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ESTIMATION OF CAPILLARY RISE IN UNSATURATED GYPSEOUS SAND SOILS

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Abstract: The phenomenon of capillary rise happens in soils, and it has a crucial effect on many engineering applications. Many researchers have concluded several experimental equations to estimate this height. This paper presents a comparative and practical study of the three most important equations used in most researches, which are Lane and Washburn, Fetter, and P-K equations. The estimated heights by these three equations were compared with the experimental tests on sand samples taken from Al-Adalah, Al-Furat, and Al-Jameah districts located in Al-Najaf city in the southwest of Iraq. The percentage change for each equation compared with the experimental work. The results illustrated that the Fetter equation is the closest equation to experimental height and gives moderate values, unlike the Lane and Washburn and P-K equations, to save estimation of the pollutants penetration in unsaturated soils.

Keywords: Unsaturated gypseous, Sandy soil, Capillary rise, Sieve analysis

1. Introduction

The capillary phenomena are related to research work carried out in the field of environmental geotechnics. Capillary water movement into the soil is vital in many practical environmental engineering applications and problems in connection with pollutant behavior in soils like highways construction [1], [2]. Consequently, the problem of rising water in initially dry soil, which in touch with water at the base and exposed to the atmosphere, should be clarified [3].

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In arid and semi-arid areas, as in Iraq, where gypsiferous soils are found, the topsoil layers are mostly in unsaturated [4], [5]. The water content is low in the vadose zone relative to the saturated zone and referred to as the unsaturated zone [6], [7]. When the water rises in the porous media, it will displace the air until the pressure of the water level is in an equilibrium state [8]. The capillary pressure head increases as soil moisture decreases. Capillary forces or matric potentials are dominant during the phase of infiltration [9]-[11]. The saturation decreases the strength of the soil and changes the modulus of elasticity of its substructures under the loading [12].

Many researchers have concluded that there was a decreasing in the soil stiffness and increasing in the soil deformations with increasing of the gypsum content due to wetting progress in Iraq [13]-[16]. Groundwater pollution depends on the movement of the contaminants in saturated aquifers, which is depended on the permeability of the vadose zone with a component that is a function of capillarity. The flow in unsaturated materials can be described by using Darcy's Law, and the rate pass through the vadose zone is equaled to the rate of leachate seepage into a water table [17]. The importance of the vadose zone in wastewater reactions is clear after the success of millions of local and commercial septic systems [6]. Al-Najaf city soil is mainly sand with different percentages of the gypsum [5], [18].

In this work, an experimental study was conducted to verify that the empirical equation proposed in the literature to find the maximum capillary rise cannot be used arbitrarily for any type of soil. The water content, salts, gypsum, etc. may play a crucial role in identifying, which capillary rise equation is appropriate for specific soil. This experiment has used three types of sandy soils different in the substructure to measure the capillary rise in each of them. Lane and Washburn [12], Fetter [18], and P-K [8] equations are used as a case study to identify their validity for the three types of soil. The experiment shows that, for instance, Lane and Washburn may be appropriate for soils that have high water content and low gypsum percentage. Other details for the rest of the equations are illustrated in detail in the respective sections.

2. Background of capillarity

Capillary action is the motion of water upwards due to the adhesion cohesion forces and force of water molecules with each other [19].

In the construction industry, the capillary rise is essential. It is necessary to know the increasing moisture in building materials. The foundation of the building may be above the water table but maybe within the capillary fringe. If the building within the capillary fringe can increase the building's base moisture, which can contribute to mold problems [8]. Terzaghi's assumes that Darcy's law is valid for the capillary rise and expressed in mathematical terms as follows

$$q = k_s i = n \frac{dz}{dt}, \tag{1}$$

where q is the discharge velocity conductivity of the soil; k_s is the saturated hydraulic conductivity of the soil; i is the hydraulic gradient for the capillary rise; z is the distance measured positive upward from the elevation of the water table; t is a time of the capillary rise and n soil porosity [20].

The capillary tube diameter, the density of the liquid, the viscosity of the fluid, and surface tension are some of the many parameters that should be considered in the estimation of the magnitude of capillary rise in a particular soil.

Washburn's, Lane and Washburn, Peck and Hanson, Kumar and Malik, Fetter, P-K, and others' equations are common equations and methods introduced in the literature to estimate the height of the capillary rise through soils. Lane and Washburn, Fetter, and P-K equations, as it is shown in *Table I,* are chosen as case studies for the purpose of comparison with the real height from the experiment.

Table I

Commonly used equations to find maximum capillary rise

Equations	Expression	Parameter
Lane and Washburn [12]	$h_c = -990\left(\ln D_{10}\right) - 1540$	D_{10} is the effective size is the diameter in the particle-size distribution curve corresponding to 10% finer
Fetter [18]	$h_c = \dfrac{2\sigma \cos\lambda}{\rho_w g R}$	h_c is the height of the capillary rise (L in cm or mm); σ is the surface tension of the fluid (M/T^2 in g/s^2 or kg/s^2); λ is the contact angle of the fluid meniscus with the capillary tube wall (degrees); ρ_w is the density of the fluid (M/L^3 in g/cm^3 or kg/m^3); g is the acceleration of gravity (L/T^2 in cm/s^2 or m/s^2); constant R is the radius of the capillary tube (L in cm or m); according to Fetter R of capillary equal to $0.2d_{10}$
Polubarinova-Kochina (P-K) [8]	$h_c = \dfrac{0.45\left(\dfrac{1-n}{n}\right)}{d_{10}}$	n is the porosity [19] $n = 100\left(1 - \dfrac{\rho_b}{\rho_m}\right)$

3. Methodology and materials

3.1. Study area

The studied area is located in AL-Najaf Governorate (161 km southwest of Baghdad) in the southwest of Iraq in the Middle East as it is shown in *Fig. 1*. Najaf has an area of 29,000 km^2; it constitutes approximately 7% of Iraq's total area. Its geographical area extends between longitudes 42º - 44º 45' Eastwards and 29º 50' - 32º 21' latitudes Northwards by degrees' system [21].

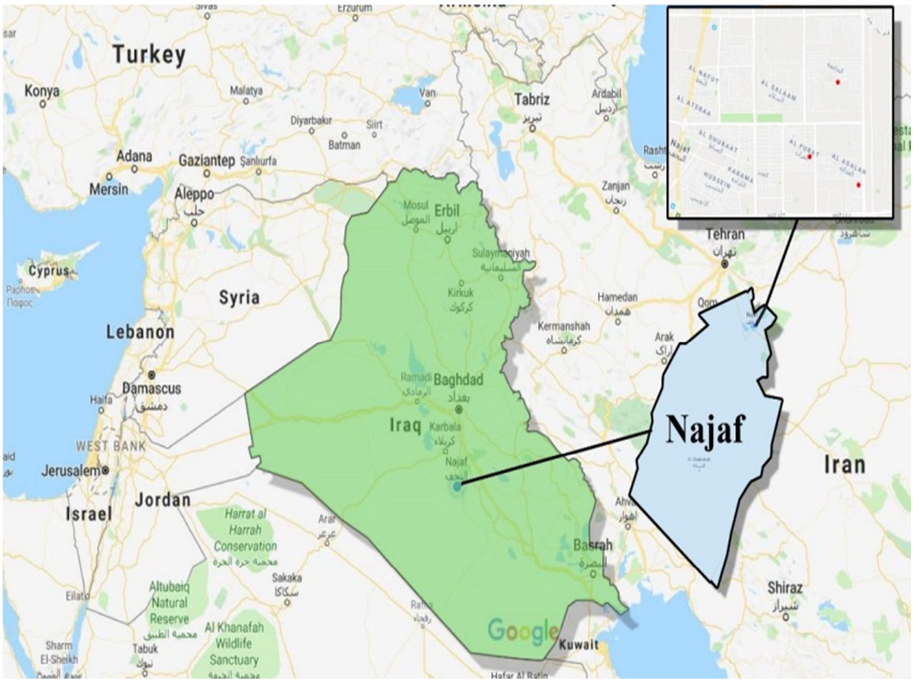

Fig. 1. Najaf city in Iraq and the location of collecting samples

3.2. Methods

After the identification and classification of the soil samples, a set of capillary rise tests were made to estimate the h_c. The experiments are performed depending on the field density of the soil. These experimental results are compared to the proposed equations, Lane and Washburn, Fetter, and P-K, that will be used to measure the capillary rise height of the selected soil samples using GNU Octave (as in appendix A).

3.3. Materials

The samples used were taken from Al-Furat district (32°01’14.8”N 44°21’08.2”E), Al-Adalah district (32°01’04.7”N 44°21’50.0”E), and Al-Jameah district (32°01’52.9”N 44°21’10.2”E) in Al-Najaf, Iraq. Samples collected from the three chosen residential areas in Al-Najaf city. These disturbed samples collected from a depth up to 2 m, as it is shown in *Fig. 2*. After collecting the samples from the field, they were kept in closed containers to save the water content from evaporation. The samples transferred to the soil laboratory at the Faculty of Engineering at the University of Kufa in Najaf-Iraq to make the necessary laboratory tests. The soil samples are symbolized as SS-1 for Al-Adalah district, SS-2 for Al- Jameah district, and SS-3 for Al-Furat district.

A sample of 500 g of soil was used for the sieve analysis test. The purpose of the test is to classify the soil and determine the effective diameter D_{10}, which will be used to determine the height of the capillary from the theoretical models. A compaction test was made to determine the density of the soil that will be used later to determine the height of the capillary where 4 kg of the soil of the proposed zones were used in the test.

Fig. 2. Sampling works

The soil samples from SS-1, SS-2, and SS-3 were gradated by a sieve analysis test, as it can be seen in *Fig. 3*. *Fig. 4* illustrates the standard Proctor tests for the different soil samples. *Table II* summarizes the properties of the soil for the selected samples.

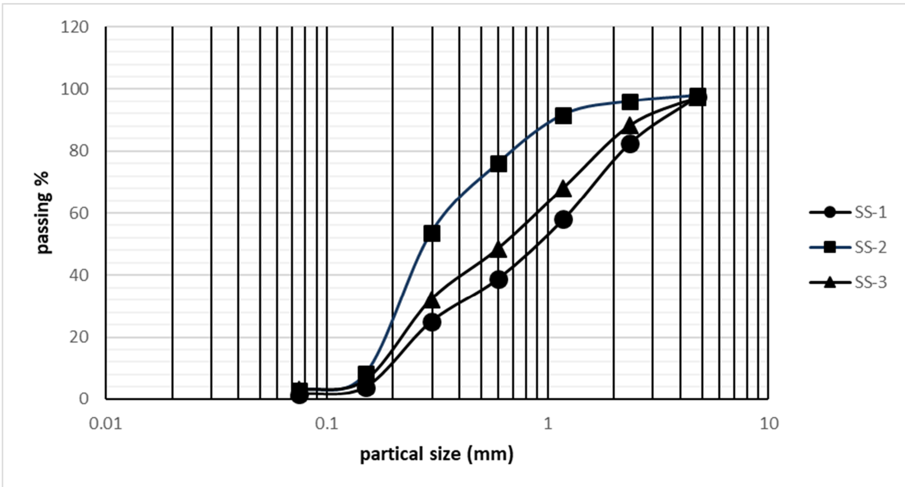

Fig. 3. The particle-size distribution curve for selected soil samples

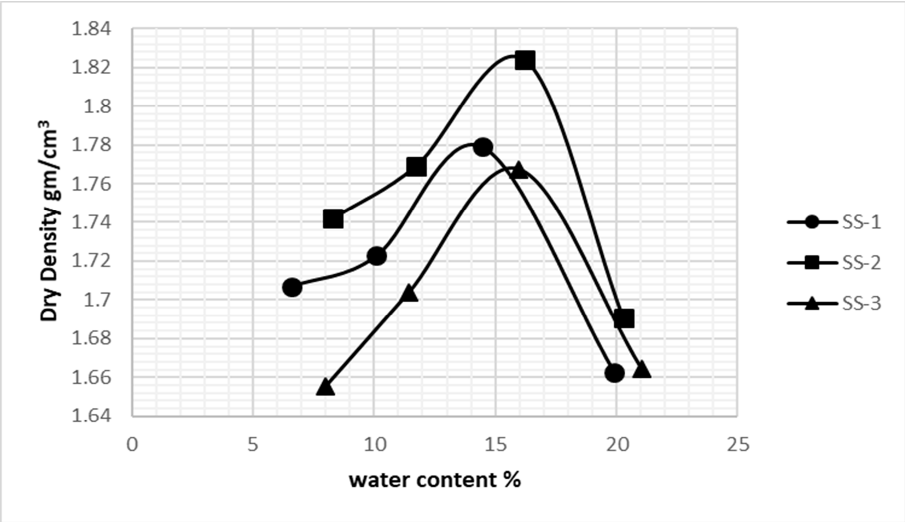

Fig. 4. The Compaction curve for the selected soil samples

Table II

Properties of soil for (SS-1), (SS-2), and (SS-3)

Characteristics	SS-1	SS-2	SS-3
Gravel, %	2.08	2.46	2.64
Sand, %	95.08	95.98	94.32
Fine, %	2.84	1.56	3.04
D_{10}, mm	0.16	0.19	0.17
$D_{30,}$ mm	0.22	0.4	0.28
$D_{60,}$ mm	0.35	1.3	0.9
Soil Classification System (USCS)	SP	SP	SP
Field density, gm/cm^3	1.8142	1.7842	1.7969
Field water content, %	6.64	2.58	3.05
Max. dry density, gm/cm^3	1.78	1.83	1.77
Optimum moisture content (OMC), %	14	16.2	16
Gypsum content, %	7.47	22.82	18.03

4. Experimental works

Three PVC pipes of 1 m long and 4.5 cm diameter have been used to model three samples of soils of the three proposed sites where each pipe has a specific soil. Water rise has been tracked through the glassy slot, as it is shown in *Fig. 5*. The water was added to the container containing the pipes so that the water touches the base of the pipes and continuous water source have been used to feed water in the pipe; with the passage of time it was noticed that the rise of water was unsteady. Finally, the highest rise was recorded for AlFurat soil, and less for Aladalah soil, and the lesser rise was recorded for Aljamia soil. It is worth to mention that the soil of Aljamia has the highest content in gypsum (Calcium sulfate $CaSo4$), which appears in the form of coarse and rough crystals of selenite. The capillary height of water decreases as the gypsum content in the soil increases [22], and that is why the soil of Aljamia has a lesser capillarity rise. The experimental work shows that the capillary height in Al Furat district is 350 mm, Al Adalah district is 340 mm, and Aljamia district is 270 mm.

Al furat Al adalah Al jamia

Fig. 5. Model of the experiments

5. Results and discussion

The h_c for SS-1 is 340 mm, for SS-2 is 270 mm, and SS-3 is 350 mm. These different values of soil samples of similar classification may be affected by other soil properties like gypsum content. The SS-2 is with higher gypsum content (22.82%), as it is shown in *Table II*. The existence of gypsum materials may clog the capillary rise, but with time, these salt materials are melting in the water. The needed time to reach the capillary rise is 320 minutes.

For comparison purposes, Lane and Washburn, Fetter, and P-K mathematical models are applied to determine the height of capillary rise in the proposed areas. The surface tension of the water was taken to be $71.20 \cdot 10^{-3}$ N/m at 30 C^o [23], and the particle density for silica sand equal to 2.65 g/cm^3 [24]. The results of the equations are shown in *Table III*. *Fig. 6*, *Fig*. 7 and *Fig.* 8 present the comparison of the h_c for the different soil samples. All the selected theoretical models gave a variety of h_c values but not close to the experimental h_c. The model of Lane and Washburn gives the lowest value of h_c and less than the experimental one for all soil samples, while Fetter and P-K models give lager h_c values than the h_c from experiments. The extreme result of h_c was from the P-K model, above 50% increase than the h_c from the tests, and increases up to twice the experimented *hc*, as in the case of SS-2. The nearest model of capillary height h_c is Fetter to save estimation of the pollutant penetration in the selected unsaturated soils in Al-Najaf city.

Table III

Comparison of the capillary rise for soil samples from different theoretical and experimental models

Soil Sample	Experimental h_c, mm	Theoretical h_c, mm		Change, %
SS-1	340	Lane and Washburn	274.25	-19.34
		Fetter	453.61	33.41
		P-K	575.43	69.24
SS-2	270	Lane and Washburn	104.123	-61.44
		Fetter	318.99	18.14
		P-K	528.64	95.79
SS-3	350	Lane and Washburn	214.237	-38.79
		Fetter	426.93	21.98
		P-K	532.6	52.17

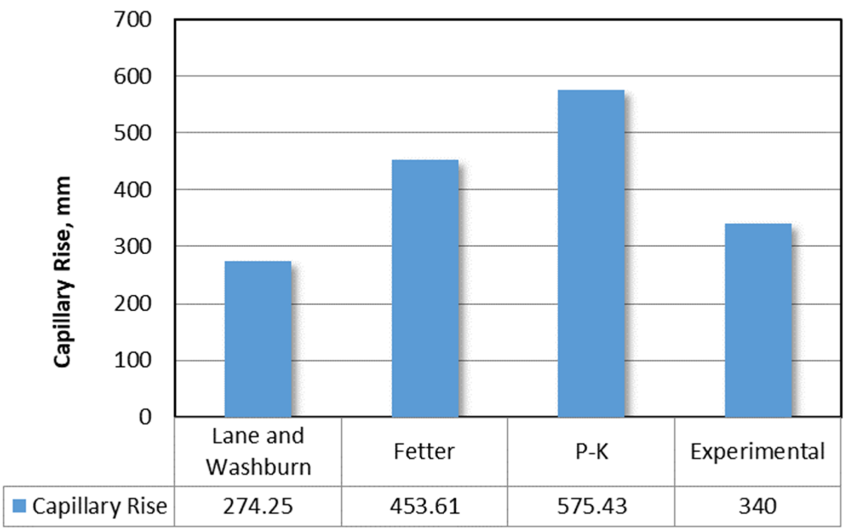

Fig. 6. The experimental equations vs. Real height for (SS-1)

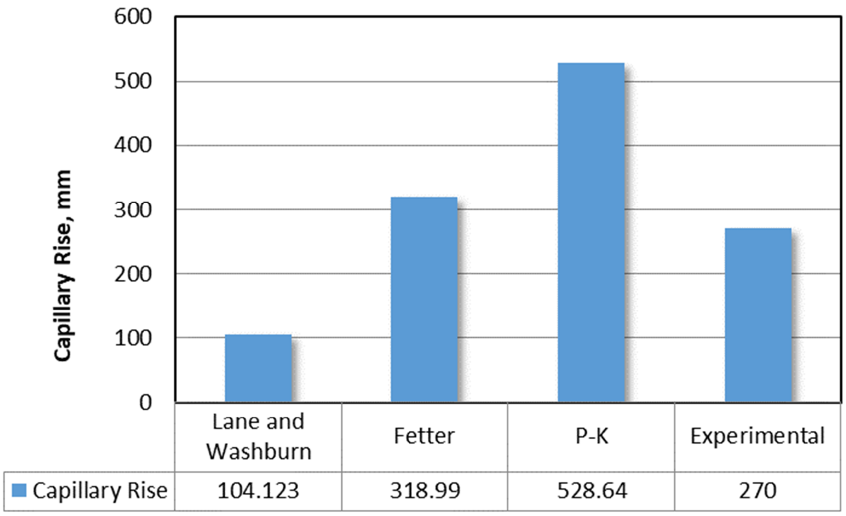

Fig. 7. The experimental equations vs. Real height for (SS-2)

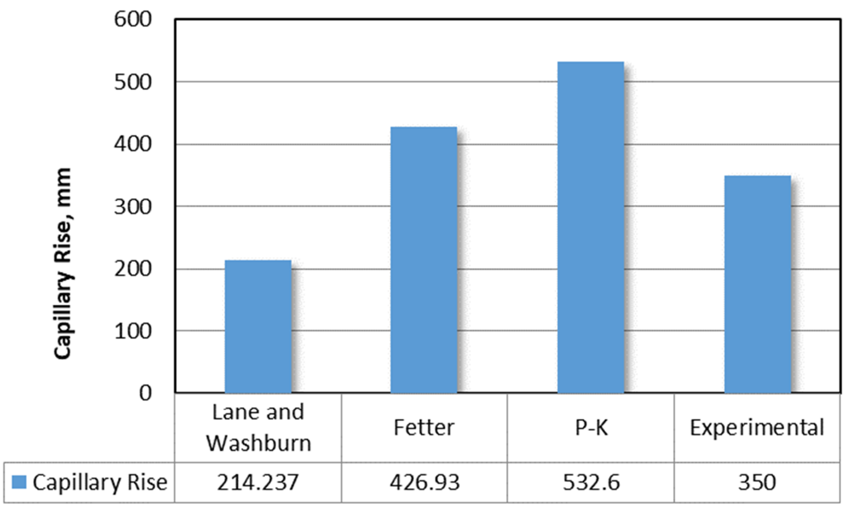

Fig. 8. The experimental equations vs. Real height for (SS-3)

The soil used for the experiment is sandy gypsum soil; in general, the capillary rise of water decreases as the soil gypsum content increased, High moisture with time causes the dissolved gypsum, especially small size, which leads to increased permeability. The estimated behavior in the distribution of particle and pore size is within the limit of experimental errors caused by non-homogeneity. The experimental results presented here are only preliminary because a single solid-liquid coupling was considered.

However, they allow the introduction of new hypotheses about the effect of capillary rise, which has not yet been considered in the literature. Because the soil is complex with numerous pores and is not uniformly packed, capillary rise in soils is very difficult to predict. A mathematical model should be expected to fail to make accurate predictions over longer periods of time. Predictions using this approach are very difficult to make and to take into account all the factors that may occur over time, so the longer time makes the prediction less accurate.

6. Conclusion

The capillary rise in soil represents the upward movement of water overhead the water table resulting from the gradient in the water potential across the air-water interface at the wetting front. For many engineering applications, calculation of the maximum capillary rise is important, and several works have proposed experimental relationships to find this height. In this paper, a comparative study was done to find the best equation that returns the nearest height to reality. Lane and Washburn equation, Fetter equation, and P-K equation were chosen for this study where all the required parameters are calculated from laboratory tests for three sandy zones located in Iraq-Najaf. Depending on the value of the effective size (D_{10}), this is obtained from sieve analysis. This paper has estimated all the heights using the proposed equations. The experiment consists of three pipes; each pipe has 1 m long and 4.5 cm diameter as well as a central slot of glass to track the rising water through the sandy soil. The real value of the capillary rise as compared with those obtained from the three equations. Fetter equation can be considered the closest equation because it gives moderate values compared to other equations, Subject to the site conditions of the soil in terms of moisture and gypsum content to save estimation of the pollutant penetration in the selected unsaturated soils in Al-Najaf city.

References

[1] Rezzoug A. I. S., König D., Triantafyllidis T. Scaling laws for centrifuge modeling of capillary rise in sandy soils, Journal of Geotechnical and Geoenvironmental Engineering, Vol. 130, No. 6, 2004, pp. 615–620.

[2] Buzas K., Budai P., Clement A. Contamination and treatment of highway runoff, Pollack Periodica, Vol. 3, No. 3, 2008, pp. 79–89.

[3] Hird R., Bolton M. D. Clarification of capillary rise in dry sand, Engineering Geology, Vol. 230, 2017, pp. 77–83.

[4] Ahmed K. I. Effect of gypsum on the hydro-mechanical characteristics of partially saturated sandy soil, *PhD Thesis*, Cardiff University, 2013.

[5] Al-Shakerchy M. Sh. M. Geotechnical properties of Al Najaf City soil with emphasis on the infiltration and strength characteristics, *PhD Thesis*, department of Building and Construction, University of Technology, Bagdad, 2007.

[6] Panda B., Chidambaram S. Influence of the vadose zone on groundwater pollution, A review, *International Journal of Civil, Environmental and Agricultural Engineering*, Vol. 1, No. 1, 2019, pp. 41–44.

[7] Kozma Z., Ács T., Koncsos L. Hydrological modeling of the unsaturated zone -Evaluation of uncertainties related to the FAO soil classification system, *Pollack Periodica*, Vol. 8, No. 3, 2013, pp. 163–174.

[8] Salim R. L. Extent of capillary rise in sands and silts, MSC Thesis, Western Michigan University, 2016.

[9] Al-Saoudi N. K. S., Al-Shakerchy M. Sh. M., Al-Janabi S. A. A. Water infiltration characteristics for artificial lake in Bahr Al-Najaf, *Engineering and Technology Journal*, Part A, Engineering, Vol. 31, No. 19, 2013, pages 1–12.

[10] Al-Saoudi N. K. S., Mahmood M. Sh. Water infiltration characteristics of Al Najaf City soil, in T*he 4th International Conference on Geotechnical Engineering and Soil Mechanics,* Tehran, Iran, 2-3 November 2010, pages 1–8.

[11] Delleur J. W. (Ed.)*The handbook of groundwater engineering,* CRC press, 2010.

[12] Li Y., Zhang C., Chen C., Chen H. Calculation of capillary rise height of soils by SWCC model*, Advances in Civil Engineering*, Vol. 2018, 2018, Paper No. 5190354, pages 1-10.

[13] Mahmood M. Sh. Effect of time-based soaking on shear strength parameters of sand soils, *Applied Research Journal*, Vol. 3, No. 5, 2017, pp. 142–149.

[14] Abdalhusein, M. M., A. Akhtarpour, Mahmood M. Sh. Effect of soaking on unsaturated gypseous and soils, *International Journal of Civil Engineering and Technology*, Vol. 10, No. 5, 2019, pp. 550–558.

[15] Mahmood M. Sh. Effect of soaking on the compaction characteristics of Al-Najaf sand soil, *Kufa Journal of Engineering*, Vol. 9, No. 2, 2018, pp. 1–12.

[16] Mahmood M. Sh., Aziz L., Al-Gharrawi A. M. B. Settlement behavior of sand soil upon soaking process, *International Journal of Civil Engineering and Technology*, Vol. 9, No. 11, 2018, pp. 860–869.

[17] Martin J. P., Koerner R. M. The influence of vadose zone conditions on groundwater pollution: Part I: Basic principles and static conditions, *Journal of Hazardous Materials*, Vol. 8, No. 4, 1984, pp. 349–366.

[18] Al-Saoudi N. K. S, Mahmood Sh. M. Statistical analysis of some geotechnical properties of Najaf City, in *Proceedings of International Geotechnical Conference,* Moscow, Russia, 7-10 June 2010, pp. 1173–1180.

[19] Al-Hadi, S.S., Effect of bitumen emulsion application in water movement by capillarity in different textures of soil, *al-Kufa University Journal for Biology*, Vol. 6, No. 1, 2014, pp. 22–39.

[20] Lu N., Likos W. Rate of capillary rise in soil, *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 130, No. 6, 2004, pp. 646–650.

[21] Kadhim A. P. K. N., Al-Baaj G. A. J. The geotechnical maps for gypsum by using GIS for Najaf City (Najaf-Iraq), *International Journal of Civil Engineering and Technology*, Vol. 7, No. 4, 2016, pp. 329–338.

[22] Al-Hadithi I. K. The effect of saline water, gypsium content in soil on saturated hydraulic conductivity and height of capillary water, Anbar Journal of Agricultural Sciences, Vol. 5, No. 2, 2007, pp. 1–11.

[23] Vargaftik N., Volkov B., Voljak L. International tables of the surface tension of water, *Journal of Physical and Chemical Reference Data*, Vol. 12, No. 3, 1983, pp. 817–820.

[24] Rashid R. A., Shamsudin R., Hamid M. A. A., Jalar A. Low temperature production of wollastonite from limestone and silica sand through solid-state reaction, *Journal of Asian Ceramic Societies*, Vol. 2, No. 1, 2014, pp. 77–81.

Appendix A

Software Program

For the purpose of numerical calculations, GNU Octave program has been developed to estimate the h_c by using proposed equations Lane and Washburn, Fetter, and P-K equation. This program is useful in the case of calculating *hc* in case of we have a specific range for each parameter, for example, if the effective size D_{10} ranges from (0.10-0.38) with an increment of 0.01.

```
clear;
clc;
disp('Input the parameters of the equatin of Lane and Washburn');
D10= input('Enter the value of D10 (m):    ');
disp('Input the parameters of the equatin of Fetter');
gamaa= input('Enter the value of surface tention of the fluid (N/m):    ');
linda= input('Enter the value of contact angle of the fluid meniscus (degree):    ');
roo= input('Enter the value of density of the fluid (kg/m^3):    ');
R= 0.2*D10*0.001;
g=9.81;
disp('Input the parameters of the equatin of P-K');
density_soil = input('Enter the value density of the soil (g/cm^3):    ');
density_Silica = input('Enter the value density of the Silica (g/cm^3):    ');
n=(1-density_soil/density_Silica);
%%%%%%%%%
disp('All hieghts in mm')
Lane_and_Washburn = -990*(log(D10*1000))-1540
Fetter = (2*gamaa*cos(linda))/(roo*g*R)
P_K = 10*(0.45*((1-n)/n))/(D10*100)
```