# SIMULATION OF SETTLEMENT DUE TO WETTING OF NORMALLY CONSOLIDATED UNSATURATED CLAY LAYER

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## ABSTRACT

Almost 40 percent of natural soils on the earth surface are in an unsaturated state. The settlement due to wetting of unsaturated soil layer affects building structures situated in the arid areas. Thus, this paper presents the simulations of settlement due to wetting of normally consolidated clay layer with the initial matric suction ranging from 50 to 300 kPa. The simulations were performed using the elasto-plastic model for unsaturated soils based on effective stress principle. The model simulations were conducted by expressing the governing equations of the model and were then solved as a series of initial value problems. The simulation results show that the compression occurs during wetting the normally consolidated clay to saturated state for all values of initial matric suction. The settlement, which was obtained by converting the volumetric strain to the settlement of clay layer with thickness of 5 m, increased with decreasing matric suction. Furthermore, the settlement due to wetting to saturated state increased with the initial matric suction.

**Keywords:** unsaturated soils, wetting process, elasto-plastic model, suction.

## INTRODUCTION

In the design of building foundation, a geotechnical engineer must consider, in addition of safety factor against bearing capacity, the settlement of the clay layer beneath the foundation. Typically, the settlement of building foundation with a relative high value of safety factor against bearing capacity is less than the allowable value. The settlement of foundation generally includes the immediate settlement occurring during construction and the consolidation settlement occurring after construction. The immediate settlement occurs under constant volume change condition while the consolidation settlement occurs during dissipation of excess pore water within the soil. There have been several methods to estimate these two types of settlement (e.g. Janbu *et al*., 1956; Schmertmann *et al*., 1978; Das, 1999). These methods are based on the classical soil mechanics assumption, in which fully saturated and completely dry conditions are assumed for soils below and above ground water level, respectively.

However, almost 40 percent of natural soils on the earth surface are actually in an unsaturated state. This type of soils can be found in arid and semi-arid regions. The mechanical properties of unsaturated soils can change with variation of water content or matric suction. The settlement due to decreasing matric suction, which is so called collapse upon wetting, can be encountered for the soil under partially saturated condition, particularly for lightly and normally consolidated clay (Uchaipichat, 2013). Ignoring this type of settlement can cause the excessive settlement of foundation, affecting the important components of structure above the soil surface.

Thus, the objective of this research is to simulate the settlement due to wetting of normally consolidated clay layer under partially saturated condition with the initial matric suction ranging from 50 to 300 kPa. The simulations were performed using the elasto-plastic model for unsaturated soils proposed by Uchaipichat (2011). The advantage of this model is that the loading collapse curve for drying and wetting paths are coincide, therefore, the numerical analysis can be simplified. The simulation results were presented in the form of stress path, the variation of settlement with matric suction, and the variation of settlement due to wetting to unsaturated state with the initial matric suction.

## EFFECTIVE STRESS IN UNSATURATED SOILS

Several investigators have been proposed the elasto-plastic model for unsaturated soils based on the effective stress approach (Kohgo *et al*., 1993; Loret and Khalili, 2002; Gallipoli, 2003; Sheng *et al*., 2003; Uchaipichat, 2013). In this approach, the matric suction and net stress are included in the effective stress equation, which can be expressed as (Bishop and Blight, 1963),

$$p' = p_{net} + \chi s \tag{1}$$

in which, $p'$ is the mean effective stress. $p_{net}$ is the mean net stress, which is defined as the total stress in excess of pore air pressure. $s$ is the matric suction, which is defined as the difference between pore air pressure and pore water pressure. $\chi$ is the effective stress parameter equal to unity for a saturated soil and zero for a dry soil.

The parameter $\chi$ can simply be expressed in terms of degree of saturation ( $S_r$ ) as (Masin, 2010),

$$\chi = (S_r)^{\gamma/\lambda_p} \tag{2}$$

where, $\lambda_p$ is the slope for unsaturated portion of soil-water characteristic curve in terms of $S_r$ on the double-logarithmic plot and $\gamma$ is equal to 0.55.

## ELASTO-PLASTIC CONSTITUTIVE RELATIONS

Uchaipichat (2011) derived the elasto-plastic constitutive relations for unsaturated soils base on effective stress concept, which can be expressed,

$$dp_{net} = D_{pp} d\varepsilon_v + D_{pq} d\varepsilon_s + a_{ps} ds - s d\chi \quad (3)$$

$$dq = D_{qp} d\varepsilon_v + D_{qq} d\varepsilon_s + a_{qs} ds$$

with

$$D_{pp} = K\left(1 - \frac{1}{H} K \frac{\partial g}{\partial p'} \frac{\partial f}{\partial p'}\right) \quad (4)$$

$$D_{pq} = K\left(-\frac{1}{H} 3G \frac{\partial g}{\partial p'} \frac{\partial f}{\partial q}\right)$$

$$D_{qq} = 3G\left(1 - \frac{1}{H} 3G \frac{\partial g}{\partial q} \frac{\partial f}{\partial q}\right)$$

$$D_{qp} = 3G\left(-\frac{1}{H} K \frac{\partial g}{\partial q} \frac{\partial f}{\partial p'}\right)$$

$$a_{ps} = -\chi - \frac{1}{H} K \frac{\partial g}{\partial p'} \frac{\partial f}{\partial s}$$

$$a_{qs} = -\frac{1}{H} K \frac{\partial f}{\partial p'} \frac{\partial g}{\partial s}$$

in which, $\varepsilon_s$ and $\varepsilon_v$ are shear and volumetric strains, respectively. $q$ is deviator stress. $g$ and $f$ are the plastic potential and yield function. $K$ and $G$ are the bulk and shear moduli. $\varepsilon_v^e$ and $\varepsilon_s^e$ are the elastic volumetric and shear strains of the soil skeleton. The incremental form of elastic strains can be expressed as,

$$d\varepsilon_v^e = \frac{1}{K}\left(dp_{net} + \chi\ ds + s\ d\chi\right) \quad (5)$$

$$d\varepsilon_s^e = \frac{1}{3G} dq$$

$K$ can be expressed in terms the slope of the unloading-reloading line (Wood, 1990),

$$K = \frac{(1+e)p'}{\kappa} \quad (6)$$

where, $\kappa$ is the slope of the unloading-reloading line in the semi-logarithmic compression plane and $e$ is the void ratio.

The relationship between shear modulus and bulk modulus can be expressed as,

$$G = 3K(1-2\nu)/2(1+\nu) \quad (7)$$

in which, $\nu$ is Poisson's ratio.
$H$ is the modulus depending on suction, and is defined as,

$$H = -\frac{\partial f}{\partial \varepsilon_v^p} \frac{\partial g}{\partial p'} + \frac{\partial f}{\partial p'} K \frac{\partial g}{\partial p'} + \frac{\partial f}{\partial q} 3G \frac{\partial g}{\partial q} \quad (8)$$

## YIELD FUNCTION

The modified Cam-Clay model is used to define the plastic framework in this paper. In this model, the shape of the yield surface is assumed to be elliptical in the $p' - q$ plane. Moreover, the associated flow rules are assumed. The yield surface is defined as,

$$f = q^2 - M^2\left[p'\left(p'_c - p'\right)\right] = 0 \quad (9)$$

in which, $p'_c$ is the preconsolidation pressure or yield limit, which can be obtained from the variation of the preconsolidation pressure with matric suction (Loading Collapse curve, LC curve).

## SIMULATIONS OF SETTLEMENT DUE TO WETTING OF NORMALLY CONSOLIDATED UNSATURATED CLAY LAYER

The simulations of settlement due to wetting of normally consolidated clay layer with thickness ($H_c$) of 5 m were performed using the material parameters reported by Uchaipichat (2010a, b). The material is kaolin and its parameters are summarized in Table-1. The values of $\lambda$ and $\kappa$ are assumed to be independent of matric suction. A typical value of $\nu$ is assumed to be 0.20 since the determination of $\nu$ from experiments using conventional equipment is found to be difficult at the strains at small deformations. Uchaipichat (2013) presented the equation to define the LC curve of the kaolin samples reported by Uchaipichat (2011). The LC curve function can be written as,

$$p'_c = -0.0017 s^2 + 1.1846 s + 200 \quad (10)$$

The settlement simulations for normally consolidated clay layer with the initial matric suction ranging from 50 to 300 kPa were conducted using Equation (3). The model simulations were conducted by expressing the governing equations of the model and were then solved as a series of initial value problems. In the case of wetting under constant net pressure and isotropic condition ($dp_{net} = 0$ and $dq = 0$) and following the principle of associated flow, Equation (3) can be rearranged as,

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$$d\varepsilon_v = \frac{1}{D_{pp}}\left(sd\chi - a_{ps}ds\right) \tag{11}$$

where

$$D_{pp} = K\left[1 - \frac{1}{H}K\left(\frac{\partial f}{\partial p'}\right)^2\right] \tag{12}$$

$$a_{ps} = -\chi - \frac{1}{H}K\frac{\partial f}{\partial p'}\frac{\partial f}{\partial s}$$

**Table-1.** Model parameters.

| Parameters | Values |
|---|---|
| $\kappa$ | 0.02 |
| $\lambda$ | 0.06 |
| $\nu$ | 0.20 |
| $M$ | 0.88 |
| $\lambda_p$ | 0.0685 |
| $H_c$ | 5 m |

Figure-1 shows the stress paths for the volume change of unsaturated clay due to wetting with the initial matric suction of 50, 100, 200 and 300 kPa on the plot between void ratio and isotropic effective stress. For all cases, the initial state is normally consolidated and the volume contraction occurs along wetting path. It can be noticed that the change in void ratio increases with the initial suction.

The settlement of clay layer ($S_c$) can be calculated as,

$$S_c = \varepsilon_v H_c \tag{13}$$

Figure-2 shows the settlement of clay layer with thickness of 5m due to wetting at different values of matric suction. It can be seen that the settlement increases with decreasing matric suction. At saturated condition ($s$ = 0 kPa), it can be observed that the settlement due to wetting to saturated state increases with the initial matric suction. The variation of settlement of clay layer due to wetting to saturated state with matric suction can clearly be noticed from Figure-3.

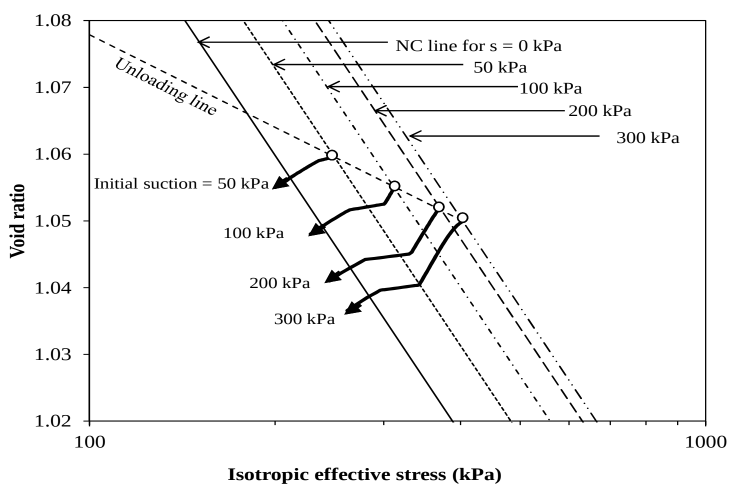


**Figure-1.** Stress paths for volume change of unsaturated clay due to wetting with initial matric suction of 0, 50, 100, 200 and 300 kPa.

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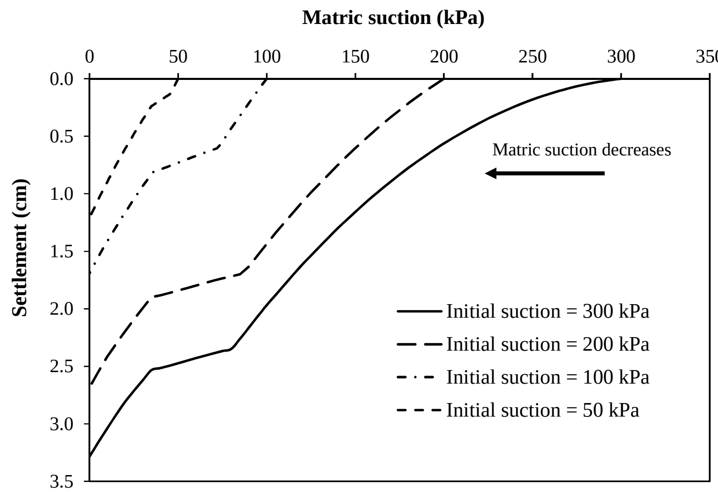


**Figure-2.** Settlement of clay layer with thickness of 5 m due to wetting at different values of matric suction.

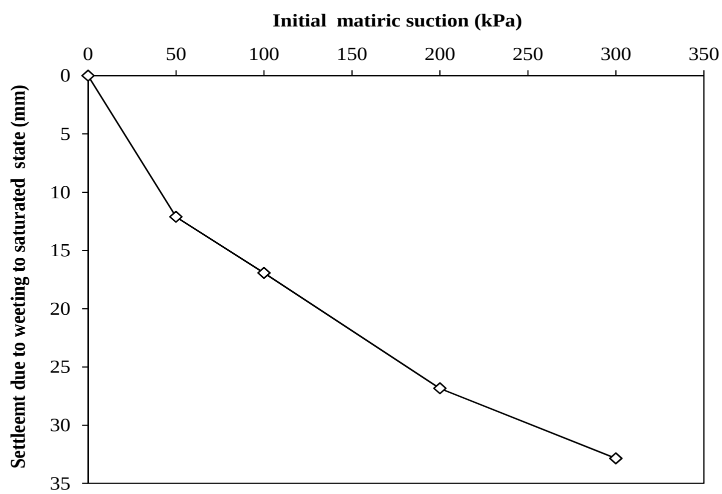


**Figure-3.** Variation of settlement of clay layer due to wetting to saturated state with matric suction.

## DISCUSSIONS

From the simulation results, compression occurs during wetting the normally consolidated clay to saturated state for all values of initial matric suction. This phenomenon is so called "collapse upon wetting", which always occurs in the soil layer in loose or soft state (Jenning and Knight, 1975; Phein-wej *et al*., 1992; Houston *et al*., 2002; Modero *et al*., 2009). The collapse upon wetting is caused by a combination of two effects occurring during wetting process. The first effect is that the effective stress within the soil decreases with decreasing matric suction during wetting process. The second effect is that the yield surface shrinks with decreasing matric suction (Wheeler and Sivakumar, 1995; Cui and Delage, 1996; Uchaipichat, 2010b). In other words, the preconsolidation pressure or yield limit decreases during wetting process. If the rate of decreasing effective stress is less than that of decreasing preconsoildation pressure, the collapse will occur as shown in Figure-1.

The values of settlement, which was obtained by converting the volumetric strain to the settlement of clay layer with thickness of 5 m, can be as high as 33 mm, which is greater than the allowable differential settlement of 25 mm for typical building structures (Cudoto, 2001).

## CONCLUSIONS

The simulations of settlement due to wetting of normally consolidated clay layer with the initial matric suction ranging from 50 to 300 kPa were performed using the elasto-plastic model for unsaturated soils proposed by Uchaipichat (2011). The model simulations were conducted by expressing the governing equations of the model and were then solved as a series of initial value problems. The simulation results show that compression occurs during wetting the normally consolidated clay to saturated state for all values of initial matric suction. The settlement, which was obtained by converting the volume change to the settlement of clay layer with thickness of 5 m, increased with decreasing matric suction. Furthermore, the settlement due to wetting to saturated state increased with the initial matric suction.

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