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Abstract

Matric suction, ground movement, water content, ground temperature, and daily weather data including: precipitation, potential evaporation, air temperature, relative humidity, sunshine hours, and wind speed have been monitored from 1992 to 1996 at an expansive soil site in Nanning, a city of southern China. This paper presents the measured data and discusses the long-term field suction measurements. Measured matric suction and ground movements correlate reasonably well with seasonal changes in climate. Predictions of ground movements based on measured matric suction appear to be in close agreement with field measurement. Data obtained from this long term field monitoring can also be used to verify the theory of unsaturated flow and flux boundary conditions.

Introduction

Field monitoring is important for the implementation of unsaturated soil mechanics. A long-term matric suction monitoring site was built in Nanning, China in 1992. The natural environment and instrumentation of this site was introduced in details at the Unsat'95 conference, Paris [1]. This paper presents an analysis of the data collected from this site.

Soil Properties and Site Instrumentation

The site is on a gently rolling slope. The slope consists of weathered lacustrine sediments that can be roughly divided into three layers (Table 1). Layer 1 is a red, stiff, clay with open cracks. Layer 2 is mainly a yellow-gray clay with closed cracks that open upon drying. Layer 2 contains a thin layer (0.3-0.4 m) of clay silt and a thin layer (0.1m) of organic clay. Layer 3 is the slightly weathered, dense, silty, green-gray mudstone. There is no permanent groundwater table in the slope. Infiltrating rainwater in rainy seasons result in a transient groundwater pattern.

Table 1. Soil properties

	Thickness	Water content	Density	Void ratio	Liquid limit	Plastic limit	Plastic Index	Free swelling rate	water content after free swelling	Shrinkage limit	Infiltration rate
		w	γ	e	w_L	w_p	$I_p^{\cdot}$	Fs	w'	w_s	k
	m	%	kN/m³	-	%	%	-	%	%	%	cm/s
1	0.6~1.3	12~25	19.5~19.9	0.6~0.73	35.3	17.2	18.1	27.8	25.9	11.2	10^{-4}
2	3.0~3.5	18~30	20.1~20.9	0.55~0.72	44~49	20~23	21~27	50~79	28.9	14.4	10^{-6}
3	--	16~19	21.5~21.9	0.47~0.5	30.7	16.4	14.3	21	25.2	12.3	10^{-7}

Notes: 1) k was obtained from standard double-ring field infiltration tests.

AGWA-II thermal conductivity sensors were chosen for the matric suction measurements. The instrumentation for this site is shown in Fig. 1 and Fig. 2.

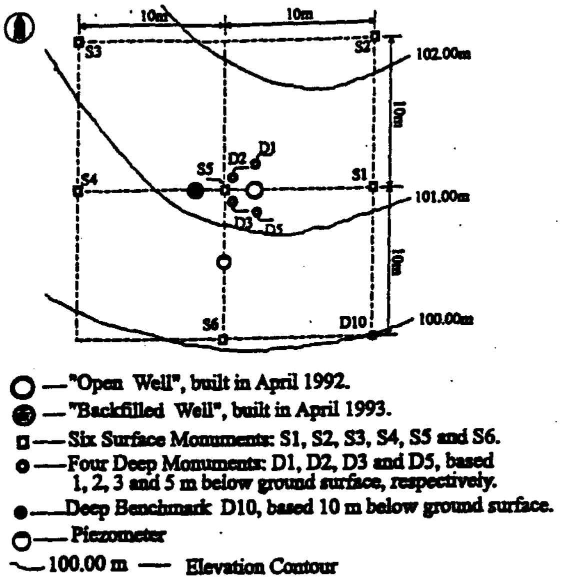

Fig. 1 Layout of instrumentation

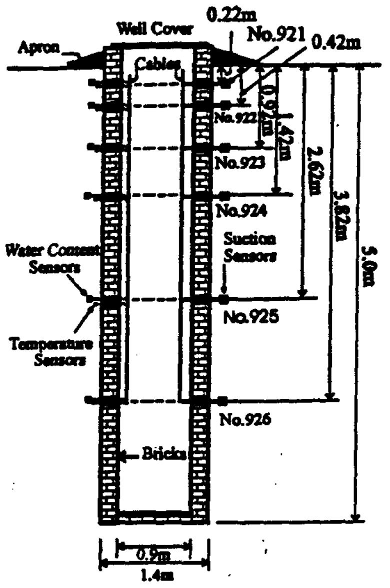

Fig. 2 Cross-section of the "open" installation well

Presentation and Analysis of Measured Data

(1) Matric Suction in the Uppermost Soil Layer

In the uppermost surface soil layer, the climate changes control the suction changes. As shown in Fig. 3a, the suction readings from sensor No. 921 and No. 922 closely follow the climatic changes. These two sensors were installed at 0.22m and 0.42m below ground surface, respectively.

The climate is seasonal in Nanning. The climate can be roughly divided into two seasons based on the distribution of rainfall; namely, the rainy season and the dry season. About 80% of the rainfalls are in the rainy seasons, which regularly occur from April to September. The measured matric suctions are low in the rainy seasons and high in the dry seasons. The measured suctions are often as low as zero in the rainy seasons, but may be as high as 300 kPa in the dry seasons. Seasonal climate influence is pronounced.

Short time weather changes should also be mentioned. Because of the high permeability of the cracked surface soil layer, the response on suction to climatic change is quick. Several dry days in the rain season may result in a suction increase and on the contrary, a rain during the dry season may dramatically reduce the suctions.

(2)Matric Suction in the Deeper Soil Layers

Measured matric suction changes at locations of 0.92, 1.42 and 2.62 m below ground surface are shown in Fig. 3b. Suction values during a rainy season are generally lower than in a dry season. In 1992, measured suctions ranged from about 0 to 40 kPa during the rainy season, and from 10 to 100 kPa during the dry season. In 1993, the suction values ranged from about 30 to 110 kPa during the rainy season, and about from 100 to 250 kPa during the dry season. Short time weather changes have little effects on matric suction changes in the deeper soil layers. However, seasonal climatic changes are still an important factor causing suction changes.

(3) Surface Ground Movement

The ground surface movements are very similar to the suction changes in the uppermost surface soil layer, in the way they responses to the climate changes. The influence of seasonal climate changes is pronounced. The soil swells during rainy seasons and shrinks during the dry seasons (Fig. 3c).

The ground surface movement for the monitored slope is differential. In 1992 and 1993, the maximum relative elevation changes were about 10, 10, 10, 15, 30, and 25 mm for monuments S_1, S_2, S_3, S_4, S_5, and S_6, respectively. Surface monument, S_4 and S_6, both located on the southwest corner on the downhill part of the monitoring zone, measured the highest ground movements.

A characteristic of Fig. 3c is that the ground surface swelled to a maximum point during the rainy seasons. In the rainy seasons of both 1992 and 1993, measured ground surface elevations were nearly the same. A reasonable estimation is that the ground surface elevation in Nanning was nearly the same for every rainy season because of abundant rainfall provided by the subtropical monsoon climate. The surface ground movement in Nanning behaves as a spring, depressed in dry seasons and released completely during rainy seasons. The magnitude of swelling is dependent upon, and should be equal to the magnitude of shrinkage during the dry season, as was measured at this site.

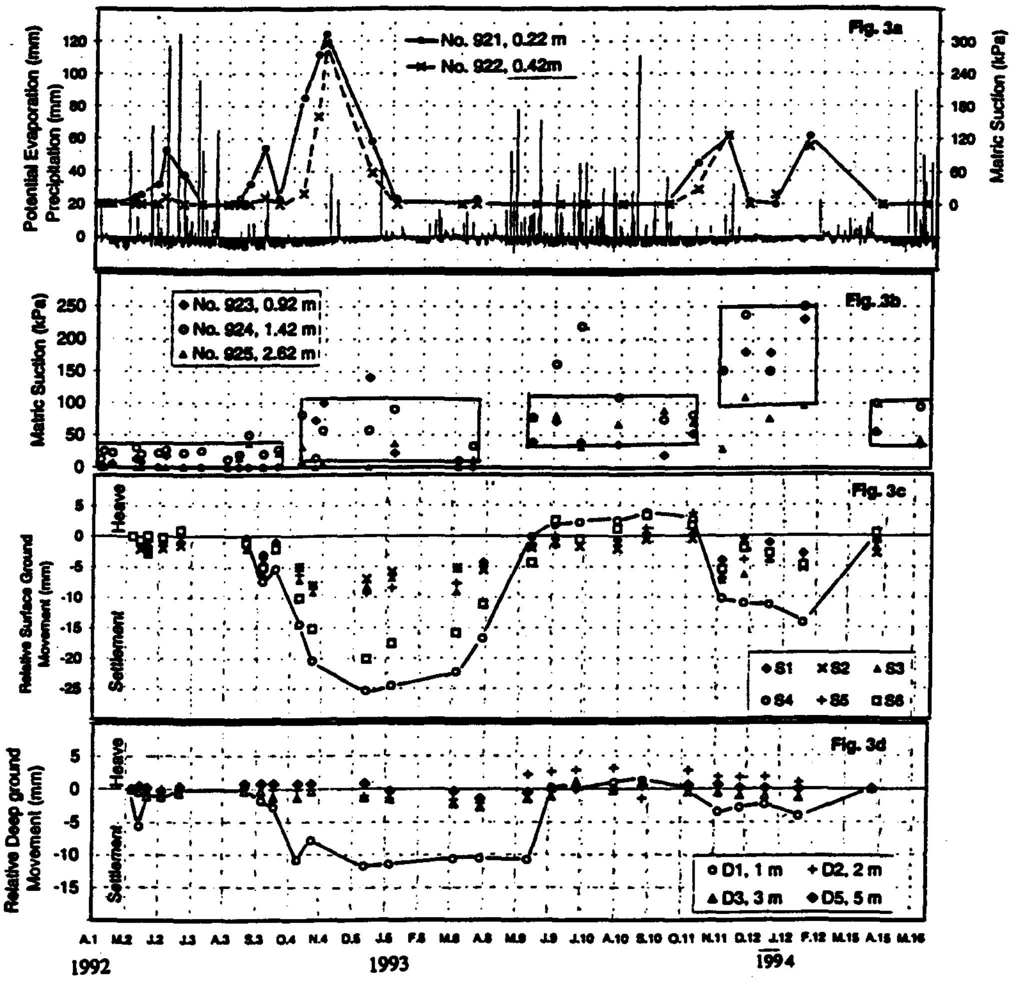

Fig. 3 Measured matric suctions and ground movements versus elapsed time

(4) Deep Ground Movement

The deeper the location of the point under consideration, the weaker is the climatic influence on ground movement. Seasonal climatic movements are obvious at 1 m below ground surface. However, a weak climatic influence was measured at 2, 3, and 5 m below ground surface (Fig. 3d). Measured maximum relative ground movements are about 13 mm at 1 m below ground surface, but, only about 4, 3, and 2 mm at 2, 3, and 5 m below the ground surface, respectively.

(5) Water Content and Ground Temperature

Readings from water content sensors show that there is a correlation with climatic changes. However, due to difficulties in the calibration of the sensors, these readings could not be converted to water content data with desirable accuracy. The water content profiles shown in Fig. 4 were measured by sampling with a small manual boring tool (ϕ 40 mm) on June 17, 1996 and Nov. 11, 1996. For different locations in the monitoring zone, the measured water content profiles were nearly the same from ground surface to about 0.6 m, reflecting the controlling influence of climate on this layer. From a depth of 0.6 m, water content at the southwest corner was generally higher. At boring K2, below 1.5 m, the water content became much higher, because the soil became higher in plasticity. The water content difference at different locations indicates that the soil profiles differ, and may produce different groundwater distributions. That is the main reason for the differential surface ground movement.

The soil from ground surface to about 0.4 m is dry during dry seasons. That may result in high suction which are out of the range of measurement for AGWA-II sensors (i.e., these limit is about 500 kPa).

Ground temperature data correlates well with climate change (Fig. 5). The influence of climate is weaker at deeper locations. At 3.82m below ground surface, seasonal temperature changes are still significant.

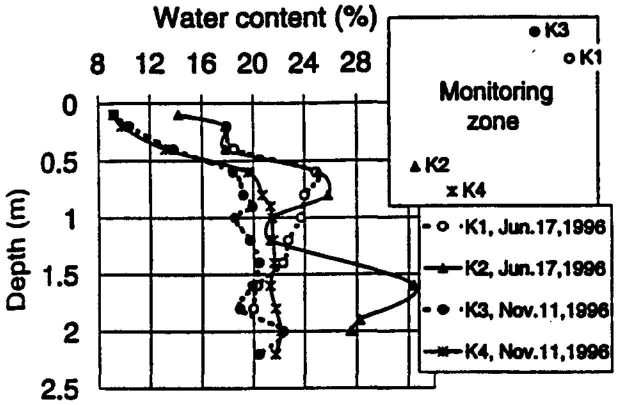

Fig. 4 Water content profiles

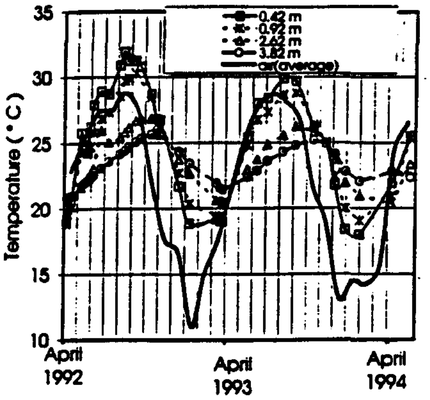

Fig. 5 Ground temperature versus elapsed time

Prediction of Ground Movement Using Measured Matric Suction

Light structures built in an expansive soil area commonly suffer from severe distress due to ground movements caused by climate changes. Climate causes changes in matric suction, which, in turn, result in ground movements. The prediction of ground movements has probably received more attention than any other analysis associated with an expansive soil. However, there are still not many field verification research projects on the prediction of ground movement based on matric suction.

In unsaturated soil mechanics, two independent stress state variables $(\sigma - u_a)$ and $(u_a - u_w)$ control the mechanical behavior of unsaturated soils [2]. The volume-mass form of the constitutive relations can be written as:

$$de = C_t \, d\log(\sigma - u_a) + C_m \, d\log(u_a - u_w) \qquad (1)$$

$$dw = D_t \, d\log(\sigma - u_a) + D_m \, d\log(u_a - u_w) \qquad (2)$$

where: de, dw represent changes in void ratio and water content, respectively.

C_t, C_m, D_t and D_m represent indices that can be obtained from consolidation tests, pressure plate tests and shrinkage tests.

Equation (2) is not used in this discussion, since ground movements result from changes in void ratio. For the monitored slope, $(\sigma - u_a)$ can be treated as a constant (i.e., $d\log(\sigma - u_a)$ is equal to 0). Equation (1) therefore become:

$$de = C_m d(u_a - u_w) \qquad (3)$$

C_m can be obtained from e vs. $\log(u_a - u_w)$ curve (Fig. 6), which is the combination of the soil-water characteristic curve (i.e., w vs. $\log(u_a - u_w)$) and shrinkage curve (i.e., e vs. w). The value of C_m is dependent upon the suction range. Changes in void ratio, Δe, can be calculated using Eq. (3) or obtained directly from the e vs. $\log(u_a - u_w)$ curve. The amount of vertical swelling or shrinkage for a soil layer can be calculated using the formula:

$$\Delta h_i = \frac{\Delta e}{1 + e_0}\left(\frac{\varepsilon}{\varepsilon_v}\right) h_i \qquad (4)$$

where: Δh_i is the vertical settlement or heave of a soil layer,

h_i is the thickness of the soil layer under consideration,

e_0, Δe are the initial void ratio and change in void ratio, respectively, and

$\varepsilon / \varepsilon_v$ is the ratio of vertical strain and volumetric strain, measured from a shrinkage test.

A calculation of ground movement using measured matric suction is tabulated in Table 2. The average of suction measured by sensor No. 921 and No. 922, the average of suction measured by sensor No. 922 and No. 923 and the suction measured by sensor No. 924 are used for soil layer 1, layer 2 and layer 3, respectively (Fig. 7). The calculated settlement is 9.3 mm. Compared with the measured settlements, which ranged from 6 to 15 mm, the calculated results are reasonable (Fig. 8).

Table 2 Prediction of ground movement based on measured matric suctions

Layer	Thickness	Initial suction	Final suction	Initial void ratio	Final void ratio				
	h_i	$(u_a - u_w)_0$	$(u_a - u_w)_f$	e_0	e_f	Δe	$\varepsilon / \varepsilon_v$	Δh_i	$\Delta h = \Sigma\Delta h_i$
	mm	kPa	kPa					mm	mm
1	500	5.5	217.5	0.716	0.65	-0.066	0.28	-5.4	-9.3
2	500	0	116.5	0.72	0.663	-0.057	0.28	-4.7	
3	1000	27	14	0.72	0.725	0.005	0.29	0.8	

1. Initial date: September 20, 1992; Final date: October 26,1992

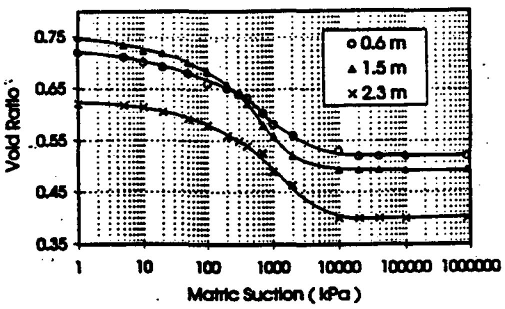

Fig. 6 Void ratio versus. log($u_a - u_w$)

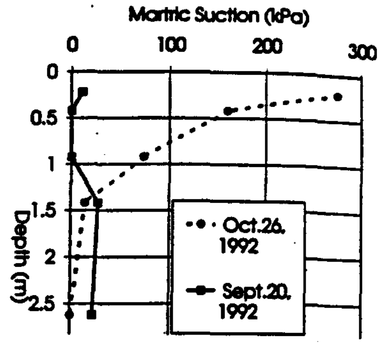

Fig. 7 Measured matric suction profiles

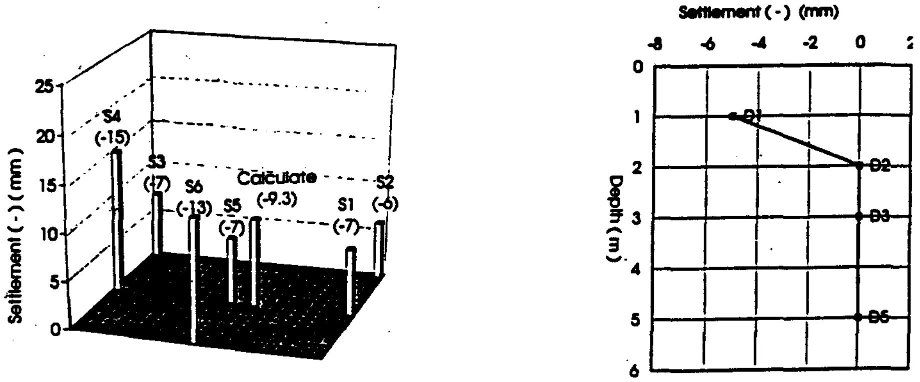

Fig. 8 Relative ground movement (from Sept. 20, 1992 to Oct. 26, 1992)

Discussions on the Monitoring of Nanning Site

(1) Installation Well

A primary problem encountered during the measurement of matric suction at the Nanning site is that rainwater infiltrated the well through the surface layer during the rainy seasons. The accumulated water was removed every time the site was visited. However, the water quickly accumulated again. The water filled about 1.5 to 2 m, and occasionally even 3 m, of the bottom part of the installation well during the rainy season.

Sensor No. 926, located 3.82 m below ground surface, was influenced by the accumulated groundwater. The soil surrounding this sensor was fully saturated during the rainy season and kept saturated during the dry season. Suctions measured by this sensor were always zero. This sensor failed after April, 1993.

A "backfilled" installation well was built 4 m west of the "open" installation well in April, 1993. The well was backfilled with excavated soil, compacted to about the initial density, after sensors were installed in the same way as in the "open" installation well (Fig. 9).

Fig. 10 shows the collected data collected from the "backfilled" well. Fig. 10a and Fig. 10b are similar to Fig. 3a and Fig. 3b, respectively, in the manner of data point distribution. The two wells measured similar suction changes. The "backfilled" well obtained higher suction for the surface soil layer. It is possible that the suction profile may be different at different locations, similar to the ground movement and water content profiles. There is no evidence that sensor No. 921, No. 922, No. 923 and No. 924 were significantly influenced by the accumulated groundwater in the "open" well. Sensor No. 925 may had been influenced to some extent, since the accumulated ground water table was higher than the location of this sensor sometimes.

Suction data from sensor No. 936, 4.2 m below the ground surface in the "backfilled" well are generally higher than 100 kPa during both the rainy and dry season. This indicates that there was not a groundwater table at this location. The assumption that there would have been no accumulated ground water in the "open" well if it were not left "open" is correct.

(2) Performance of the AGWA-II Thermal Conductivity Matric Suction Sensors

The AGWA-II thermal conductivity sensors proved to work reasonably well in an environment with a subtropical monsoon climate such as is found in Nanning. The sensors showed reliable outputs and remained in good working condition for a monitoring period of more than two years. Of the 12 sensors used, only one failed. For the measurements on June 17, 1996 and Nov. 11, 1996, more than 4 years after installation, the sensors still measured suction values reflecting climate changes, although the readings were somewhat unstable. Problems that were encountered with the sensor include:

a. The range of measurement (i.e., 0 ~ 500 kPa) is not sufficient for the uppermost soil layers.
b. The accuracy of the field measurements needs to be improved. Measured ground movements and ground temperature data correlate better with the climate changes than do the suction measurements.
c. The ceramic block of the sensor is not durable enough.
d. The sensors are too expensive.

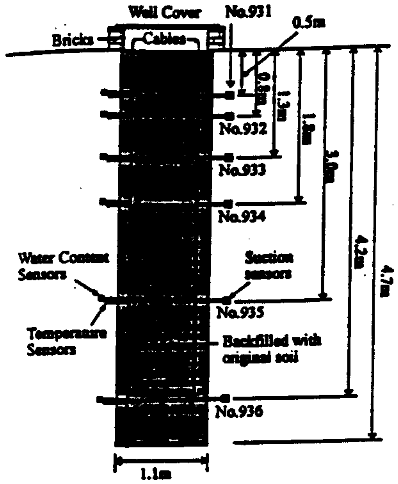

Fig. 9 Cross-section of "backfilled" well

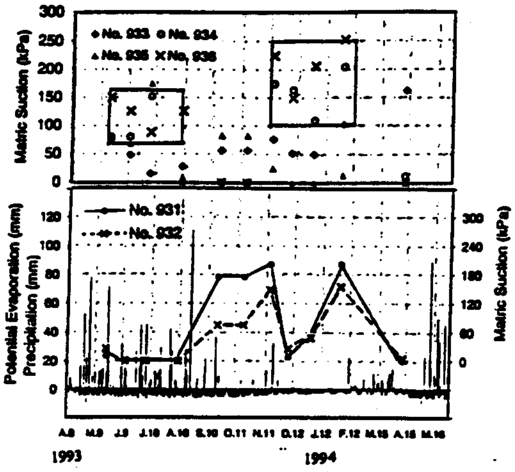

Fig. 10 Suctions measured in the "backfilled" well

(3) Difficulty in Field Water Content Monitoring

The calibration of the water content sensors required soil samples from locations close to the sensors. Small round holes through the brick wall of the "open" well had been designed for this purpose. The unanticipated problem is that groundwater infiltrated into these holes after the first sampling, changing the water contents significantly.

Conclusions and Recommendations

(1) The matric suction and ground movement monitored correlated reasonably well with seasonal climatic changes.
(2) The Prediction of ground movements based on matric suction appears to be in close agreement with the field measurements.
(3) The "backfilled" installation well is recommended in the area which has a monsoon subtropical climate.
(4) The AGWA-II sensors worked reasonably well for this study. However, matric suction sensors that are cheaper, stronger, higher in accuracy, and have a wider measurement range should be produced.

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