Estimation of the wetting front depth in a loess soil deposit in response to environmental factors

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ABSTRACT
The extent of wetting depth in loess soil deposits associated with environmental factors is the key information that is required for reliable prediction or estimation of collapse settlement. This information is also required for better understanding of rainfall-induced loess landslides. In this paper, case study results of a site in Northwestern China are discussed in greater detail. The moisture content variation of soil within 10 m below the surface was monitored for a period of one year. The wetting front extension was determined graphically by understanding the progressive trends of soil moisture in response to environmental changes at various levels of depth. In addition, VADOSE/W was used to simulate the flow behaviour in loess deposits to predict the variation of the soil water content profile due to the influence of environmental factors. The VADOSE/W is found to be a useful tool for reasonably simulating the flow behaviour corresponding to changes of environmental factors in loess soils.

RÉSUMÉ
L’étendue de la profondeur humide dans les dépôts de sol de lœss associé à des facteurs environnementaux est une information clé qui est nécessaire pour la prédiction fiable ou pour l’estimation des tassements à l’effondrement. Cette information est également nécessaire pour mieux comprendre l’effet des précipitations sur les glissements de terrain dans les sols de lœss. Dans cet article, les résultats de l’étude d’un site au nord-ouest de la Chine sont discutés plus en détail. La variation de la teneur en eau du sol, sur une profondeur de 10m, a été surveillée pendant un an. L’avancement du front humide a été déterminé graphiquement avec la compréhension des tendances de l’humidité du sol en fonction des changements environnementaux à différentes profondeurs. En outre, Vadose/W a été utilisé pour simuler le comportement d’écoulement dans les dépôts de lœss afin de prédire le profil de variation de la teneur en eau due à l’influence des facteurs environnementaux. Le Vadose/W se trouve à être un outil utile pour simuler raisonnablement le comportement d’écoulement correspondant aux variations des facteurs environnementaux dans les sols de lœss.

1. INTRODUCTION
Loess is one of the widely distributed soils in semi-arid and arid regions of the world. China, U.S.A., Russia, U.K., and New Zealand are some of countries where these deposits are extensively found (Taylor, 1983). These soils are typically collapsible (i.e. a sudden decrease in soil volume) due to an increase in natural water content under a practically unchanged vertical stress (Barden, 1973; Lawton, 1989). It is widely acknowledged that the engineering properties of loess soils deposited during the Quaternary period (more than 1.0 million years ago) are significantly influenced by environmental factors. Chinese researchers classified the loess soils developed in early Quaternary (1.2-0.7 million years ago), middle Quaternary (0.7-0.1 million years ago) and late Quaternary (0.1-0.05 million years ago) as “Wucheng”, “Lishi” and “Malan” loess soils, respectively, after the regions where they are available (Liu, 1962, 1978, 1985). Loss deposits thickness varies from 200 to 500 m in Northwestern Loess Plateau in China (Zhang, 1973; Sun, 1986; Ding, 1989; Yue, 1996; Sun, 1997). However, only the upper Lishi loess and Malan loess show the characteristics of collapsibility on soaking; loess soil deposits always become more stable with depth as well as with geological age (Zhang, 1973; Liu, 1994; Gao, 1994). Although all collapsible loess soils, especially in the top 10 to 20 m thick depth zone are assumed to collapse in practice (Ni, 2006; GB50025-2004), significant change in soil properties and volume change behaviour is commonly confined within the extent of wetting front depth (Houston, 1988; Fredlund, 1994). Therefore, reliable procedures for the estimation of depth of the wetted zone along with the collapse settlement would be useful for suggesting reliable design procedures for structures in collapsible soils which contributes to considerably reducing the engineering costs (Ehwany, 1990).

On the other hand, landslides in loess deposits induced by natural agents and other human activities are not completely understood. The high water sensitivity of loess soils makes rainfall infiltration as one of the primary factors that trigger landslides in loess deposits. Statistically, 70% of the total loess landslides are attributed to rainfall (Zhang, 1995), and 95% of these landslides occur in wet seasons, from July to September (Zhang, 2011). The shear strength and soil volume decrease dramatically when there is an increase in soil moisture content; this behaviour is attributed to the material composition of loess soils and the influence of...
environmental factors during the deposition of loess soils (Xie, 2001). The sliding surface is generally not only affected by geological conditions of the loess slope such as fissures and stratum condition, but also the depth of wetted zone. For these reasons, the wetting front extent is a key parameter for predicting the potential sliding surface and scale of loess landslides.

During last few decades, the extent of wetting depth has been determined by artificial field rainfall tests, laboratory infiltration tests as well as numerical methods (Ehwany, 1990; Zhan, 2003; Li, 2005; Liu, 2008; Tu, 2009; Li, 2010). From these studies, it is concluded that the extent of wetting depth is influenced by soil properties, local climate factors (i.e. rainfall, evaporation, relative humidity, etc.) and vegetation conditions (i.e., the leaf area index (LAI), the plant moisture limiting point (PML) and the root depth (RD)). In other words, the extent of wetting depth varies from site to site. Although field tests may provide the most reliable results compared with the other two methods, equipment required for measuring soil moisture content or suction are expensive and need trained professional for gathering reliable data. Also, there are limitations of the presently available sensors for continuously collecting reliable data over a long period of time. Field water immersion tests are typically conducted for important projects such as railroads and high-rise buildings. The laboratory infiltration tests are easy and economical to perform and may provide satisfactory results for many cases. However, it is difficult to simulate the variability of in-situ soil stratum conditions in the field. Laboratory tests are always conducted on small size homogeneous soil samples. The size and boundary effects may have a significant influence on the results. Numerical methods are the most economical compared with the other two methods. The results of these methods are reliable provided reliable parameters of the soil permeability are known. In recent years, some commercial programs have provided tools to simulate the flow behaviour in soils taking account of both water flow in unsaturated soils and the corresponding changes of soil behaviour with respect to environmental changes. For example, VADOSE/W is commercial software that can be used for addressing this objective. Vanapalli & Adem (2012, 2013) and Adem & Vanapalli (2013a, 2013b) proposed an elasticity modulus-based method for estimating the 1-D heave of expansive soils taking account of the influence of environmental factors. The variation of soil suction which is related to the elasticity modulus variation and soil volume change is estimated using VADOSE/W as a tool; this method has been found to be useful for estimation of soil deformations associated with environmental changes.

In this paper, case study results of a site from Northwestern China are discussed, where the soil moisture content variation within 10 m below the surface was monitored for a period of one year. The depth of the wetted zone was determined extending a graphical procedure by understanding the progressive trends of soil moisture at various levels of depth in response to environmental changes. In addition, VADOSE/W is used as a tool to simulate the water flow in this loess soil deposits to estimate the corresponding variations of the soil water content profile with respect to time. As per the comparison study made between results of field measurement and numerical simulation, VADOSE/W is found to be a useful tool for reasonably simulating the flow behaviour corresponding to changes of environmental factors in loess soils. The results of the present study are promising as they provide reliable estimation of the wetting front depth in loess deposits from both field measurement and numerical simulation. The results of the study are useful and can be used in the prediction of collapse settlements and the stability analysis of loess slopes.

1 INTRODUCTION OF CASE STUDY

The site was selected in Longdong Loess Plateau in Northwestern China, where has more than 120 m thick loess soil deposits. The moisture content variation within 10 m, below the soil surface was monitored at this site; in addition, undisturbed samples were collected to understand the stratigraphic division and to determine soil properties from laboratory tests. Soils within the top 8.5 m were recognized as Malan loess, with the average properties as follows: dry density $1.24 \times 10^3$ Mg/m$^3$, natural gravimetric water content 16.3%, void ratio 1.18, plastic and liquid limits 17.7% and 28.3% respectively, below which is the first paleosol layer. In the zone from 8.5 to 10 m deep, the average properties are: dry density $1.35 \times 10^3$ Mg/m$^3$, natural gravimetric water content 21.9%, void ratio 1.01, and plastic and liquid limits are respectively, 18.3% and 31.1%.

![Figure 1. Installation of soil moisture meters and stratigraphic characteristics of the site](image)

An exploratory well of 1 m in diameter and 10 m in depth was excavated and 21 soil moisture meters in total were installed unevenly along the well wall taking account of the reported wetting front depth that were estimated.
from either field or laboratory tests. The schematic diagram of instruments installation is shown in Figure 1.

The well wall was painted with straw-reinforced mud, cement mortar and waterproof paint from inner to exterior for preventing lateral seepage. Electric cables connecting probes and output ports of soil moisture meters were collected to the surface to facilitate the collection of data with ease on the surface at any time.

The soils in the site were kept undisturbed during the test and their moisture contents were monitored for a period of one year, from Nov. 19, 2012 to Nov. 18, 2013, for exploring the wetting front depth in loess soils responding to changes of environmental factors.

Soil moisture contents were measured by soil moisture meters with the measuring range of 0-100% and the resolution of 0.01%. The measured volumetric moisture contents were compared with gravimetric water contents measured in the laboratory by oven drying method. The variation of soil dry density with respect to depth were calculated using the data collected from both methods were close to each other. The results suggest that these soil moisture meters are reliable to measuring the data with a reasonable degree of confidence.

2 SOIL MOISTURE VARIATIONS WITH RESPECT TO TIME

The variations of soil moisture contents with respect to time at several depths are shown in Figure 2. The soil moisture content variations below 3 m are not shown because they have remained constant during the entire period of testing. The variations of soil moisture contents provide valuable information with respect to influence of environmental factors (i.e., precipitation, evaporation, relative humidity and vegetation conditions).

The study area is located in Eastern Gansu, where the climate is typically arid. The average annual precipitation is about 620 mm while the annual evaporation can reach 1500 mm. This area has four distinct seasons; in winter the precipitation only accounts for less than 3.5% of the total annual amount, and the evaporation takes up about 16% of the annual amount due to the low air humidity. The precipitation concentrates in summer and autumn, typically from June to October, during this period the precipitation accounts for more than 80% of the total annual precipitation and the evaporation during this period is close to 50% (Li, 2013, 2014).

Based on the climate conditions described above, the initial decrease in soil moisture contents in the shallow (i.e., above 1.0 m approximately) depth of loess deposits may be attributed to a decrease of precipitation in winter season, along with the contribution of a relatively high evaporation. In the long term; however, soil moisture contents reach an equilibrium condition. During the summer and autumn (i.e., from June to October), soil moisture contents changes rapidly responding to the sharp increase in both precipitation and evaporation. Precipitation results in soil moisture contents increase, while they reduce rapidly due to the high evaporation rate when it stops raining.

The soil moisture content however varies only within a certain extent, which is defined as the wetting depth or active zone. The water flow in soils within the extent of wetting front depth is controlled by precipitation and evaporation. Typically the deeper the active zone depth, weaker would be the effect of precipitation and evaporation on soil moisture contents. The extent of wetting depth is not always the same as it depends on soil properties (i.e., soil type, coefficient of permeability and stress state, etc.) and environmental factors. From the test results, it is inferred that the extent of wetting front depth is about 2 m in the study area, because soil moisture contents below 2 m is almost not influenced by climate changes and is found to be constant during the entire period of data collection.

Figure 2. Variations of soil moisture contents with respect to time at different levels of depth

3 SIMULATION OF THE FLOW BEHAVIOUR IN LOESS SOILS USING VADOSE/W

The water flow behaviour of unsaturated collapsible soils is rather complex. The form in which water flows (i.e., liquid or vapor phase) depends on the degree of saturation and suction state in the soil (Vanapalli et al. 1996). For this reason, the flow behaviour of unsaturated soils is predicted using the soil-water characteristic curve (SWCC), which is the relationship between the degree of saturation and soil suction.

Several commercial software such as VADOSE/W and SVFlux have been tools to simulate the flow behaviour taking account of both water flow in unsaturated soils and corresponding changes of soil behaviour with respect to environmental factors (i.e., climate and vegetation parameters). Such techniques are simpler and more economical compared with direct measurement of soil moisture or suction (Vanapalli & Adem, 2012, 2013; Adem & Vanapalli, 2013a, 2013b). In this paper, finite element program VADOSE/W is used as a tool to simulate the water flow in unsaturated loess soils and the corresponding variations of soil water content profile in response to changes of environmental factors for determining the extent of wetting depth in study area.
VADOSE/W is able to predict the actual evaporation as a function of climate parameters (i.e., relative humidity, temperature and wind speed, etc.), to provide a direct and complete evaluation of water flow in the soil. The input information required for the VADOSE/W program includes (i) material properties such as the SWCC, coefficient of permeability function, soil thermal conductivity and heat capacity; (ii) climate parameters; namely, the daily precipitation, the maximum and minimum daily temperature and relative humidity and the average daily wind speed; (iii) vegetation parameters, including the leaf area index (LAI), the plant moisture limiting point (PML), the root depth (RD); (iv) geometrical boundary conditions and the ground water level (GWL).

The case study considered in this paper is a 1-D problem assuming there is no lateral dimensional flow, the 6 m thick loess soil deposits were modeled because the extent of wetting front was reported by other researchers to be around 2~4 m (El-Ehwany, 1990; Zhan, 2003; Liu, 2008; Tu, 2009; Ding, 2011). Since the flow behaviour is significantly influenced by the initial water content condition of soil, the 6 m thick soils were divided into several layers taking account of the initial water content distribution (Figure 3). The initial water content profile indicates not only the different water storage capacity but also the various soil suction conditions at different levels. However, to simplify, all layers were assumed to have the same soil properties (i.e., the SWCC and coefficient of permeability function), but different initial pore-water pressure.

As the SWCC measurement of the loess soil deposit at investigation site was not available, the one point method proposed by Catana & Vanapalli (2006) for the estimation of the entire SWCC of compacted fine-grained soils was used to develop an approximate SWCC for the loess soil. The rate of desorption curve was found to be linearly related to conventional soil properties (i.e., liquid limit coupled with clay content) of the compacted fine-grained soil (Catana & Vanapalli, 2006). In addition to
Vegetation parameters (i.e., the LAI, plant moisture limiting point and root depth) were defined taking account of the local climate condition, as shown in Figure 6. The function for LAI was estimated based on a standard shaped function for a "good" quality grass, the growing season was assumed to be from March 1 to October 31. The moisture limiting function indicated that plant stomas start to open at a soil suction of 100 kPa and close at 1500 kPa. The roots were assumed to be at a depth of 50 mm on the first day of the growing season which grow to a depth of 0.3 m by the third month. For the remainder of the growing season, the root depth was assumed to be constant.

4 COMPARISON BETWEEN THE RESULTS OF TWO METHODS

The variations of volumetric water content profile with respect to time for a period of one year were estimated using the VADOSE/W program. Comparisons between the predicted and measured volumetric water content of soil at the end of each month are summarized in Figure 7. The scatter in some predicted values may be attributed to the assumption that the soils below 2 m in the model were as a homogeneous layer with the same initial water content condition for simplicity. There is a reasonable agreement between the predicted and measured volumetric water content profile at the end of each month. Figure 8 summarizes the predicted volumetric water content profile at end of each month. As environmental factors change, water content reduces either due to evaporation from the ground surface or by evapotranspiration from a vegetation cover. On the other hand, rainfall and other forms of precipitation provide a downward flow into the soil, which leads to increase in soil water content. The soil water content condition is exclusively controlled by environmental factors. The extent of wetting front depth can be well defined from the variations of soil water content profile.

The simulation results with respect to the variation of soil volumetric water content profile are consistent with the difference between precipitation and evaporation. In the study area, where a typical arid climate condition persists, the evaporation is always much higher than the precipitation. For this reason, it is the difference between evaporation and precipitation rather than precipitation alone which plays a key role in controlling the flow of water in the soil.

From both the measured and predicted results of soil water content profile variation with respect to time, it can be observed that large difference between evaporation and precipitation occurred during a period of four months (April, May, June and July) because evaporation increased at a higher rate than precipitation even though there was relatively high precipitation. The soil water contents are typically lower during this period in comparison to that in other months. However, during the months of February and March there was considerably low precipitation and evaporation. For this reason, the difference between evaporation and precipitation was relatively low. For the other months (i.e., August, September and October) there was low difference between evaporation and precipitation because precipitation increased being close to evaporation. During
these months the soils are in a relatively wet state with quite high water contents.

It is shown that only the soil water contents within a certain zone are variable due to changes in environmental factors, which well defines the extent of wetting depth or environment affected zone. The simulation results are in good agreement with the measured values in the field. The derived wetting front depth is slightly greater than 2 m from the simulation results, which agrees well with the value determined from the field measurements. The wetting front extension in loess soil in study area could be regarded as about 2 meters from both field measurement and simulation result. VADOSE/W is found to be a useful tool for reasonably simulating the flow behavior corresponding to changes of environmental factors in loess deposits.

Figure 7. A comparison between the predicted and measured volumetric water content of soil at the end of each month

Figure 8. Variation of soil volumetric water content profile with respect to time

5 CONCLUSION

The extent of wetting depth is a key information required for a reliable estimation of loess collapse settlement and stability analysis of loess slopes. Many factors which include the soil properties and environmental factors such as climate and vegetation conditions influence the wetting depth. In this paper, case study results of a site with collapsible soil deposits from Northwestern China are provided and discussed in greater detail. The moisture contents of soils within 10 m below the surface were monitored for a period of one year. The wetting front extension was determined graphically from the progressive trends of soil moisture at various levels of depth as about 2 meters. In addition, the VADOSE/W program was used to simulate the flow behaviour to get the corresponding variations of the soil water content profile with respect to changes of environmental factors. The simulation results using the VADOSE/W program considering the environmental factors are in good agreement with the measured results in the field for the loess soils. The results of present study are promising as they can be used for reliable estimation of field collapse settlements and stability analysis of loess slope with respect to the extent of wetting depth.

REFERENCES


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