain level of stresses after which the collapse decreases [33]. Table 7 also shows that the collapse potential (Cp) decreases almost linearly, when the water content or the energy of compaction increases for a 200 kPa pressure and this type of soil behavior is the same regardless of the applied pressure. Results observed in Tables 7 and 8 agree with those obtained by some researchers [34].

5. Conclusions

In general, founded on the results obtained from the field and laboratory tests; one may assess the collapse potential in accordance with different criteria. The collapse potential can be evaluated by using the soils physical properties as an indirect method and using values of the collapse potential as a direct method.

Soil collapse is a very complex phenomenon that involves a large number of intrinsic and adjacent parameters. Results obtained defined the soil behaviour in the face of collapse potential. The results of identification tests, consistency and compressibility confirmed the collapsible behaviour of the soils found in the study area.

The collapse potential may be reduced by using compaction. The compaction and the consolidation tests contribute to a suitable description of the collapsible soil.

This work determined the cause of collapse experienced by different types of constructions built in the study area and can be used as a policy statement for similar areas to reduce the collapse incidence on constructions.

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