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Effect of Crude Oil on Soil-Water Characteristic Curve of Clayey Soil

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***Abstract*—**The measured soil suction values when related to water content is called suction-water content relationship (SWR) or soil-water characteristic curve (SWCC) and forms the basis of unsaturated soil behavior assessment. The SWCC can be measured or predicted based on soil index properties such as grain-size distribution and plasticity index. In this paper, the SWCC of clean and contaminated clayey soil classified as clay with low plasticity (CL) are presented. Laboratory studies were conducted on virgin (disturbed-uncontaminated soil collected from vicinity of Tehran oil refinery) soil and soil samples simulated to varying degrees of contamination with crude oil (i.e., 3, 6, and 9% by dry weight of soil) to compare the results before and after contamination. Laboratory tests were conducted using a device which is capable of measuring volume change and pore pressures. The soil matric suction at the ends of samples controlled by using the axis translation technique. The results show that contamination with crude oil facilitates the movement of water and reduces the soil suction.

***Keywords*—**Axis translation technique, clayey soil, contamination, crude oil, soil-water characteristic curve.

I. Introduction

In most cases, in situ compacted soils are unsaturated and are characterized by soil suction, which plays a significant role in determining the performance of soil as foundation materials in terms of permeability, strength and volume change [1]. Further, many of the geotechnical engineering problems, especially in arid or semi-arid climatic areas, are associated with unsaturated soils [2]. Matric suction refers to a measure of the energy required to remove a water molecule from the soil matrix without the water changing state. It represents the difference between the pore air pressure and the pore water pressure [3]. SWCC is a fundamental property of an unsaturated soil that is used to predict multiphase flow and transport through porous media. It is described as the relationship between the degree of saturation, S_r, (or the volumetric water content, θ) and the matric suction, $S = u_a - u_w$, where u_a and u_w are pore air and pore water pressures, respectively. SWCC usually obtained by drying or wetting a soil sample under constant stress while monitoring the changes of water content in the soil. The curve is also called the soil moisture characteristic curve or the soil water retention curve.

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As introduced by [4], the entire suction range of the SWCC can be divided into three zones such as boundary effect zone, transition zone and residual zone and they are separated by air-entry value and residual suction (see Fig. 1).

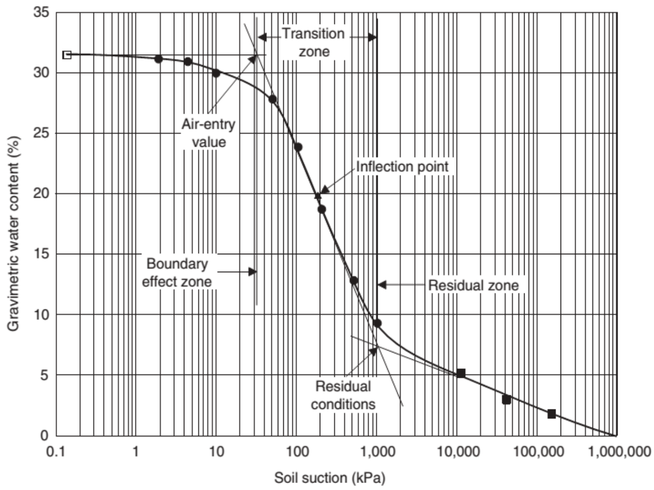

Fig. 1 Desaturation zones defined on SWCC [4]

Different best-fit equations, such as proposed by [5]-[9], have been developed to describe SWCC that relates the amount of water in a soil to the matric suction.

Many experimental tests had been done to obtain the SWCC for different types of soil under different conditions. A number of mathematical equations have been proposed in the literature to represent SWCCs. References [7] and [10] reviewed a range of proposed SWCC models along with parametric studies. Most of the equations described earlier are empirical in nature and based on the shape of the SWCC. Reference [11] also summarized numerous mathematical models of the SWCC. The mathematical models presented in their paper can be categorized in a number of ways to illustrate the characteristic equations such as parametric studies, as well as their advantages and disadvantages. Models such as those of [5]-[8] and [12]-[19] were analyzed. The most commonly employed classical retention models are the sigmoid function models by [12] and [6] and the power function model by [5].

Exploration, production, storage, refining and transportation etc. are some of the major activities related to crude oil. These are potential sources for spills or releases of crude oil and its products to the soil. These spills or releases may be either accidental or natural. The total number of damaged oil well in the Gulf War in 1991 was 1120. Out of these, 639 wells were on fire, crude oils were flowing into desert from 42 wells and 439 wells were damaged [20]. The extent of contamination depends on the filtration and retention properties of the soil [21]. Such contamination not only results in immediate or future damage to the soil environment, but also changes the physical and mechanical properties of the soil.

The spilled or gushing oil moves down to the ground water under gravity. The soil is partially saturated by the oil on its pathway. After reaching the ground water, the liquid spread horizontally by migration within the capillary zone [22]. This may lead to serious soil contamination. The petroleum hydrocarbons wastes released on the ground ultimately find its way to the soil system changing the properties of pore fluid. Change of liquid limit (LL), plastic limit (PL), plasticity index (PI), unconfined compressive strength (UCS), free swell index (SFI), differential free swell index (DFSI), pH value, and electrical conductivity (EC) of soil with increase in the level of contamination with crude oil in case of CL and CH was also observed [23]-[25].

Reference [26] investigated the changes in drying SWCC parameters of a sandy soil due to the addition of fly ash. The study indicates that Van Genuchten SWCC parameters of the sandy soil vary due to the addition of fly ash.

Reference [27] evaluated the change in water-holding properties and the SWCC of Ottawa sand contaminated with varying degrees of motor oil. SWCCs for oil contaminated Ottawa sand constructed during this study were different from the soil-water retention curve of clean Ottawa sand. The soil-water retention curves indicate that the introduction of a relatively low amount of oil contamination inhibits the movement of water. The results of this research indicate that the introduction of petroleum hydrocarbons to a soil changes that soil's hydraulic properties. At higher suction values, the contaminated samples had a higher water- holding capacity.

Reference [28] studied the behavior of engine oil contaminated CL soil and observed that soil suction decreased with increasing amount of oil.

Reference [29] performed a parametric assessment of sandy loam water retention at presence of petroleum in three phase system (NAPL-water-air). The results showed that in a given amount of soil liquid phase, more suction is needed to drain out fluids in three-phase (NAPL-water-air) systems compared to two-phase (water-air) system. Thus, in a given quantity of NAPL, the porous media provide more retention for three-phase systems. Also, the calculated statistics indicated that van Genuchten model provides more reasonable predictions for NAPLs retention in three-fluid phase systems.

II. Materials and Methods

A. Materials

The soil samples were natural fine-grained soil, obtained from vicinity of Tehran oil refinery in the southern part of Tehran. The soil samples were collected at a depth between 0.25 and 0.50 m below the ground surface. Table I shows the summary of basic geotechnical properties for the uncontaminated soil. According to USCS, the soil is categorized as CL.

TABLE I
Geotechnical Properties of Clean Soil

C_u	C_c	G_s	PL	LL	PI	γ_{dmax} (kN/m^3)	ω_{opt} (%)	Silt or Clay (%)	Sand (%)
9	0.44	2.69	24	40	16	17.5	20.5	91.9	8

The results of the XRF showed the presence of clay minerals (SiO_2= 35.8% and Al_2O_3= 8.4%) and of calcite (CaO= 17.7%). The relatively high amount of silica reflected the presence of quartz. Table II includes the properties of the oil used in this study that were provided by refinery experts.

TABLE II
The Crude Oil Properties (from the Supplier)

Viscosity (cp)	Density (g/cc)	API Gravity (at 60°F)	Flash Point (°C)	Specific Gravity (at 25°C)	Dielectric Constant
41.3	0.891	26.8	44.1	0.89	2.1

B. Sample Preparation

The air dried soil was first pulverized to eliminate the agglomerated particles. The pulverized soil was mixed with sufficient distilled water to reach the proper sample water content. Generally, level of contamination is defined as the percentage weight of crude oil with respect to dry weight of soil. The maximum percentage of crude oil present in disturbed and undisturbed contaminated soil samples is within 10% [22]. Based on this consideration, artificially contaminated samples were prepared by mixing with 3, 6, and 9% crude oil by weight of dry soil until sufficient homogeneity is achieved. It should be mentioned that sum of water content and crude oil content of each sample was restricted to optimum water content (i.e., 20.5%). For example, in case of 6% contamination, 14.5% distilled water was added to the specimen. Thereafter, the samples were placed in insulated plastic containers for one week at temperatures of 20 to 25°C to simulate aging effects. This period of time is consistent with the 3-7 day period proposed in the literature for soil-contaminant mixtures [30]. All specimens were compacted in five equal layers by means of tamping. The relative compaction of all specimens was kept constant and equal to 95% (γ_d= 16.63 kN/m^3).

III. Results and Discussion

Laboratory tests were performed using a SWCC determination apparatus which consists of a double walled cell, volume change and pressure transducers, and a data acquisition system. The device was equipped with porous stones and five-bar ceramic disks at both the bottom pedestal and the top cap to control and measure the soil matric suction at the ends of specimens using axis translation technique. Volume change transducers were used for automatic pore water and total volume change measurements. The SWCC of clean and contaminated soil were measured using cylindrical specimens 38 mm in diameter and 40 mm in height and are shown in Fig. 2. The first phase of each test consisted of a wetting stage during which specimens were brought to zero matric suction, followed by gradually increased matric suction to 450 kPa and measuring the corresponding water content.

Matric suction of clean soil after remolding was also measured to be on the average of 58.7 kPa. This test was implemented on three samples with similar initial condition to ensure repeatability of measured suction values.

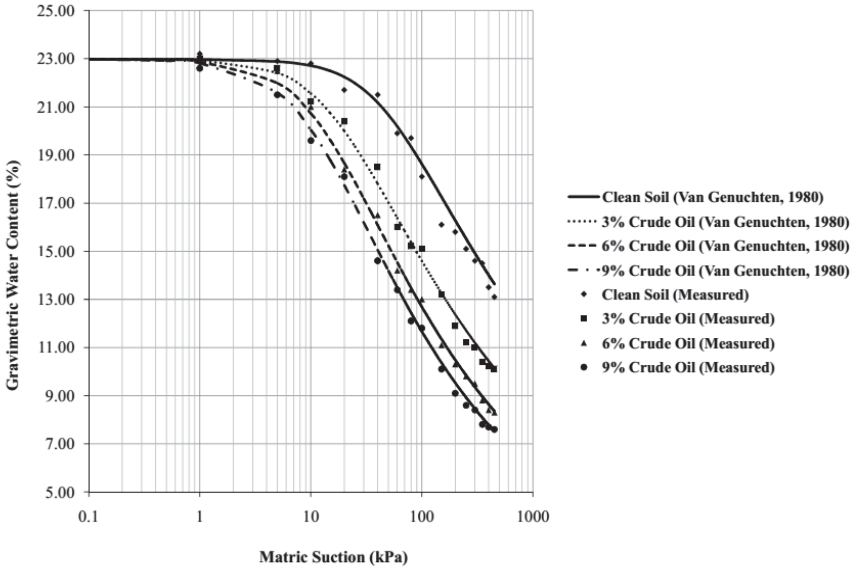

Fig. 2 SWCCs of clean and contaminated soil

As stated earlier, the Van Genuchten equation is one of the most commonly used SWCC equations. It is referred to as a three-parameter equation and takes the following form for representing water content as a function of soil suction:

$$w(\psi) = \frac{w_s}{\left[1+(a\psi)^n\right]^m} \qquad (1)$$

where, w (ψ): water content at desired suction, w_s: saturated water content, ψ: desired suction, a, n, m: fitting parameters.

For comparison, the gravimetric water content SWCC was best-fit with the Van Genuchten equation using a computer program RETC (version 6.02) and yielded parameters presented in Table III. RETC is widely used to forecast SWCC in terms of Van Genuchten model. The nonlinear least square method is adopted in this software and initial values of Van Genuchten equation parameters need to be set.

TABLE III
BEST-FIT PARAMETERS OF VAN GENUCHTEN EQUATION

Sample	a	n	m
Clean Soil	0.01538	1.26871	0.21180
Contaminated with 3% Crude Oil	0.04014	1.28674	0.22284
Contaminated with 6% Crude Oil	0.06667	1.30284	0.23245
Contaminated with 9% Crude Oil	0.08333	1.31543	0.23979

The results indicate that the best-fit SWCCs using Van Genuchten equation closely describe the SWCC data of the soils and is sufficiently accurate to estimate the behavior of samples before testing.

Air-entry value (AEV) which is defined as the suction at which air starts entering the largest pores present in the soil sample [26] for clean and contaminated samples is determined from Fig. 2 and presented in Table IV. As could be observed, air-entry value of soil decreases as a result of crude oil contamination.

The differences of the SWCCs are determined by the differences of the SWCC parameters such as the air-entry value and best-fit soil parameters of a, n, and m. Best-fit parameters increase with crude oil content and the rate of growth decreases at higher degrees of contamination. Clean soil has the smallest a, n, and m values of 0.01538, 1.26871, and 0.21180 respectively and soil contaminated with 9% crude oil has the largest a, n, and m values of 0.08333, 1.31543, and 0.23979, respectively. Air-entry value of clean soil decreased from 30 kPa to 7, 6, and 5 kPa when contaminated with 3, 6, and 9% crude oil, respectively. In other words, the air-entry value of clean soil decreased 77, 80, and 83% due to contamination with 3, 6, 9% crude oil, respectively. Furthermore, as illustrated in Fig. 2, crude oil contamination causes the SWCC to move down and left. Typical SWCCs for different are shown in Fig. 3 [7]. As could be observed, SWCC of silty soil and sandy soil move down and left with respect to that of clayey soil.

TABLE IV
AIR-ENTRY VALUE OF SAMPLES

Sample	AEV (kPa)
Clean Soil	30
Contaminated with 3% Crude Oil	7
Contaminated with 6% Crude Oil	6
Contaminated with 9% Crude Oil	5

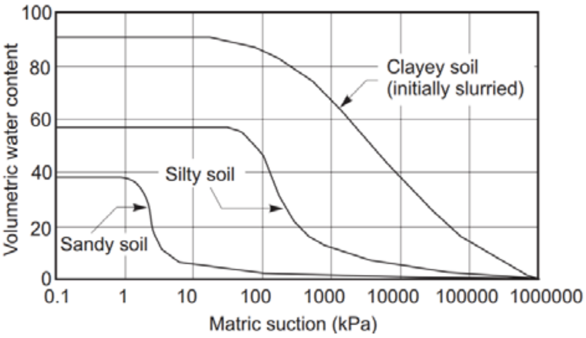

Fig. 3 SWCCs of sandy soil, silty soil, and clayey soil [7]

By considering the stated subjects, it could be concluded that crude oil contamination causes the SWCC of clayey soil to tend towards that of cohesionless soil. In addition to viscosity, the dielectric constant of pore fluid has been shown to impact the geotechnical properties of soil. The effect of changes in physicochemical interactions between the fine soil particles and water on the properties of soil has been observed in several studies. Such changes in soil fabric have been attributed to the thickness of the double layer and related to changes in soil properties [31]. The thickness of double layer has been correlated with particle orientation and, therefore, with changes in soil fabric. Several studies have shown that when the pore water (dielectric constant $\varepsilon \approx 80$) is replaced with an organic fluid of lower dielectric constant, double layer shrinks, soil particles flocculate and the flocculated particles form clusters which act like silt-sand grains [32]-[36].

IV. Summary and Conclusions

Drying SWCCs were investigated for clean and contaminated clayey soil (CL) mixed with 3, 6, and 9% crude oil by weight of dry soil using a SWCC determination apparatus. The SWCC test data were best-fitted using the Van Genuchten equation using a computer program RETC. Specific conclusions from this study can be summarized as follows:

(1) Contamination of clayey soil with crude oil causes the SWCC to move down and left and tend towards that of cohesionless soil.
(2) Presence of crude oil results in smaller air-entry values and the soil tendency for water retaining will be decreased.
(3) It seems that when pore water with high dielectric constant is replaced with an organic fluid of lower dielectric constant (such as crude oil) double layer thickness reduces and the clayey soil behaves more like cohesionless soils.

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