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INFILTRATION IN CRACKING CLAY SOILS AS AFFECTED BY INITIAL SOIL MOISTURE CONTENT

B. MOSTAFAZADEH AND H.M. MALANO[1]
College of Agriculture, Isfahan University of Technology, Isfahan, Iran and International Development Technologies Center, Department of Civil and Agricultural Engineering, University of Melbourne, Parkville Vic. 3052, Australia.
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ABSTRACT

Infiltration of water in cracking clay soils is influenced by soil shrinkage as the soil moisture content decreases. The results of field experiments for two typical border irrigation cracking clay soils of southeast Australia showed that as the soil moisture content decreases the crack-fill increases and there is a non-linear relationship between crack-fill and soil moisture content. The relationship between coefficient of a two-term infiltration equation with constant exponent and soil moisture content was found to be linear. A general, two-term infiltration equation with constant exponent was developed which takes into account the changes of coefficient and crack-fill as they are affected by soil moisture content. There was a good agreement between prediction of this equation and field data. The results of the experiment for a wide range of soil moisture content changes showed that a third degree polynomial fits the data of soil surface subsidence, crack volume, and volume change vs soil water loss with high correlation coefficient. Soil surface subsidence and crack volume expressed in terms of unit area was found to be higher for field experiments compared to the laboratory experiments. The effect of crack volume on soil bulk density was found to be significant.

1. Assistant Professor and Coordinator of Irrigation and Water Resources Program, respectively.

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تاثیر رطوبت اولیه خاک بر میزان نفوذ در خاک های رسی درز و شکاف دار

بهروز مصطفی زاده و اچ. ام. ملانو

به ترتیب استادیار دانشکده کشاورزی، دانشگاه صنعتی اصفهان، اصفهان، ایران و هماهنگ کننده برنامه های آبیاری ومنابع آب، مرکز بین المللی توسعه تکنولوژی، بخش مهندسی عمران و کشاورزی ، دانشگاه ملبورن، استرالیا.

چکیده

نفوذ آب به خاک در خاک های رسی درز و شکاف دار با کاهش رطوبت خاک، تحت تاثیر انقباض خاک قرار می گیرد. نتایج مطالعات صحرائی برای دو مزرعه معرف آبیاری نواری با خاک رسی درز و شکاف دار واقع در جنوب شرقی استرالیا نشان داد که با کاهش رطوبت خاک، مقدار آب پرشدگی درز و شکاف های خاک افزایش یافت و رابطه ای غیر خطی بین مقدار آب پر شدگی درز و شکاف های خاک و رطوبت خاک وجود داشت. رابطه بین ضریب معادله نفوذ در حالت نمای ثابت با رطوبت خاک، خطی بود. یک معادله عمومی نفوذ با نمای ثابت به دست آمد که می تواند تغییرات ضریب معادله و مقدار آب پر شدگی درز و شکاف های خاک را که تحت تاثیر رطوبت خاک قرار دارند در نظر گیرد. همبستگی خوبی بین پیش بینی این معادله و داده های به دست آمده در صحرا به دست آمد. نتایج مطالعات آزمایشگاهی برای دامنه وسیعی از تغییرات رطوبتی خاک نشان داد که یک معادله چند جمله ای درجه ۳، با داده های نشست سطح خاک،

حجم درز و شکاف های خاک و تغییرات حجم خاک نسبت به کاهش رطوبت خاک با ضریب همبستگی بالائی برازش می یابد. داده های نشست سطح خاک و حجم درز و شکاف های خاک که به صورت واحد سطح ارائه شده اند برای مطالعه صحرائی در مقایسه با مطالعه آزمایشگاهی بیشتر بود. تاثیر حجم درز و شکاف های خاک بر روی جرم ویژه ظاهری خاک معنی دار بود.

INTRODUCTION

Cracking clay soils are found worldwide. According to Hubble (8), Australia, after Africa and Asia, has the largest area of these soils. These soils are characterized by swelling and shrinkage as the soil moisture content changes. The infiltration of water into these soils is affected by these swelling and shrinkage phenomena. The characteristics of infiltration of water into cracking clay soils has been studied both theoretically and empirically by many researchers (e.g., 1, 11, 12, 18). Bronswijk (3) developed a model to calculate water balance, crack volume, and subsidence of cracking clay soils by introducing shrinkage characteristics of soil into existing infiltration models. He adapted the upper boundry condition of the existing models for the situation when rainfall with a known intensity reaches the surface of a cracked clay soil. Hoogmoed and Bouma (7) simulated infiltration into dry cracked clay soil by combining two existing physical simulation models for vertical and horizontal infiltration using boundry conditions for horizontal infiltration that were defined by morphological data. They also used rainfall with a known intensity as input to their model. Maheshwari and Jayawardene (9) used empirical approaches to study infiltration characteristics of cracking clay soils at different field sites in southeast Australia. They concluded that the average water content of soil profiles before irrigation and also the cracking and swelling of the soils during irrigation cycles have considerable influence on the infiltration characteristics. Turral's (13) empirical study on surge flow response in border irrigation on cracking clay soils in the southeast of Australia has shown that the effect of antecedent soil moisture content on crack-fill and infiltration is important and needs to be studied.

Since shrinkage and swelling are the most important characteristics of cracking clay soils, many researchers (i.e., 2, 5, 15, 16) have developed equations to relate measured vertical soil movements to crack volume, three-dimensional volume change, and water content changes of the soil. Some of these equations are presented here.

For a saturated clay with vertical dimension Z (cm) and volume V (cm^3), the relationship between volume change of soil matrix and soil surface subsidence can be described by the following equation (5):

$$1-\frac{\Delta V}{V}=\left(1-\frac{\Delta Z}{Z}\right)^{rs} \qquad [1]$$

where ΔV = the decrease in volume of soil matrix (cm^3) as a result of shrinkage, ΔZ = the decrease in soil thickness (cm) as a result of shrinkage, and rs=the dimensionless geometry factor which determines the partition of total volume change over the change in layer thickness and change in crack volume. For one-dimensional subsidence, rs = 1 and for three-dimensional isotropic shrinkage, rs =3.

For three-dimensional isotropic shrinkage, crack volume is calculated by the following equation:

$$V_{cr} = \Delta V - A\Delta Z \qquad [2]$$

where V_{cr} = crack volume (cm^3) and A = soil surface area at saturation (cm^2).

When a cracking clay soil dries, shrinkage in a non-linear manner in response to decrease in soil moisture content will occur. Therefore, four different shrinkage phases have been defined (5) which are structural shrinkage, normal shrinkage, residual shrinkage, and zero shrinkage. Yule (14) studied the relationship between vertical shrinkage, soil bulk density, and soil water content and concluded that with the knowledge of cation exchange capacity, bulk density or water content at swelling limit, the shrinkage curve can be developed for any cracking clay soils. Yule (14) defined three phases for shrinkage as: a) structural water loss phase from saturation to the volumetric water at swelling limit; b) shrinkage water loss phase from the swelling limit to shrinkage limit where the process in this phase is equidimensional and normal; and c) a residual water loss phase from shrinkage limit to oven dry. Among these three shrinkage phases, the shrinkage water loss phase is more important for field conditions, and its relationship can be developed by simplifying Eq. [1] which results in the following equation (16):

$$WL = 3\Delta Z - 3\frac{\Delta Z^2}{Z} + S \qquad [3]$$

where WL= water loss from saturation (cm), and S=water loss in the structural shrinkage phase (cm).

In craking clay soils, bulk density is also affected by shrinkage and swelling between soil moisture content changes. Fox (6) conducted field experiments to study the relationship between soil bulk density and soil moisture content for a swelling soil. He found a second degree polynomial relationship between dry bulk density and gravimetric soil moisture content which as the soil moisture content decreases, the dry bulk density increases. He also pointed out that the accuracy of the soil bulk density determination in the field falls off with decreasing soil moisture content due to the increasing hardness of the soil.

Previous studies have shown that the effect of initial soil moisture content on infiltration in cracking clay soil is important. However, the effect of different levels of infitial moisture content on infiltration and crack-fill in cracking clay soil has not been studied yet. Therefore, the main objective of this study was to determine the effect of soil moisture content on crack-fill and infiltration.

MATERIALS AND METHODS

Soil

The first field tests were conducted during three successive irrigations in a LASER-graded border (bay) irrigation field with heavy clay soil located about 15 km southeast of Kerang northern part of Victoria in southeast Australia on a soil classified under group 5B (10) . The soils in this group are generally considered as nonsaline soils with low permeability. They are low-lying soils subjected to occasional inundation and have drainage difficulties. This field was a typical border irrigatiion field for heavy cracking caly soils of the northern Victoria and was planted to alfalfa. The border length and width were about 400 and 80 m, respectively, with average slope in the direction of irrigation of about 0.15% and average cross slope of almost zero.

The soil used in this study had a silty clay texture with 59.3% clay, 28.1% silt, 12.1% fine sand and 0.2% coarse sand. Selected chemical properties of the soil are shown in Table 1.

Table 1. Some properties of soil for the first field experiment.

CEC	Ca	Mg	Na	K	ESP	EC	pH
		cmol kg^{-1}			%	dS m^{-1}	
16	8.9	9.0	0.7	0.6	4.37	0.102	7

Note: Soil particle density is 2.57 g cm^{-3}.

Field Experiment

Ten cylinders were installed in a line in the direction of irrigation in a selected area of the field where the soil was more uniform. The first cylinder was installed about 50 m from the upper end of the field. The distance between two cylinders was about 3 m. Six of these cylinders were used for the infiltration study. Each cylinder had a sharpened cutting edge, a height of 65 cm and a diameter of 45 cm. The cylinder infiltrometers were made of iron and each cylinder had a wall thickness of 0.005 m with two handles at the top to carry the cylinder and to remove the cylinder from the soil following installation. About 10 cm from the top, each infiltrometer cylinder had two holes each with a diameter of about 2 cm. The holes were set in direction of irrigation, and each cylinder was installed in such a way that the bottom of the holes were nearly at the same level as the ground surface. The cylinders were irrigated when the border is irrigated, because during irrigarion water flows in and out from each cylinder. Before measuring crack-fill and infiltration, the holes were plugged. To install the cylinder infiltrometers when the soil was saturated enough, metal weights (11) including two 220-liter barrels filled with water were loaded at the top of each cylinder and the cylinders were.pushed into the soil by hammering. To remove the cylinders, a mechanical jack was installed under the cylinder's handle and the cylinders were pulled out. The rest of the cylinders that were installed in the field were smaller cylinders with diamerer and height of about 35 cm and were used for soil surface elevation readings.

Infiltration tests with three replications were conducted at different levels of soil moisture content following irrigation. Before each infiltration test, to measure crack-fill, the cracks inside the test cylinder were filled with a known volume of water in less than one minute until ponding started at the soil surface. Then, the infiltration test under ponding condition started immediately, and the test was continued fot two hr where infiltrated depth was measured with respect to time. To start the infiltration test, the volume of water equivalent to a depth of 6 cm was applied to the cylinder which was almost equal to normal depth of irrigation. The term crack-fill in this study referes to water filled crack and initial soil water absorption for a time of less than one minute. Soil samples at depth of 0, 10, and 20 cm were taken to determine soil moisture content by gravimetric method. Time domain reflectometry (TDR) was used to determine integrated volumetric moisture content of the soil for depths of 10 and 20 cm. Soil bulk density was measured at a depth of 10 cm. Each measurement was made with three replications before each infiltration test. Soil bulk density measurements were used to convert gravimertic soil moisture content to volumetric soil moisture content. To measure soil moisture content by TDR, three rods having a lenght of 10 or 20 cm were connected to the probe head and inserted vertically into the soil until the probe head reached the soil surface. After establishing the connection between TDR components, the reading of soil volumetric moisture content was made from the portable computer connected to the TDR. The TDR components included TDR unit, probe head, insertion rods, 12-volt battery, and portable computer. Before irrigation, most of the cracks in the field had depths of less than 30 to 35 cm and the maximum crack width was about 1.5 to 2 cm.

The vertical soil movements following irrigation were measured at different levels of soil moisture content using 13 fixed points including top of the cylinders and three metal plates installed at the soil surface in the field. Benchmark was selected about 100 m from the upper end of the border at the top of a concrete section of diversion point of the main irrigation channel which always was carrying water.

The second field test was conducted in another cracking clay soil at a border-irrigated farm which was also LAZER graded and was to be used for annual pasture. This farm was located about 8 km east of Kerang with a soil type similar to the first farm (10). The border length and width were about 400 m and 150 m, respectively, with an average slope in direction of irrigation about 0.1 % and average cross slope of almost zero. The border had not been irrigated before and most of the cracks had a depth less than 40 cm and their maximum crack width was about 1.5 to 2 cm. To measure crack-fill and infiltration for moisture contents before the first irrigation, three cylinders with a diameter of 45 cm and a height of 65 cm were installed almost in the middle of the field with cylinder distance of 5 m. The cylinders were installed a few days before the first irrigation. They were pushed vertically into the soil using a scraper machine loaded with about 7 tons of soil.

Laboratory Experiment

One cylinder with a diameter of 50 cm and height of 24.5 cm was used to take saturated, undisturbed soil samples from the first field. A sand base with dimensions similar to soil cylinder and a height of 25 cm was placed at the bottom of the soil cylinder to allow drainage and also to saturate the soil from the bottom. The soil cylinder had a metal screen at the bottom to hold the soil inside the cylinder. The sand base had a valve at the bottom which was connected to another valve at the bottom of a 20-liter water supply container. After the soil sample was saturated, the excess water was removed from the soil by opening the drainage valve. The average soil surface distance from the top of the cylinder at saturation was 1 cm. Soil sample was then lifted and connected to a load cell mounted to a metal frame. The load cell was connected to a datataker 500 and a computer connected to the dataker stored the data continuously. A power supply provided constant 10 volt input to the load cell, and the load cell output was voltage corresponding to the cylinder weight. The calibration equation developed for the load cell was used to convert the stored data to soil water loss. At the beginning of the experiment when there was no drainage water existing, the bottom of the soil cylinder was coverd by a plastic sheet to avoid evaporation from the bottom of the soil cylinder was covered by a plastic sheet to avoid evaporation from the bottom of the soil cylinder. Soil moisture content at depths of 10 and 20 cm was measured at different stages of drying using TDR. A reference level was set above the soil cylinder and the average soil surface subsidence during drying phase was measured at four fixed points using a vernier micrometer. Maximum crack depth and maximum crack width were measured directly as the soil dried. Maximum crack depth was measured by inserting a wire into the deepest crack. At different levels of soil-moisture content a photograph with high resolution was taken of the soil surface using a Quick-Take 100 camera. The photographs were transferred to the computer, and an image analyzer software called Photostyler 2.0 was used to compute the cracked area of the soil surface. In this method, the surface area of soil is divided by pixels. By selecting darker background for the cracked area and dividing the number of dark pixels by the total number of pixels, the percentage of the cracked area could be computed. To dry the soil faster, a 1500 watt lamp and a fan were used a few days after the start of the experiment. Near the end of the experiment when the soil-water loss rate became small, an electrical heater was used to increase the temperature of the surrounding area of the cylinder to help faster drying. The experiment took 35 days. The view of the laboratory experiment which with some modifications is similar to the laboratory experiment conducted by Bronswijk (4) and Yule and Ritchie (17) is shown in Fig. 1.

At different levels of shrinkage, dry bulk density was computed by dividing the mass of dry soil by the volume of soil. Volume of soil with cracks was calculated by subtracting soil volume change from saturated volume of soil and adding the volume of cracks using Eqs. [1] and [2] because the volume of crack was considered to be the result of horizontal shrinkage only. The volume of soil without cracks was calculated by subtracting soil volume change from saturated volume of soil. The mass of dry soil was assumed to be equal to the weight of soil at the end of the experiment. A similar approach was used to compute wet bulk density where the weight of wet soil was divided by volume of soil including or excluding crack volume.

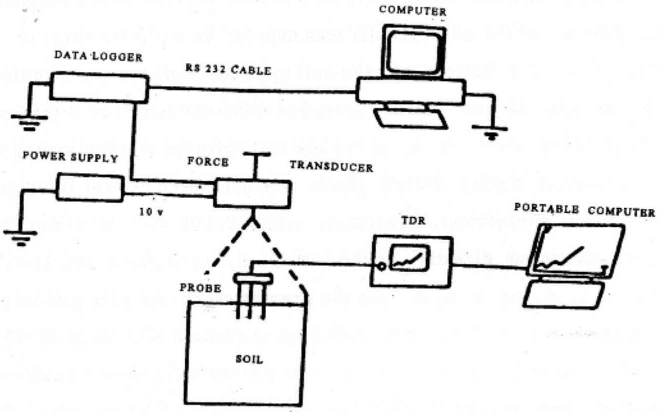

Fig.1. Schematic view of the laboratory experiment.

RESULTS AND DISCUSSION

The infiltration curves for different initial soil moisture contents are shown in Fig. 2. Different symbols shown in Fig. 2 are field data. For each curve, the corresponding two-term infiltration equation is presented where the second term shows the measured value of crack-fill. The equation for each curve was found by a best-fit, least-square method. The corresponding soil-moisture content related to each curve is shown in Table 2. Soil-moisture contents shown in Table 2 are the averages for depths of 10 and 20 cm using gravimetric method. The range of soil-moisture content changes that are presented in Table 2 are the practical range because field data were collected during normal irrigation practices. As shown in Fig. 2, the effect of initial soil-moisture content on infiltration and crack-fill is significant, and this effect mainly reflects crack-fill because as the initial soil-moisture content changes, the shape of the infiltration curve nearly stays the same while the crack-fill changes significantly. In Fig. 2, curve No. 6 is for annual pasture field (second field) where the soil was very dry, and the farm was not irrigated before. The rest of the curves belongs to the first field. By comparing curve No. 6 to other curves in Fig. 2, it can be observed that the shape of infiltration curve for both fields are nearly the same and the differences are mainly due to crack-fill values.

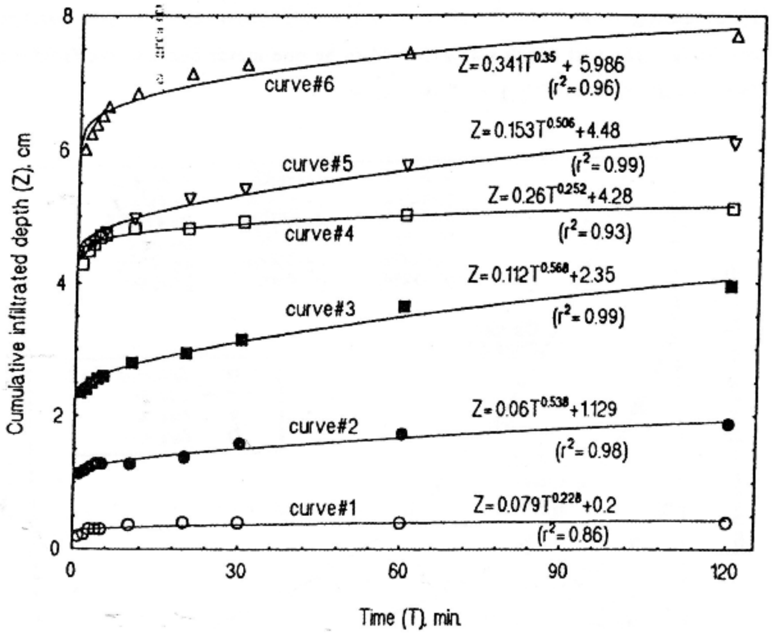

Fig.2. Infiltration curves for different soil moisture contents for the field experiment.

Table 2. Gravimetric soil moisture content for field experiment.

Curve No.	1	2	3	4	5	6
Soil moisture, %	28.40	21.55	18.37	16.30	15.18	7.57

The relationship between soil moisture content with soil crack-fill, crack volume, and vertical shrinkage for the first field is shown in Fig. 3. The related best-fit function for each curve is also presented. Curve No. 1 shows that as the soil-moisture content decreases the crack-fill increases, and there is a non-linear relationship between crack-fill and soil moisture content. This curve also shows that at higher range of soil -moisture contents at which the cracks start to develop, the changes in crack-fill compared to the lower range of soil moisture contents are smaller. Curve No. 2 and curve No. 3 (Fig. 3) are similar to curve No. 1, and they also show similar results i.e. as the soil moisture content decreases, the crack volume and vertical shrinkage increase. Crack volume in Fig. 3 was calculated using Eqs. [1] and [2] assuming a soil depth of one meter and three-dimensional isotropic shrinkage. The soil depth was assumed to be one meter because the field was planted with alfalfa with deep root system.

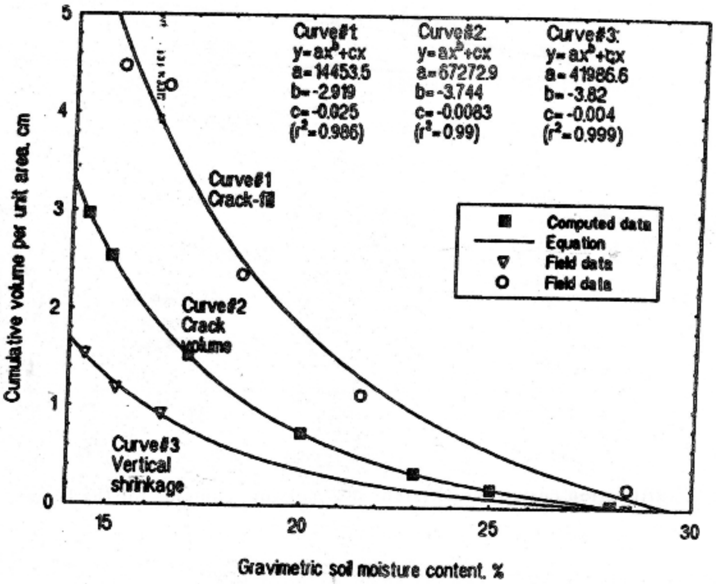

Fig. 3. Soil vertical shrinkage, crack volume, and crack-fill vs. gravimetric soil moisture content for the field experiment.

Since changes of soil moisture content have less effect on the exponent of the infiltration equation as compared to the coefficients of the infiltration equation, an attempt was made to develop two-term infiltration equations with constant exponent and reflect the effect of soil moisture content changes on the coefficient of infiltration equation. The second term of the equation is the measured value of crack-fill. The constant value of exponent was found by arithmetic mean of the exponents of infiltration equations (Fig. 2). The results of such study which was done by best-fit least square method are shown as solid curves with related infiltration equations in Fig. 4. From results of Fig.4 and Table 2 it can be concluded that as the soil moisture content decreases the coefficient of infiltration equation increases. The

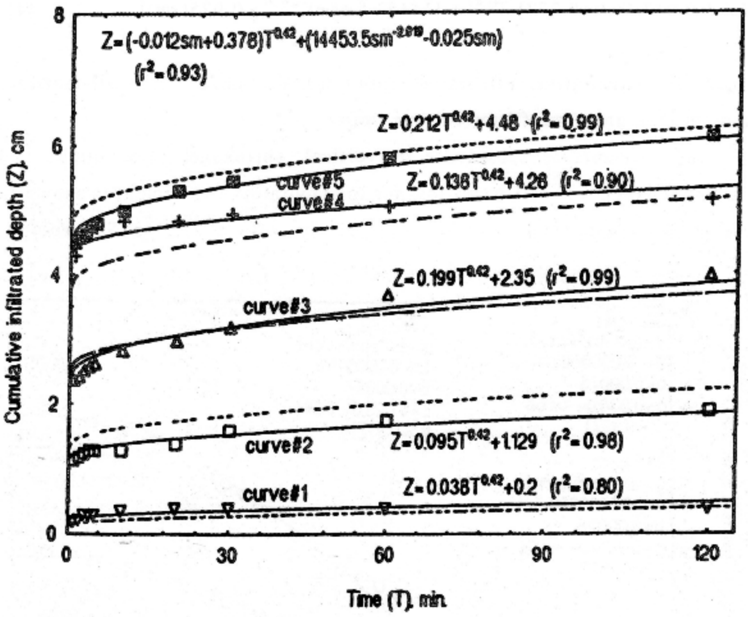

Fig. 4. Infiltration curves with constant exponent for different soil moisture contents for the field experiment.

relationship between soil moisture content and coefficient of infiltration equation was found to be linear. This linear function and function of crack-fill versus soil moisture content which was developed earlier was then used to develop a general two-term infiltration equation with constant exponent which takes into account the changes of coefficient and crack-fill as they are affected by soil moisture contents changes. The prediction of this equation for different soil moisture contents against field data are shown as broken curves in Fig. 4. Field data are presented as different symbols in Fig. 4. The overall coefficient of determination for this equation was 93% and as shown in Fig. 4 good prediction of the equation indicates that the equation can be used to predict crack-fill and consequently infiltration for different soil moisture contents for field condition. This equation which is shown in Fig. 4 is also presented here:

$$Z = [-0.012\,(sm)+0.378]\,T^{0.42} + [14453.5\,(sm)^{-2.919} - 0.025(sm)] \qquad [4]$$

where Z= cumulative infiltrated depth (cm), sm= gravimetric soil-moisture content (%), and T=infiltration time (min).

The soil surface subsidence or vertical shrinkage, crack volume, and volume change vs soil-water loss for the laboratory experiment is shown in Fig. 5. The respective best fit functions are also presented. Soil volume

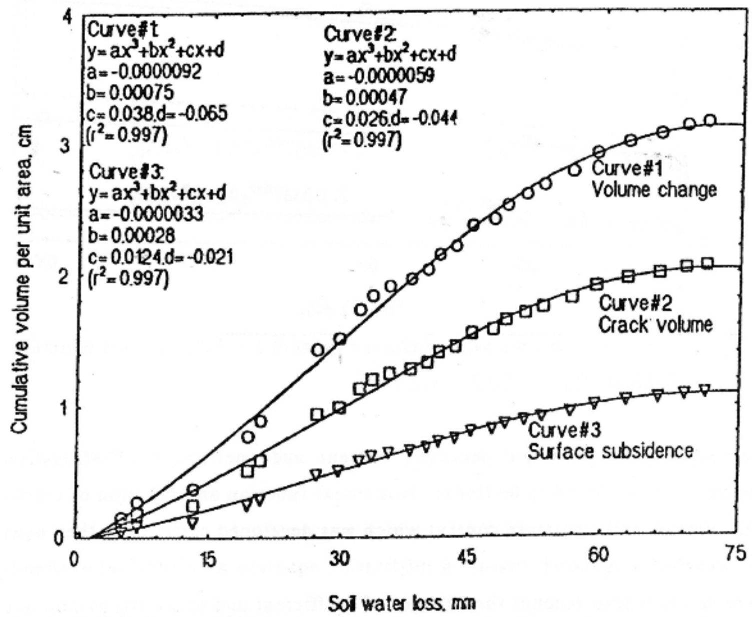

Fig. 5. Soil surface subsidence, crack volume, and volume change vs. soil water loss for the laboratory experiment.

change and crack valume were calculated by Eqs. [1] and [2], respectively, assuming three-dimensional isotropic shrinkage. Results in Fig.5 show that the relationship between soil water loss and soil surface subsidence, crack volume, and volume change is not linear and a third degree polynomial fits the data best. In general, the nearly S-shaped pattern of the curves show different shrinkage phases as they were defined earlier, but the exact characterization of the phases is difficult. At the beginning of the soil water loss or in structural water loss phase, soil is loosing water with nearly little or no subsidence. At the normal water loss phase, the changes of soil surface subsidence with respect to soil water loss is almost linear. At the residual water loss phase, the slope of the curve decreases, and the decrease in slope becomes higher as the curve approaches zero shrinkage phase. Comparison of results of the laboratory and field tests (Fig. 6) show that the soil surface

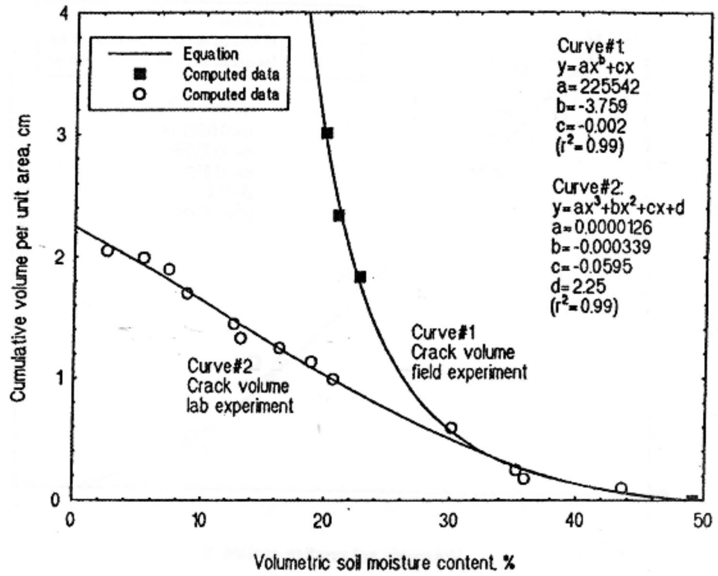

Fig. 6. Comparison of crack volume for field and laboratory experiments.

subsidence and crack volume for the field experiment are higher than those for the laboratory experiment. The differences are mainly because under field conditions the soil is deeper and also the extraction of water by crop roots from deeper soil causes deeper crack development.

In Fig. 7, soil surface subsidence vs TDR volumetric soil moisture content is shown for the laboratory experiment. The upper range data points are the TDR readings for depth of 20 cm and the lower range data points are the TDR readings for depth of 10 cm. A pattern nearly similar to that of Fig. 5 can be observed. At the higher and lower range of soil moisture contents, the changes on soil surface subsidence are small compared to the middle range of soil moisture contents. By comparison of horizontal axis of Fig. 5 with horizontal axis of Fig. 7, it can be observed that any soil water loss in the range of data presented can be converted to the volumetric soil moisture content. Therefore, expressing the laboratory experiment results in terms of volumetric soil moisture content or soil water loss is possible.

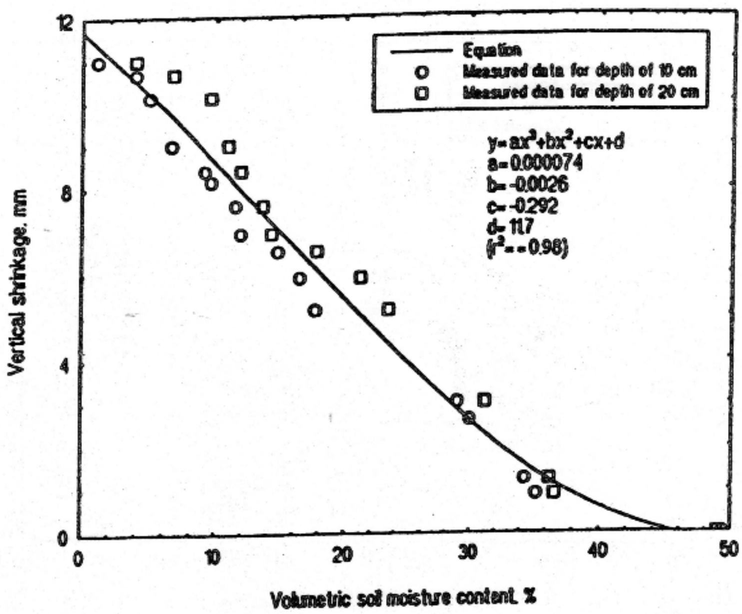

Fig. 7. Volumetric soil moisture content vs. soil vertical shrinkage for the laboratory experiment.

In Fig. 8, dry bulk density vs soil water loss with the related best-fit function is shown for the laboratory experiment. Curve No. 1 is the dry bulk density excluding crack volume in computation of soil bulk density and curve No. 2 is the dry bulk density including crack volume in computation of soil bulk density. By comparing two curves it can be concluded that crack volume

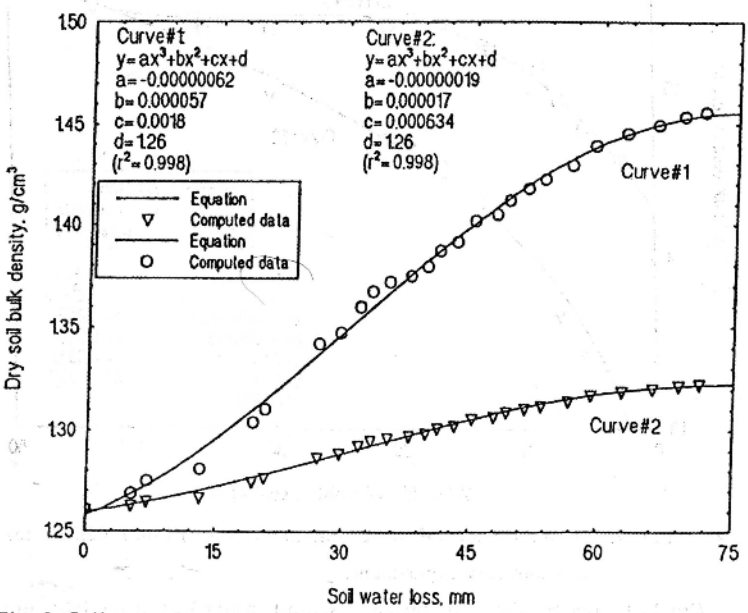

Fig. 8. Soil water loss vs dry soil bulk density for the laboratory experiment.

has considerable effect on dry bulk density, and dry bulk density is lower including crack volume. Both curves also show that as soil water loss increases or as soil moisture content decreases, dry bulk density increases and the dry bulk density will reach almost a constant value at the upper range of soil water loss. In Fig. 9, wet bulk density is shown vs volumetric soil moisture content for the laboratory experiment. In Fig. 9, curve No. 1 is the wet bulk density excluding crack volume and curve No. 2 is the wet bulk density including crack volume. Comparison of curve No. 1 with curve No. 2 in Fig. 9 shows that also wet bulk density including crack volume is lower.

Fig. 9 shows that at the upper range of soil-moisture contents, the wet bulk density is nearly constant, but there is a sharp decrease in wet bulk density as soil moisture content decreases.

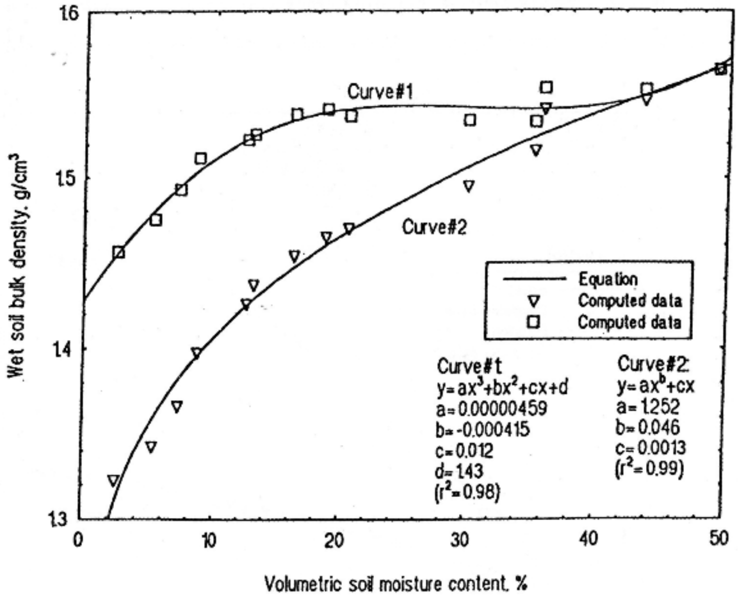

Fig. 9. Volumetric soil moisture content vs. wet soil bulk density for the laboratory experiment.

Cracked area at the soil surface vs. soil water loss of the laboratory experiment is shown in Fig. 10. Maximum percentage of the cracked area was found to be about 8 percent. Above that no more cracks were developed and the above percentage remained nearly constant.

In Fig. 11, maximum crack depth and crack width vs soil water loss is shown for the laboratory experiment. Fig. 11 indicates that after a short water loss, crack width reaches the maximum value and beyond that it remains constant. The maximum crack width that was measured directly was 1.9 cm. The results in this figure also show that while the crack width is reaching its maximum value the crack depth is increasing as the soil water loss increases.

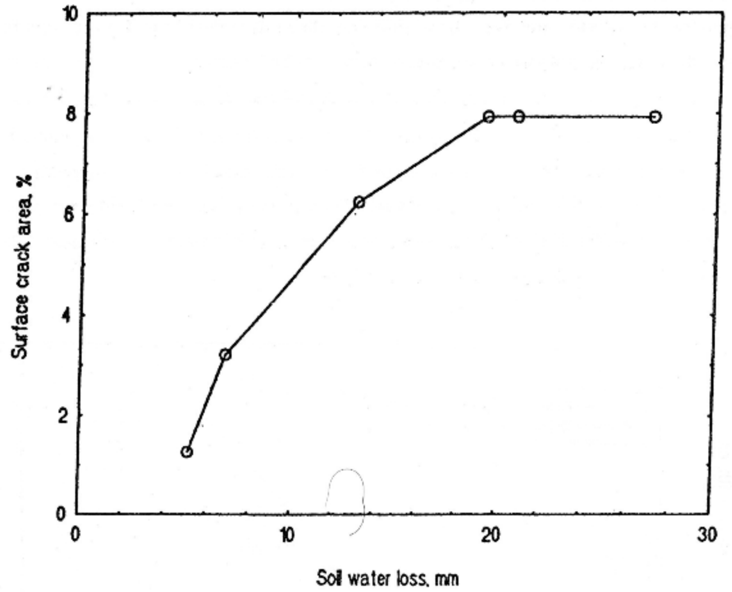

Fig. 10. Soil surface crack area vs. soil water loss for the laboratory experiment.

CONCLUSIONS

The results of the infiltration study at different levels of soil moisture content for two typical cracking clay soils showed that as the soil moisture content decreases, the crack-fill increases and there is a non-linear relationship between crack-fill and soil moisture content. Both of the field results showed that after crack-fill, the infiltration rate becomes nearly constant and small. A similar shape of infiltration curve was found for both fields. A general two-term infiltration equation with constant exponent was developed which can closely predict crack-fill and infiltration for field conditions at different soil moisture contents.

The results of laboratory experiments showed that the crack volume has significant effect on soil bulk density, and soil bulk density is lower including crack volume. Dry bulk density reached nearly a constant value at the upper range of soil-water loss. It was found that after a short water loss, the cracked area at the soil surface and crack width reach maximum values and beyond that they remain constant, but the crack depth continues to increase as the soil looses water. Comparison of the results of laboratory and field experiments showed the maximum values of soil surface subsidence and crack volume for field experiments are higher.

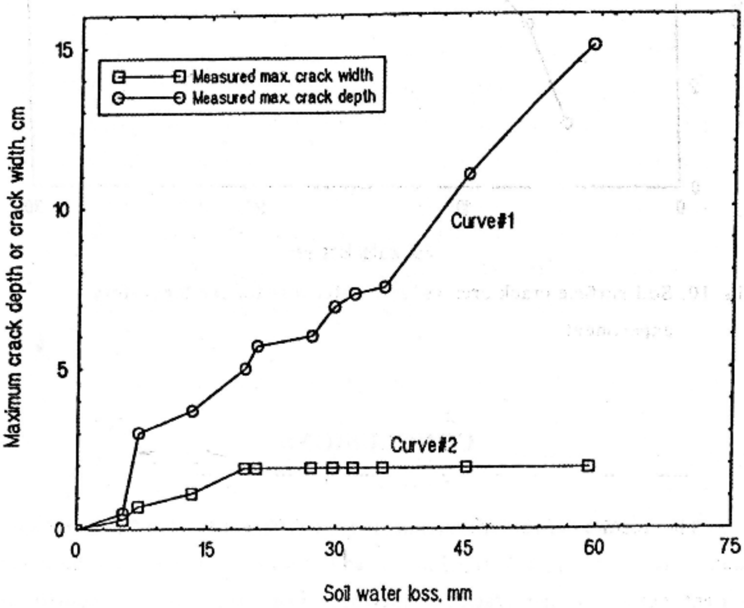

Fig. 11. Maximum crack depth and crack width vs soil water loss for the laboratory experiment.

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