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Determination of interaction factor for energy piles in unsaturated soil

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Abstract

Energy piles are innovative piles that are subjected to cyclic thermal and mechanical loading and based on this determining the displacement and thermo-mechanical response of these piles is very intricate. In addition to that these piles are mostly constructed in unsaturated soil. furthermore, in reality, energy piles are constructed as group and displacement of one pile effect displacement of the adjacent pile. Consequently, the interaction of piles should be taken into consideration. While an enormous amount of research is conducted on mechanical response and thermos-hydro-mechanical behavior of energy piles, yet in most of these studies, the soil is considered to be saturated or dry. In previous studies, the impact of suction, pore pressure water, thermal conductivity coefficient, and other parameters on the thermos-mechanical response of energy piles are neglected.

In this study, the first thermos-hydro-mechanical consecutive model is developed based on the basic Barcelona model using C++ software. Second, developed code is used to simulate a single energy pile, in order to verify the mechanical model, and results were compared with studies of Alonso(1990). Afterward, another simulation is done to verify the thermal model comparing the results of the current study with studies of Ghasemzadeh and Villar. In the next section, simulation of a single energy pile in unsaturated soil is done using Flac3D software version6 of 2016. Moreover, the impact of the placement of a single energy pile in a group of 2, 4, 9,16, and 25 piles on the interaction factor is analyzed. In this study impact of length to diameter, Poisson ratio, soil modulus, and suction are taken into consideration.

Keywords: unsaturated soil, energy pile, thermos-hydro-mechanical consecutive model, interaction factor, suction, and Flac3D

Table of content Page

List of figures **page**

List of tables **page**

N

Preface

1.1 Introduction

Geothermal energy is thermal energy generated and stored in the Earth which is used to generate electricity. Increasing the depth temperature increases in a way that in earth's core temperature is equal to 500 degrees celsius. Geothermal energy from inside and sun's energy from outside creates a situation in which temperature stays constant in about 10 meters from the earth's crust. In this depth, geothermal energy can be extracted directly using heat pomps and energy piles. Energy piles are an innovative type of piles that reduced the cost of heating or cooling of structures. Moreover, since these piles use sustainable and clean energy, it is compatible with the environment. One of the most important aspects of using these piles is reduction ic carbon dioxide and as a consequence pollution. A combination of some energy piles and heat pomps allows the extraction of heat from the earth in winter and the injection of heat to the soil in summer [1].

1.2 Importance of the issue

Since the resources of nonrenewable energy are limited and the population is increasing all over the world, it is crucial to find renewable resources of energy. Energy piles are piles with the dual responsibility of bearing structural load and extracting energy from the earth. These piles are used vertically under buildings and diagonally under structures and sea platforms and horizontally at bridges. While this innovation is a recent advancement introduced, yet it resulted in a dramatic reduction in nonrenewable energy consumption in some countries. This subject was subject to various studies and gained considerable attention among researchers. During the past few decades, various studies are conducted using idealization, thus it is critical to do more research with assumptions close to the real case scenario.

1.3 Study objectives

Energy piles show intricate behavior in a real situation. to study the behavior of these piles one should consider the impact of loading, a saturation of the soil, interaction of piles in a group, and many other factors together to have an exact result. Up to date, various studies have been conducted considering the impact of each of these parameters separately, yet the impact of unsaturation of soil for a group of energy piles is not taken into consideration in many studies. energy piles are mostly used in urban areas in which soil is unsaturated and the degree of saturation is a function of climatic condition and mechanical characteristic of soil, this study considers the following objectives.

Fist objective is to choose a proper consecutive model to explain the behavior of unsaturated soil. although various models were introduced for unsaturated soil subjected to hydro-mechanical loading, most of these models can not analyze all of the unsaturated soil problems [2]. For this purpose first strength and weakness of each of these models in simulation of the behavior of unsaturated soil is studied.

The second objective is to implement the unsaturated soil consecutive model to Flac3d software, which is one of the most used software in geotechnical studies. This study uses the finite difference method to solve the problem. Most of the available studies either can not analyze unsaturated soil behavior or very simple models are implemented in them were do not show the impact of heat transfer accurately.

The third goal is to model energy piles and determine the interaction factor in unsaturated soil. moreover using interaction factor method displacement of each pile and the impact of loading one pile on the displacement of another pile is calculated.

1.4 The innovation of the study

- Adding equations of heat and water transfer to the basic Barcelona model and implementing it into Flac3Dsoftware
- Analyzing the behavior of energy pile in unsaturated clay soil
- Determining the interaction factor for a group of energy pile in unsaturated soil
- Studying the impact of geometrical characteristics of the pile and mechanical and thermal properties of soil on the interaction factor method

1.5 Outline of the study

This study is organized in the following way:

- Chapter one presents the scope, objectives, and importance of the study
- Chapter two gives a literature review on the subject
- Chapter three describes code development, validation of the thermos-hydro-mechanical model with water, and heat transfer in unsaturated soil.
- Chapter four presents modeling, analyzing and results of the subject of study
- Chapter five includes the conclusion and suggestions for further studies
- At last, references are listed

chapter 2
literature review

2.1 Introduction

The goal of this study is to determine the interaction between energy piles and to determine the interaction factor in unsaturated soil. in this chapter, first energy piles are introduced. Then studies on consecutive models are presented and at last section studies of energy pile in unsaturated soil are presented. Up to now most of the studies are conducted on energy piles placed in saturated soil and interaction factor values in unsaturated soil are not presented. On should consider that technological advancement and new resources of renewable energy makes it necessary to do more research on the subject.

2.2 Energy piles

Energy piles were first introduced in 1984 in Austria. During Decades after that, geothermal energy, as a source of renewable energy, catch the attention of various countries such as the United States, the Philippine, Indonesia, turkey, and a new island. Figure 2.1 shows the amount of energy extracted from these countries on Mega Pascal in February 2018 [3].

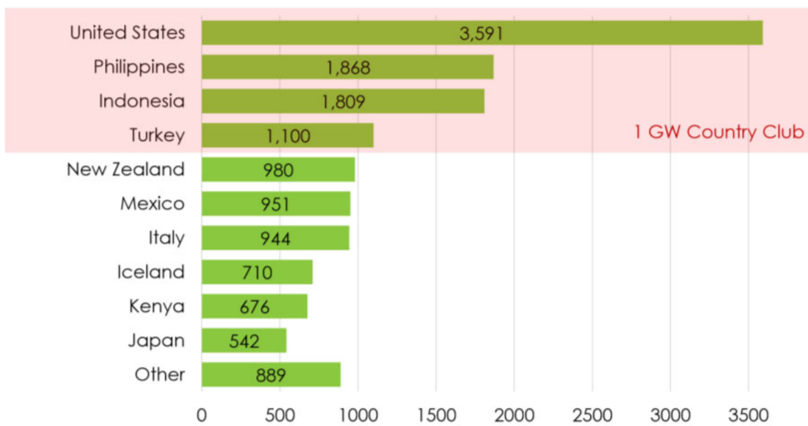

Figure 2.1: Geothermal energy extracted in February 2018 [3]

Moreover, Figure 2.2 shows the number of energy piles utilized each year and the impact of using energy piles in carbon dioxide reduction between 2007 to 2017. Based on this construction and utilization of these piles is increasing and using energy piles resulted in carbon dioxide reduction of 8000 tons in 2017. [4]

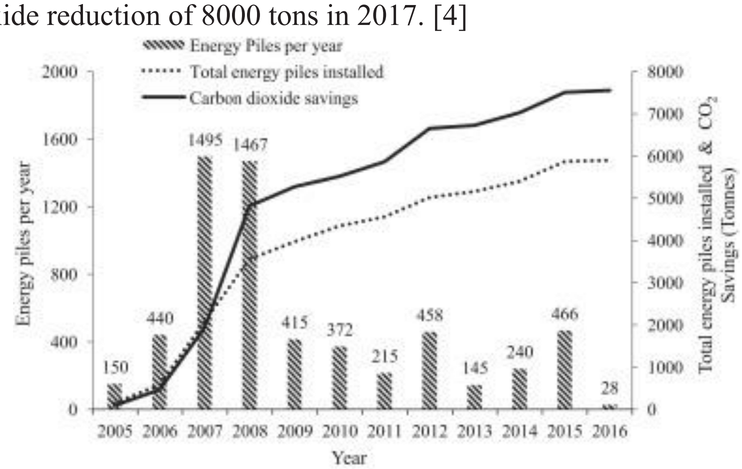

Figure 2.2: Number of energy piles and the amount of carbon dioxide reduction [4]

Energy piles include two main parts. The first part is the deep foundation which is in charge of loading bearing of structure and the second part is geothermal loops that are in charge of transferring heat and energy. Figure 2.3 shows the structure of a unit of energy pile [1].

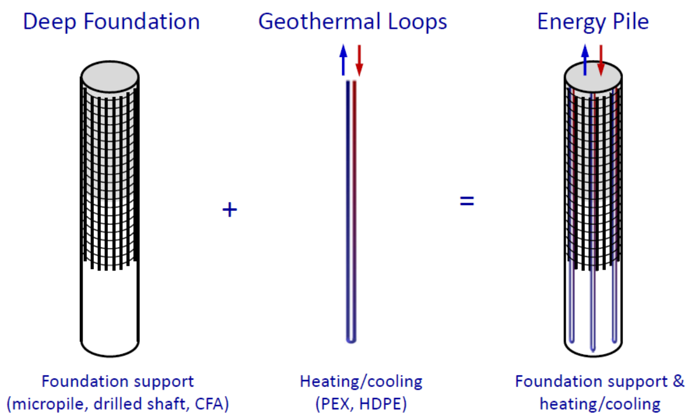

Figure 2.3: Structure of energy pile [1]

Geothermal loops have different characteristics and various shapes that are not discussed here. However, energy pile types are explained in the next section in detail.

As discussed earlier, energy piles have a dual function. Heat transfer in these piles is like a closed-loop system. In these piles, a fluid that is mostly water or water with ethylene glycol is circulated in the loops and transfers heat between pile and soil [5].

Soil can have three main states which are dry, fully saturated, and unsaturated. If the soil is fully dry, loading would be mechanical and thermal in this case. When soil is fully saturated loading can be mechanical, thermal, and hydraulic.in unsaturated soil, however, while loading is thermo-hydro-mechanical, the impact of variation of suction and flow os heat and water and vapor in the soil should be taken into consideration. In unsaturated soil coupled impact of these parameters should be taken into consideration. For instance, while increasing temperature might cause an increase of friction resistance, the decreasing temperature may cause a decrease of soil strength and movement of soil in the pile-soil surface and all of these factors result in a change of bearing capacity, displacement, and efficiency of the pile [6].

2.3 Heat transfer mechanism

Each body has a certain amount of internal energy which is related to the random movement of its atomic particles (i.e. kinetic and potential energy) and its specific phase (i.e. liquid, solid, gas); this internal energy is commonly referred to as thermal energy. Temperature is the average value of a body’s particle's thermal energy. The transfer of thermal energy is defined as heat and is measured in Joules (J). Heat flow can occur due to phase changes, which is not considered in this thesis, or by three distinct mechanisms: conduction, convection, and radiation.

2.4 Energy piles types

Piles are generally used as building foundations to avoid excessive settlements of the upper structure, as bridge foundations to reduce the erosion due to the water flux and in off-shore constructions. Their main role is to support large design loads and to overcome poor soil at shallow depth. An efficient design of such foundations should account for: (i) ground and groundwater conditions, (ii) methods of installation, (iii) safety and comfort of the building, (iv) environmental impact and (v) arrangement of the ground beam which transfers the load to the foundation and governs the interaction between the piles. The most common types of piles used in practice are:

2.4.1 displacement piles,

which include pre-cast concrete, pre-fabricated steel, cast-in-situ concrete, or screw piles. They are realized without removing soil. Also called *driven piles*, they are put inside the ground using a pile driver and the main advantage, at least in sand foundations, is that the surrounding soil is compressed during the process. This means greater friction at the sides of the piles and the result is an increase in load-bearing capacity. In the case of fine-grained soils, at the beginning of the installation, the ground is in virtually undrained conditions and constant volume deformation appears, causing the other piles eventually installed all around to be pushed upwards. At the same time, the high values of pore pressure result in a decrease in the horizontal effective stresses at the interface, facilitating the installation. When the consolidation process takes place the horizontal effective stress increases, the void ratio reduces and the bearing capacity improves;

2.4.2 Non-displacement piles,

which include bored, continuous flight auger, and mini piles. They are realised by injecting concrete into a borehole previously prepared, generally with rotary boring techniques. The construction method depends on the geological characteristics of the site, and the boring condition which is either dry ground conditions or through 'wet boring'. In particular cases, drilling fluids (such as bentonite suspension) is employed to maintain a stable shaft. The excavation of it may yield to swelling phenomena and an increase in water content at the interface, which is recovered only partially. Wall collapse at the shaft results in the failure of such piles and the formation of a reduced section and reduced load-bearing. Hence, at least one-third of piles in projects with a large number of piles are tested for uniformity using a Pile Integrity Test.

Piles are also often classified as:

- e*nd-bearing piles*, that transmit most of the load at the tip. This is more likely in granular soil or when a stiff layer is reached at the pile basis;
- *floating piles*, that, on the contrary, transfer the quasi-totality of the load to the soil through the lateral surface. This is more likely in fine-grained soils.

2.5 Connection of energy piles and the structure

An energy geostructure system is composed of three circuits (Figure 2.4): the first concerns the heat exchange between the soil mass and the geostructure, the second that between the geostructure and the heat pump, and the third one between the heat pump and the heating-cooling plant situated inside the building. Relatively minor modifications are required to transform a conventional geostructure into an energy geostructure. Mainly, a system of polyethylene pipes, with a heat carrier fluid that circulates through them and exchanges heat with the ground is hooked up to the reinforcing cage within the structures (Figure 2.4).

To maximize efficiency, the temperature in the third circuit (building) should not exceed 35-45 °C and the extraction temperature in the pipes should not fall below 0-5°C (Brandl, 2006) [7].

Besides, the thermal properties of soils might vary considerably in freezing conditions and it is recommended that excessive heat extraction causing soil freezing should be avoided (SIA, 2005) [8]. As mentioned above, in climatic regions where the cooling requirement during summer is significant, the energy geostructures can also be used to inject heat in the ground, which can be eventually (depending on the heat storage capacity of the soil) re-used during winter. This can be achieved by free cooling, active cooling, or a combination of both. In the first case, the heat-carrying fluid simply circulates in the pipes, and, as the soil is cooler than the air in the building, the heat is transferred from this latter to the ground.

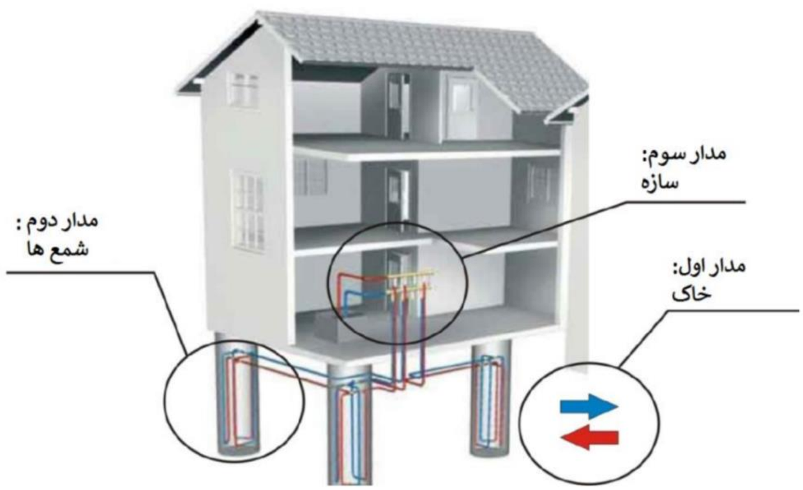

Figure 2.4: Energy pile system [7]

2.6 Unsaturated soil

Now that basics of energy piles are introduced, in this section unsaturated soil definition is given. Unsaturated soil is commonly defined as having three different phases of solids, water, and air. A most important parameter of unsaturated soil which defines its behavior is suction. Total suction includes two main parts of osmosis suction and matric suction. Total suction is defined as:

$$\psi = (u_a - u_w) + \pi$$

where ψ is total suction, $(u_a - u_w)$ is osmosis suction and π is matric suction. Variation of suction in the soil is a function of the degree of saturation and is defined by the soil water characteristics curve. Figure 2.5, shows one of these curves, it should be noted that the soil-water characteristic curve is different from one soil to another [9].

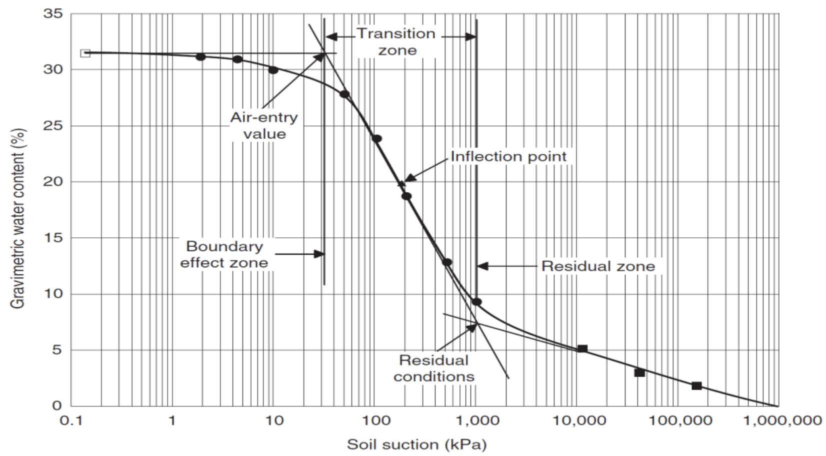

Figure 2.5: Soil water characteristics curve [9]

In the next section, former consecutive models presented by various researchers are presented.

2.7 Consecutive models of unsaturated soil

2.7.1 Cam-clay and modified cam-clay models

Cam-clay and modified cam-clay models are presented by researchers at the University of Cambridge for clayey soil. these models can present unsaturated soil behavior based on the theory of critical line [10]. In the theory of critical line status of each soil sample can be described by parameters of a mean stress, deviatoric stress, and specific volume. One of the assumptions of this model is that there is a logarithmic relation between mean stress and void ratio. Moreover, this can explain the yield behavior of soil using yield surface. Equation of yield surface of cam-clay model is defined as:

$$F_c = q + Mpln\left(\frac{-p}{p_c}\right) = 0$$

Moreover, the equation of the yield surface of modified cam-clay model is expressed as:

$$F_c = q^2 + M^2 p(p + p_c) = 0$$

In these equations F_c is yield function, q deviatoric stress, *M* slope of the critical line in $p \acute{-} q$, p stress and p_c yield stress or pre-consolidation pressure.

Later Alonso et al [11] presented a basic Barcelona model based on cam-clay and modified cam-clay model framework, which is the base of the current study as well. Since this model is very important equations are described in chapter three.

2.7.2 Wheeler model

Wheeler et al presented a model for unsaturated soil based on critical state theory in 1995 which was very similar to the Alonso model. Later in 2003, during the experimental study, they found out that variation of the degree of saturation may lead to the variation of mechanical behavior of soil at constant suction. In 2003 they introduced an elastoplastic model for unsaturated soil. this model shows that variation of the degree of saturation affects the stress-strain behavior of soil and variation of plastic volumetric strains affects hydraulic hysteresis behavior of the soil [12].

2.7.2.1 Impact of hysteresis on mechanical behavior

Studies conducted by Wheeler shows the importance of considering hysteresis. In unsaturated soil in two identical samples and specific suction, the amount of moist may be different based on the wetting or drying path each sample experienced. This is shown in Figure 2.6.

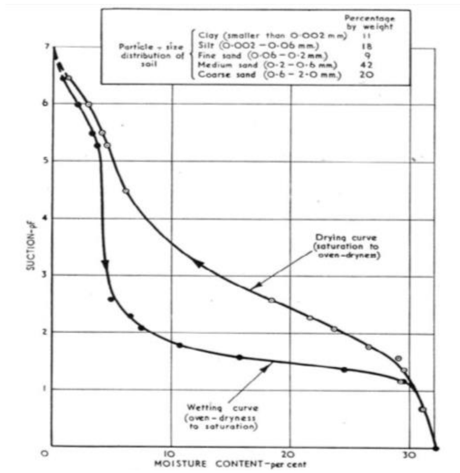

Figure 2.6: Relation of suction and moisture content based on wetting and drying path [12]

Stress variables that are used in most of the models of unsaturated soil are normal net stress, matric suction, and specific volume which don't show the impact of the degree of saturation very well.

To consider the impact of this factor on the mechanical behavior of the soil, Wheeler separated bulk water and meniscus water Figure 2.7 Wheeler pointed out that variation of the degree of saturation directly affects stress-strain and caused variation of the ratio of bulk water to meniscus water and an increasing degree of saturation leads to the increase of this value. Thus he concluded that two samples with equal external stresses and equal suction and dry density and different degrees of saturation show different behavior [12].

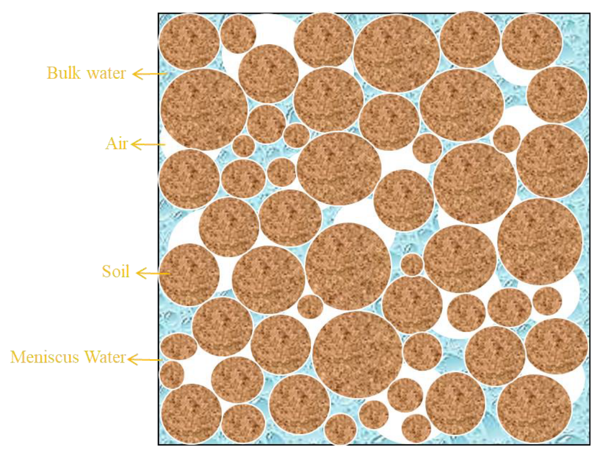

Figure 2.7: water in soil void

2.7.2.2 Formulation of Wheeler model

Wheeler introduced an additional yield surface to those previously presented by Alonso. This model has three yield surfaces of suction increase, suction decrease, and loading collapse. This model is defined by the following equations:

$$p^* = p_0^*$$

$$s^* = s_I^*$$

$$s^* = s_D^*$$

In these equations p^* is bishop's mean stress, s^* is modified suction and p_0^*, s_I^* and s_D^* determine the position of three yield curves.

The elastic volumetric strain is defined by:

$$d\varepsilon_v^e = \frac{kdp^*}{vp^*}$$

Where k is the slope of unloading line in the saturated state and in *v:lnp* and v is specific volume. When the stress path intersects the loading collapse curve, volumetric strains are plastic and are defined as:

$$d\varepsilon_v^p = \frac{(\lambda - k)dp_o^*}{vp_o^*}$$

In this equation is λ stiffness parameter and p_o^* is pre-consolidation stress in a saturated condition. In this case, flow rule is expressed as:

$$\frac{dS_r^p}{d\varepsilon_v^p} = 0$$

Where defines $d\varepsilon_v^p$ plastic volumetric strain and dS_r^p shows plastic degrees of saturation. Variation of the elastic degree of saturation is defined as:

$$dS_r^e = -\frac{k_s ds^*}{s^*}$$

k_s is the parameter that is used to determine the elastic degree of saturation. When one of SI or SD curves are reached, the variation of the plastic degree of saturation is defined as:

$$dS_r^p = -(\lambda_s - k_s)\frac{ds_I^*}{s_I^*} = -(\lambda_s - k_s)\frac{ds_D^*}{s_D^*}$$

In this equation λ_s is a parameter of stiffness for variation of suction in an initial soil sample and flow rule on SI and SD is defined as:

$$\frac{d\varepsilon_v^p}{dS_r^p} = 0$$

Variation of volumetric plastic strain and plastic degree of saturation is defined as:

$$d\varepsilon_v^p = \frac{(\lambda - k)}{v(1 - k_1 k_2)}\left(\frac{dp_o^*}{p_o^*} - k_1\frac{ds_D^*}{s_D^*}\right)$$

$$dS_r^p = \frac{(\lambda_s - k_s)}{v(1 - k_1 k_2)}\left(\frac{ds_D^*}{s_D^*} - k_2\frac{dp_o^*}{p_o^*}\right)$$

This model has 6 parameters of $k_2, k_1, k_s, \lambda_s, k, \lambda$. While the number of parameters is very limited in this model, it is capable of defining hydraulic and mechanical behavior of soil very well.

2.7.3 Wu et al model

This model which is proposed in 2004, focuses on the hydro-mechanical behavior of fine-grained unsaturated soil. In this model impact of temperature, hydraulic characteristics, soil conductivity is taken into consideration and experimental data are used to explain the behavior of soil in critical suction values. This model can relate suction and temperature variation for different stress paths [13].

2.7.4 Khalili and Musin model

This model which is proposed in 2008 is based on the theory of hypo-plastic and effective stress. This model is capable of modeling collapse due to wetting which is not possible in other models. The results of this model are verified with experimental data on compacted clay soil [14].

Proposed hypo-plastic model for unsaturated soil is based on the hypo-plastic model for clay soil and has the following formulation:

$$\dot{T} = f_s(\mathcal{L}: \dot{D} + f_a N \parallel D \parallel)$$

In this equation $\dot{T}$ is variation in quasi stress tensor, D is Euler tension tensor, $\mathcal{L}$ and N are consecutive tensors, f_s and f_a are scalar quantity which shows the impact of effective stress and porosity.

Effective stress is defined as:

$$T = T^{net} + \chi . s$$

In this equation is T effective stress T^{net} is net effective stress and χ is a parameter defined as:

$$x = \begin{cases} 1 & for \quad s \geq s_e \\ \left(\frac{s_e}{s}\right)^{\gamma} & for \quad s < s_e \end{cases}$$

s_e is a suction that separates saturated conditions from the unsaturated condition.

Differentiating previous equation and combining them we will have following equation for variation of effective stress as:

$$\dot{T} = T^{\dot{n}et} + (1 + \gamma)\chi . \dot{S}$$

As can be seen in this equation, suction and effective stress tensor are taken as stress a variable that shows a hardening effect due to meniscus water. The formulation of constant suction is presented in the following. Moreover, the formulation of collapse in wetting for both normally consolidated and overconsolidated is presented.

The mechanical response of a soil element in the general state is controlled by effective stress tensor. Suction affects effective stress and normal stresses increase which increases to soil skeleton. From the soil mechanic perspective, critical state suction caused an increase of boundary surface. This surface is a boundary for all the possible conditions for an element of soil. The following equation presents the size of this surface for unsaturated soil.

$$\ln(1+e) = N(s) - \lambda^*(s) \ln \frac{p}{p_r}$$

Where p is stress, is initial stress and equal to 1 kilo Pascal. $N(s)$ And $\lambda^*(s)$ determine the position and slope of isotropic consolidation line in $\ln\left(\frac{p}{p_r}\right) - \ln(1+e)$ for a specific suction. These two parameters are f_s and f_a in former equations and are defined as:

$$N(s) = N + n \ln\left(\frac{s}{s_e}\right)$$

$$\lambda^*(s) = \lambda^* + l \ln\left(\frac{s}{s_e}\right)$$

n and *l* parameter are soil parameters.

2.7.5 Dumont model

The proposed model in 2010 analyzes the impact of suction decrease and softening caused by temperature using experimental empirical methods. this model is capable of determining the stress path with increasing temperature under constant suction and paths of constant temperature and suction [15].

2.7.6 Pedroso and Farias model

This model is introduced in 2011 and is an extension to the basic Barcelona model which is capable of simulating elastoplastic behavior of soil subject to loading-unloading cyclic mechanical load. in this model, a relation defined between main stresses and strength of the soil. moreover, three yield surface is presented for this model [16].

2.7.7 Ghasemzadeh and Ghoreishian Amiri model

This elastoplastic model is proposed in 2013 for the isotropic loading of unsaturated soil describing its stress-strain behavior. This model is capable of explaining non-reversible volumetric changes of water in the stress-strain curve and plastic volumetric strain for hydraulic behavior. This model uses plastic boundary surface and loading sub-surfaces to describe hydraulic and mechanic behavior. Hardening rule is used to couple hydraulic and mechanical behavior. Moreover, this can be used for extremely expansive soil and collapse behavior, and the results of the model were verified with experimental data [17].

Later another model developed for the non-isotropic model with the suction increase, suction decrease, and loading collapse as shown in Figure 2.8.

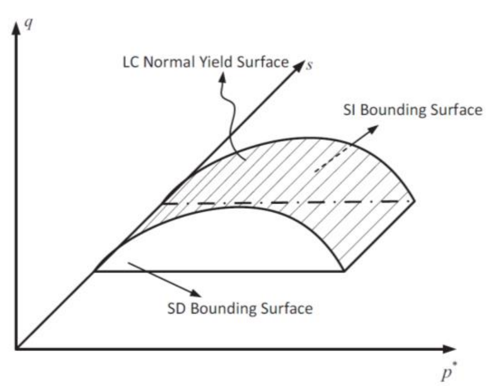

Figure 2.8: Yield surfaces for isotropic loading [18]

Formulations of yield surfaces are as follows, in these equations s_{IO} and s_{D0} are suction increase and suction decrease surfaces. Moreover, p^* defines normal effective stresses.

$p^* = p_0^*$
$s = s_{D0}$
$s = s_{I0}$

2.8 Energy pile design

To understand the behavior of energy piles, it is important to study various factors and methods used to design these piles. To design an energy pile, three main parts should be taken into consideration. The first part is related to the mechanical and thermal properties of the soil such as thermal conductivity and specific heat capacity. The second part is to study the bearing capacity, displacement, and position of piles in the group. The third part is to design lops of fluid transfer such as length and diameter, density and viscosity of fluid, velocity, and flow of fluid in the loops. Since up to now, no complete design method is available for these piles each of these parameters should be studies separately and put together. In this section, only the parameters that are directly associated with the subject of the current study are discussed here. More information on the design of energy piles can be found in [1].

2.8.1 Thermal and mechanical properties of the soil

Up to date, various studies are conducted on thermal and mechanical properties of soil considering soil in the saturated state [19]. Geothermal resources of the earth which are stored at depths lower than 400m is called shallow geothermal resources. At a depth 15 to 20 meters below the surface depth, the ground temperature usually remains constant during the year. At this depth, geological condition and daily temperature variation of the ground results in the ground temperature of +5 to +10C depending on the regions (Brandl, 2006). The advantage of the constant temperature of the ground is that it can be used for both cooling and heating of buildings.

The ground can be used as a heat source in the winter and also as storage for the heat that is wasted during the summer, providing a balanced combination for cooling and heating (Figure 2.9). In the summer, the heat pump is designed to circulate cold fluid around the building, extracting the heat from the building and transferring it to the ground. During the winter the direction of the heat pump is reversed, extracting heat from the ground and transferring it to the building. In this way, the ground works as an Underground Thermal Energy Storage.

The temperature of the soil is different based on geographic location and climatic condition which is one of the most important factors that should be taken into consideration in the design of energy piles. Wood et al used a numerical and experimental approach and reported that as the radial distance from the pile is increased, the impact of temperature variation pile on soil decreases. Moreover, if heat injection and extraction from the soil continue for a long period, the temperature of the soil decreases or increased after a few years [20].