4th Annual Paper Meet and 1st Civil Engineering Congress, December 22-24, 2011, Dhaka, Bangladesh ISBN: 978-984-33-4363-5
Noor, Amin, Bhuiyan, Chowdhury and Kakoli (eds) www.iebconferences.info

Causes of foundation failure and sudden volume reduction of collapsible soil during inundation

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ABSTRACT: Collapsible soils are known to experience significant volume decrease due to the increase of soil moisture content, without an increase in the in-situ stress level. The causes of immediate foundation problem and of sudden collapse during inundation of collapsible soil have not yet been addressed. As a result, foundation design in collapsible soil is still based on conventional soil mechanics, which gives unsafe design values during inundation and may result total failure of the structure. From this paper, practicing engineers will get an insight into the problematic behavior of collapsible soil and associated foundation problems during inundation. Causes of immediate foundation failure due to inundation of collapsible soil are addressed based on pressure-settlement curves. The reason of experiencing a sudden major collapse is also presented. How fast the void ratio of collapsible soil may decrease, when subjected to inundation, is discussed. The reasons of experiencing the transition (i.e., unsaturated to saturated) much faster in collapsible soil than in non-collapsible soil, are also presented with mathematical expressions derived in this paper. This paper identifies the key role of capillary force (alternately, matric suction) in the development of inundation induced soil collapse analytically. Therefore, the practicing engineers will recognize the importance of dealing this soil specially by considering all the issues causing soil collapse and by applying appropriate relations.

1 INTRODUCTION

In recent years, several landslides are experienced suddenly in Chittagong hill tracts, Bangladesh suddenly after heavy rainfall, while significant soil settlements near riverside zones have also been reported. Though the causes of both types of disasters have not yet been studied, the consequences resemble inundation induced collapse problem that is commonly observed in arid and semi arid climatic zones of USA, China, Algeria, Egypt, Russia, etc. Collapsible soils are known to experience significant volume decrease due to the increase of soil moisture content, without an increase in the in-situ stress level. Such soil response (i.e., landslides or significant soil settlements) to inundation could not be predicted beforehand, based on the knowledge of saturated soil mechanics and the experiences with non problematic or other kinds of problematic (such as expansive soil and sensitive clay) soils as well. The irrecoverable volume reduction (under constant stress level and only due to the inundation) of collapsible soil takes place so fast and sudden that no measures can be taken to stop the problem once it initiates.

Though identification, prediction of collapse potential and treatment of collapsible soils were studied several times in the past, the causes of immediate foundation problem and of sudden collapse during inundation of collapsible soil have not yet been addressed. As a result, foundation design in collapsible soil is still based on conventional soil mechanics, which gives unsafe design values during inundation and may result total failure of the structure. This study demonstrates that saturated soil mechanics may be applicable to investigate a foundation performance in collapsible soils (either saturated or unsaturated) remaining at a constant soil moisture condition but inapplicable to predict its behaviour if subjected to inundation.

The amount of expected collapse settlement due to full saturation depends on initial condition (in terms of initial moisture content, w_0 and initial dry density, γ_{dry}) of collapsible soil (Holtz, 1948; Hilf, 1956; Booth, 1977; Cox, 1978; Udommchoke, 1991; Fredlund and Gan, 1995; Sharma and Singhal, 2006 and Yasufuku et al, 2006 among others). The amount of collapse is expressed in terms of collapse strain ($\Delta H/H_0$), change in void ratio (Δe or $\Delta V/V_s$) or collapse settlement (ΔH) in the literature. Collapse Strain ($\Delta H/H_0$) is the settlement (ΔH) collapsible layer or sample due to inundation, as a percentage of the original height (H_0), collapse strain at 200 kPa pressure is termed collapse potential (C_p). Ayadat and Hanna (2007) presented a method of collapsible soil identification using cone penetration test results. Ayadat and Hanna (2005) presents a method of improving collapsible soil using encapsulated stone columns that is effective for building a light weight structure.

Causes of immediate foundation failure due to inundation of collapsible soil are addressed based on pressure-settlement curves. The demonstration of pressure-settlement response of collapsible soil, in relation to the change in soil moisture, will guide the practicing engineers to obtain a safe design load on foundation and the type of foundation. This paper discovers the key role of matric suction in the significant volume reduction of collapsible soil during inundation. Therefore, the theories of unsaturated soil mechanics may be applied with greater confidence in the case of collapsible soil problem towards obtaining a safe foundation design. Unsaturated soil properties are subjected to change during inundation as described by unsaturated soil property functions (Maswoswe, 1985; Lawton et al., 1991; Pereira and Fredlund, 1999, among others). This paper identifies some facts that make collapsible soil highly problematic and discussion is made based on derived mathematical expressions. The reason of experiencing a sudden major collapse is also presented. How fast the void ratio of collapsible soil may decrease, when subjected to inundation, is discussed. The reasons of experiencing the transition (i.e., unsaturated to saturated) much faster in collapsible soil than in non-collapsible soil, are also presented with mathematical expressions derived in this paper. Hence, the practicing engineers will be able to recognize the importance of dealing this soil specially by considering all the issues concerning soil collapse and by applying appropriate relations.

2 PRESSURE SETTLEMENT RESPONSE OF COLLAPSIBLE SOIL

A structure, which was operating safely for several years, may experience sudden collapse during inundation of collapsible soil, existing below the structure, while all other factors expect soil moisture remain constant. It is only possible if the response of collapsible soil is significantly different from before inundation state to after inundation state. The causes of sudden foundation problem, due to inundation of collapsible soil, are identified based on pressure settlement curves from the literature.

Figure 1 shows a typical pressure-settlement response of collapsible soil for a bearing plate in collapsible soil (unsaturated and saturated) (Grigoryan, 1997). The term ‘unsaturated’ means both dry and partially saturated conditions. Results of double oedometer tests, used to measure collapse potential, give similar trends. This implies that pressure-settlement response curve, which is obtained at a constant moisture condition, is different at different degree of saturation. At a constant moisture condition, unsaturated collapsible soil, acting under a pressure (σ) due to loads from the foundation and the overburden pressure, will experience a settlement, $\Delta H_{\sigma(un)}$, that corresponds to the pressure (σ) in the pressure-settlement curve for the soil’s current degree of saturation. This small amount of volume reduction ($\Delta H_{\sigma(un)}$) results from the compression of the fine cementing materials within the soil structure (i.e., of honeycomb type and accordingly porous).

However, collapsible soil will experience additional settlement ($\Delta H_{\sigma(inun\text{-}Si)}$) in addition to $\Delta H_{\sigma(un)}$, if the initially unsaturated collapsible soil (initial degree of saturation, $S_{natural}$) is subjected to inundation reaching the final degree of saturation, S_i, under a constant σ. The value of $\Delta H_{\sigma(inun\text{-}Si)}$ can be measured from the vertical distance between the pressure-settlement response curves for $S_{natural}$ and S_i at pressure (σ). In case of collapsible soil, $\Delta H_{\sigma(inun\text{-}Si)}$ is always greater than zero. If degree of saturation increases, $\Delta H_{\sigma(inun\text{-}Si)}$ also increases.

Figure 1 shows the maximum value of $\Delta H_{\sigma(inun\text{-}Si)}$ such as $\Delta H_{100(inun\text{-}Si)}$, $\Delta H_{200(inun\text{-}Si)}$ and $\Delta H_{300(inun\text{-}Si)}$ for three different inundation pressures 100, 200 and 300kPa, respectively. $\Delta H_{\sigma(inun)}$ is much greater than $\Delta H_{\sigma(un)}$ and it depends on the inundation pressure (i.e., the pressure under which the soil is subjected to inundation). In Figure 1, $\Delta H_{100(inun\text{-}S100)}$, $\Delta H_{200(inun\text{-}S100)}$ and $\Delta H_{300(inun\text{-}S100)}$ are the amounts of collapse or settlement ($\Delta H_{\sigma(inun)}$) due to full inundation under the inundation pressures (σ) of 100, 200 and 300 kPa, respectively. For a given soil, it can be noted that the higher the inundation pressure (σ) is, the greater the amount of collapse ($\Delta H_{\sigma(inun\text{-}S100)}$) is. From the above discussion it becomes clear that saturated soil mechanics is inapplicable to collapsible soil during inundation. This is because the vertical line (at a given σ) from unsaturated to saturated pressure settlement curves cannot represent the behaviour of collapsible soil during inundation. In that case, other parameter (i.e., matric suction) that will be addressed in the following section governs its behaviour.

If collapsible soil is subjected to partial inundation (i.e., final degree of saturation S_1, less than 100) and after experiencing collapse settlement due to inundation foundation load is increased, the collapsible soil will behave according the pressure settlement curve for S_1. While considering different stages of inundation, de-

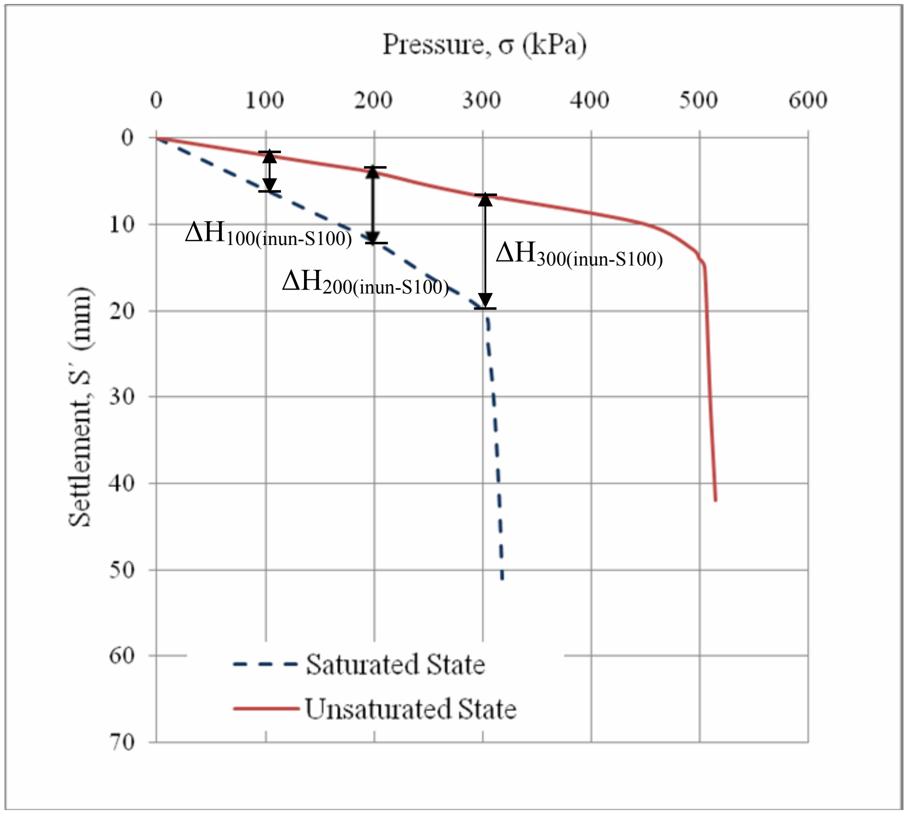

Figure 1: Typical load settlement curves of a bearing plate in collapsible soils (saturated and unsaturated)

grees of saturation are assumed $S_{natural}$ (natural degree of saturation), S_1, S_2 and 100 (fully saturated state) at time 0, t_1, t_2 and t_{100}, respectively, after the commencement of inundation. If pressure-settlement curves are drawn for each stages of saturation for a given soil, the curves for $S_{natural}$, S_1, S_2 and 100 will be found in order from top to downward direction. This indicates that the compressibility of unsaturated collapsible soil is low and increases gradually during inundation, also reported by Fredlund and Rahardjo (1993). Hence, saturated collapsible soil settles more than unsaturated one, under a constant pressure on the bearing plate or foundation.

Further, inundation causes strength reduction. Immediate foundation failure may result due to inundation, if inundation pressure exceeds the ultimate limit of soil strength at saturated condition. According to Figure 1, if this soil is subjected to a pressure greater than 300 kPa (e.g., 400 kPa) before inundation, then bearing plate will fail and settle infinitely (as compared to ΔH_{300}) due to inundation under the same pressure. In this figure, unsaturated collapsible soil can support a pressure of 500 kPa, while the same soil can support only 300 kPa after inundation.

If the foundation rests on the top of collapsible soil layer (located at a depth or near ground surface), it will experience immediate settlement equal the amount of collapse experienced by the soil layer. Even, inundation of a thin collapsible soil layer, existing at depths, may initiate such a disaster. Since low pressure on collapsible soil corresponds to low collapse settlement, only light structures can be built on shallow foundations after soil treatment (such as chemical stabilization, grouting, stone column and compaction). In order to obtain a safe design load for shallow foundation, pressure-settlement response at fully saturated state is recommended, rather than following the one that is related to natural unsaturated moisture condition. Therefore, safe foundation load can be estimated, based on the ultimate capacity at saturated state (significantly less than that at natural unsaturated state) applying a factor of safety or by keeping the maximum of soil volume reduction within an acceptable limit. Accordingly, shallow foundation is found safe and suitable only for light weight structure, as under small inundation pressure cause relatively small amount of additional soil volume reduction due to full inundation. Otherwise, pile is the only available type of foundation. However, the pile must cut through the full depth of collapsible soil and also be adequately embedded into non collapsible soil bed.

3 CAUSES OF SUDDEN SOIL COLLAPSE

Partially saturated collapsible soil (having meta-stable structure and honeycomb type particle arrangements), with low water content, is usually encountered in natural deposits. At initial state, collapsible soil has highly porous unsaturated structure, and has low unit weight accordingly. Its porosity and unit weight (unsaturated) usually range 0.8–1.0 and 12–15 kN/m^3 (Grigoryan, 1997) respectively. Instead, unsaturated soils, having stable soil structure, show insignificant volume reduction as compared to inundation induced collapse settlement. The volume sensitivity (irrecoverable volume reduction) of collapsible soil, due to the increase of soil moisture, is quite different from shrinkage and swelling, as experienced by other type of unsaturated soils; namely expansive soil. Moreover, collapsible soil experiences irrecoverable volume change (reduction) while the volume change behavior of swelling (expansive) soil is of recoverable type. Expansive soil is a stable structured unsaturated soil that increases in volume (swell) during inundation. When the swelled soil (after wetting) is further subjected to drying (e.g., due to evaporation), it decreases in volume (subsidence) due to shrinkage. The sudden volume change behavior of collapsible soil makes it difficult to predict the performance of foundation in collapsible soil during inundation. This section addresses why such collapse takes place and why it is faster than it is expected. Figure 2 **Error! Reference source not found.**shows the microstructure of collapsible loess, which is formed by wind action.

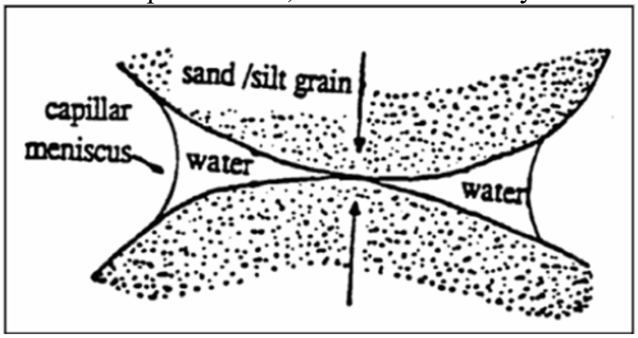

Figure 2: Bond in unsaturated soil by capillary action (Dudley, 1970)

At unsaturated state, the original porous structure, even under heavy external load, of collapsible soil can be maintained by a combined action of inter-particle bonds (cementation and capillary bonds) between coarse particles (e.g., sand and silt) resist any slip between soil grains and maintain the flocculated or honeycomb structure of collapsible soil. Capillary action within unsaturated soil matrix causes the development of negative pore water pressure ($-u_w$), as the moisture content (i.e., very low in unsaturated collapsible soil) exists within the micro-pores only, rather than in the large macro-pores between the large flocs and/or coarse grains. The higher the matric suction is, the higher the additional bond strength (due to capillary force) is. Negative pore water pressure ($-u_w$) is considered in terms of matric suction (u_a - u_w) in unsaturated soil mechanics. Pore air pressure is denoted by u_a.

The bond strength due to capillary action (or matric suction) is available only when negative pore water pressure exists within the soil matrix. Inundation causes reduction in matric suction (or negative pore water pressure, $-u_w$) due to the increase of water (or water pressure) in the pore. During inundation of any unsaturated soil, matric suction diminishes continually and becomes zero when the soil attained full saturation. Among all unsaturated soils, only collapsible soil structure is highly dependent on this bond strength (of matric suction), because of having meta-stable structure and initial high void ratio (or porosity) and therefore, matric suction plays the key role in such irrecoverable volume reduction. Tadepalli and Fredlund (1991) also showed experimentally that there is one to one relationship between volumetric strain and matric suction. A stable-structured unsaturated soil may also experience volume reduction during inundation, only if the soil is subjected to a very high stress, though it has relatively low porosity as compared to collapsible soil.

Based on the above discussion, unsaturated soil property functions, in which matric suction is considered the governing state parameter, can be applied to collapsible soil subjected to inundation with greater confidence. As these relations (e.g., shear strength and permeability functions of unsaturated soil) were first developed for unsaturated soils - volume insensitive to moisture change, there was lack in confidence in applying them in case of collapsible soil and accordingly, these relations have not yet been received adequate attention and importance in foundation design practice.

This paper identifies some important facts that make collapsible soil the most problematic one among all types of unsaturated soils. First of all, it becomes saturated very fast, as it is highly permeable due to its high porosity. Secondly, collapsible soil layer requires less amount of water to reach 100% saturation than expected for a volume insensitive (during inundation) soil (Statement 1). ‘Statement 1’ is examined by comparing collapsible soil (CS) with two different volume insensitive unsaturated soils (VIS): (i) CS and VIS have the same porous structure and (ii) VIS is denser than CS. It is to clarify here that an unsaturated porous soil may not collapse only due to inundation. In nature, there exists volume insensitive (to inundation) highly porous soil, in which other types of bond (including fine silt bond, clay bond, bond by autogenesis, ring buttress, clay bridge, etc) act as major bonds, giving high strength to porous (flocculate) unsaturated soil, in combination with matric suction (i.e., relatively minor). The collapse problem, during inundation, is much less or insignificant to some extent of inundation pressure, because of other strong bonds in addition to matric suction (minor), as noted by Pereira and Fredlund (2000). During inundation, as the percentage of the water in the pore space increases, matric suction decreases and the bond of matrix suction diminishes. If the other bond is strong enough to resist the previously applied stress level alone, the porous unsaturated soil may not collapse. However, in previous studies, it is reported that such soil also experiences collapse, as that bond fails eventually after the applied stresses exceed the limiting stress. On the other hand, in case of collapsible soil, collapse takes place, when the other bonds, if any, cannot provide sufficient resistance against the previously acting stresses (due to overburden stress, load from foundation, etc.). Therefore, soil experiences sudden and significant deformations, as the major bond strength due to matric suction (holding soil grains in a porous structure) disappeared.

To examine ‘Statement 1’, consider two unsaturated (a CS and a VIS) soil layers have the same initial void ratio ($e_{initial}$), porous structure, and equal thickness. Therefore, after reaching 100% degree of saturation,

For volume-insensitive soil,

Final water content, $w_f = \frac{e_{initial}}{G_s}$………………..……………(1)

For collapsible soil,

Final water content, $w_f = \frac{e_{initial}}{G_s}$…………….…………..…..(2)

$\Delta w = w_f - w_c = \frac{\Delta e}{G_s}$……………………..…………………..…(3)

Eqn 1, Eqn 2 and Eqn 3 demonstrate the fact that there is a difference in the final water contents required by the two soils, depending on the change of void ratio.

‘Statement 1’ is again examined by comparing a collapsible soil with a relatively dense unsaturated soil. Both soils have the same initial volume ($V_{initial}$) and equal thickness. Therefore, collapsible soil has high initial void ratio than the other soil. If both soils could have the same final water content at the end of the saturation, the collapsible soil would require less water ($W_w = w * W_s$) than the other soil, by definition of water content (Eqn 4), this is because the non collapsible (volume insensitive to moisture increase) soil is relatively dense, and the weight of soil solid (W_s) of non collapsible soil is greater than that of the collapsible soil.

$w = \frac{W_w}{W_s}$……………………..……………………………………..(4)

The concern is if water content at the 100% saturation is same in both soils. The amount of water (W_w) in soil volume can be estimated using Eqn 5, which is derived using the Eqns 6 ─ 8.

$W_w = \frac{S.e}{G_s} * W_s = \frac{S.e}{G_s} * (\gamma_{unsat} * V_{initial})$…………………..(5)

$w = \frac{W_w}{W_s} = \frac{S.e}{G_s}$……………………..……..…………………(6)

$S.e = w.G_s$……………………………...………..………(7)

$\gamma_{unsat} = \frac{W_s}{V_{initial}}$……………………………….……………..……..(8)

where, w = water content,

W_s = weight of soil solids,

W_w = weight of water,

S = degree of saturation = 1 (after full saturation),
G_s = specific gravity,
γ_{unsat} = unsaturated unit weight, ignoring insignificant amount of water at initial condition, and
$V_{initial}$ = Initial total volume.

Based on Eqn 5, the ratio of the weight of water in collapsible soil (W_{wc}) to that in non collapsible soil (W_{wnc}) at 100% degree of saturation is as follows:

$$\frac{W_{wc}}{W_{wnc}} = \frac{S_c \cdot e_c \cdot \gamma_{unsat(c)}}{S_{nc} \cdot e_{nc} \cdot \gamma_{unsat(nc)}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(9)$$

where, e_c = void ratio of collapsible soil, and
e_{nc} = void ratio of non collapsible soil.
At initial unsaturated condition,
$\gamma_{unsat(c)}$ = Initial unsaturated unit weight of collapsible soil (e.g., around 15 kN/m^3),
$\gamma_{unsat(nc)}$ = Initial unsaturated unit weight of non collapsible soil (e.g., around 20 kN/m^3),

Therefore, $\frac{\gamma_{unsat(c)}}{\gamma_{unsat(nc)}} = \frac{15}{20} = 0.75 < 1.$

After full saturation of both soils, it is obvious that both soils have equal degree of saturation. That is, S_c (degree of saturation of collapsible soil) equals S_{nc} (degree of saturation of non collapsible soil). If both soils have the same final void ratio, (i.e., $e_c = e_{nc}$), then Eqn 9 reduces to Eqn 10.

$$\frac{W_{wc}}{W_{wnc}} = \frac{\gamma_{unsat(c)}}{\gamma_{unsat(nc)}} = K \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(10)$$

where, $K < 1$,
W_{wc} = the weight of water required in collapsible soil to reach 100% saturation, and
W_{wnc} = the weight of water required in non collapsible soil to reach 100% saturation.

Eqn 10 indicates that “collapsible soil requires less amount of water than relatively dense unsaturated soil”.

Eqn 10 is used to investigate the reason why the major collapse is sudden. However, major collapse, which is more than 85% of full collapse, is observed to occur when soil attains about 80% degree of saturation (Mahmoud, 1991). Therefore, the weight of water ($W'_{w(c)}$) required to attain major collapse is 80% of $W_{w(c)}$.

$$W'_{w(c)} \approx 0.8 * W_{w(c)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(11)$$

Based on Eqn 3.10,

$$W'_{w(c)} = 0.8 * K . W_{w(nc)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(12)$$

Therefore, if the value of K is taken 0.75, the water requirement to attain major collapse ($W'_{w(c)}$) is only 60% of the water ($W_{w(nc)}$) to reach 100% saturation by non collapsible soil. In other words, the major collapse can occur due to the increase in soil moisture equivalent to make the other non collapsible soil 60% saturated.

The following demonstrates how fast the void ratio of collapsible soil may decrease, when subjected to inundation. Consider a collapsible soil (having collapse potential 10% or more) experiences significant collapse and can attain easily the void ratio as same as the other soil (e.g. having void ratio of 0.4).

By definition of collapse potential, C_p

$$C_p = \frac{\Delta e}{1 + e_{initial}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(13)$$

Also,

$$C_p = \frac{\Delta V}{V_{initial}} = \frac{\Delta e / e_{initial}}{(1 + e_{initial}) / e_{initial}}$$

Therefore,

$$C_p = \frac{\Delta V}{V_{initial}} = \frac{\Delta e}{e_{initial}} \cdot \frac{1}{\left(\frac{1}{e_{initial}} + 1\right)}$$

$$C_p = \frac{\Delta V}{V_{initial}} = \frac{\Delta e}{e_{initial}} . M \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

$$\frac{\Delta e}{e_{initial}} = \frac{C_p}{M} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

$$M = \frac{1}{\left(\frac{1}{e_{initial}} + 1\right)} < 1$$

$$\frac{1}{e_{initial}} = 1.25 - 1.7.$$

Initial void ratio of collapsible soil usually ranges from 0.55 to 0.8, and therefore, the value of M ranges 0.37─0.44. The $\Delta e/e_{initial}$ ratio is greater than the ratio $\Delta V/V_{initial}$ (i.e. collapse potential, C_p in Eqn 14). From Eqn 15, it can be noted that the void ratio change (i.e., decrease) could be as high as 50% of the initial void ratio, though the soil can have collapse potential of 20%. The average value of M is considered 0.4. Eqn 14 converts to Eqn 16, after including the effect of inundation pressure.

$$\frac{C_p}{200} . (\sigma + \gamma h) = \frac{\Delta e}{e_{initial}} . M \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

Where, $\gamma h = \text{overburden stress}$ (kPa) and
σ = Surcharge on soil surface (kPa).

By definition, collapse potential (C_p) is the percentage of volume change under the inundation pressure of 200 kPa, and it is directly proportional to the inundation pressure up to 400 kPa, as experimentally observed previously by Nouaouria (2008). The inundation pressure ($\sigma + \gamma h$) is high, when a given collapsible soil is located at a depth greater than 10 m or subjected to load from foundation (σ). Overburden stress is about 200 kPa for a collapsible bed, when the overlying non collapsible layer (unit weight, 20 kN/m^3) is 10 m deep.

4 RELATION FOR UNIT WEIGHT

Inundation causes decrease in void ratio and increase of dry unit weight. Soil dry unit weight at any stage of inundation is determined using the following relation, knowing the portion of collapse potential (PC_P) attained at that stage

$$\gamma_{dry\,(new)} = \frac{W_s}{(1 - PC_P)HA} = \frac{\gamma_{dry\,(initial)}}{(1 - PC_P)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)$$

5 CONCLUSION

This paper concludes that safe design of foundation may be difficult and complex but not impossible in collapsible soil zone. The demonstration of pressure-settlement response of collapsible soil, in relation to the change in soil moisture, will give the practicing engineers a better understanding regarding the cause of immediate foundation settlement during inundation of collapsible soil. In order to obtain a safe design load for shallow foundation, pressure-settlement response at fully saturated state is recommended, rather than following the one that is related to natural unsaturated moisture condition. Therefore, safe load on foundation can be estimated, based on the ultimate capacity at saturated state (significantly less than that at natural unsaturated state) applying a factor of safety or by keeping the maximum of soil volume reduction within an allowable limit. Accordingly, shallow foundation is found safe and suitable only for light weight structure, as under small inundation pressure cause relatively small amount of additional soil volume reduction due to full inundation. Otherwise, pile is the only available type of foundation.

This paper discovers the key role of matric suction in the significant volume reduction of collapsible soil during inundation. Therefore, the theories of unsaturated soil mechanics may be applied with greater confidence in the case of collapsible soil problem, as saturated soil mechanics (i.e., still in practice for collapsible soil) fails to give a safe design and therefore presents sudden foundation failures.

This paper identifies the facts that make collapsible soil highly problematic. Due to high porosity, this highly permeable soil becomes saturated very fast. In addition to that, it requires significantly less amount of water to reach 100% saturation than expected for a volume insensitive (during inundation) soil. Collapsible soil may attain 80 % degree of saturation (when more than 85 % of full collapse taken place) with about 60 % water required for a volume insensitive soil to saturate it 100%. For a given collapsible soil, the collapsible soil layer underlying some other soil layers causes more severe problem than that existing near ground surface, as inundation pressure is greater in the former case than the other.

ACKNOWLEDGEMENT

The research was carried out at Concordia University with the financial supports from the National Science and Engineering Research Council of Canada (through Alexander Graham Bell Canada Graduate Scholarship) and several Concordia University Awards.

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