Rainfall infiltration study of an unsaturated expansive soil slope for the South-to-North Water Transfer Project

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ABSTRACT: In order to assist in the design of one of the major infrastructure projects called the South-to-North Water Transfer Project ("Middle-route") in China, an 11m high cut slope in a typical expansive clay with medium plasticity in Zaoyang, close to "Middle-route" in Hubei was selected for a comprehensive and well-instrumented field study of the effects of rainfall infiltration on slope deformation and instability problems. The instrumentation included tensiometers, thermal conductivity sensors, moisture probes, earth pressure cells, inclinometers, a tipping bucket rain gauge, a vee-notch flow meter and an evaporimeter. Two artificial rainfall events were created during a month of field investigation and monitoring. The complex interaction amongst changes of soil suction (or water content), *in-situ* stress state and soil deformation in the slope was investigated.

1 INTRODUCTION

The Three-Gorge dam currently near completion in China is the most significant infrastructure project of the 20th century. For the 21st century, the currently proposed South-to-North Water Transfer Project (SNWTP) is another giant infrastructure project in China. The main purpose of this water transfer project is to carry potable water from the Yangtze River region in the south to many arid and semi-arid areas in the northern regions of China including Beijing. Along one of the three proposed water transport routes (East, Middle and West) for the SNWTP, the 1200 km long "Middle-route" is proposed to be an open canal along most of its route. The proposed canal is likely to be an open channel with a trapezoidal cross-section formed by cut slopes and fills. At least 180 km of the proposed excavated canal will pass through areas of unsaturated expansive soils. One of the major geotechnical problems is to design safe and economical dimensions for the cut slopes in the unsaturated expansive soils, which possess high swelling and shrinkage potential (Bao & Ng, 2000, Liu, 1997).

To improve our understanding of the fundamental mechanisms of rain-induced landslides in unsaturated expansive soils, an 11 m high cut slope in a typical medium-plastic expansive clay in Zaoyang, close to the "Middle-route" of SNWTP in Hubei, China, was selected for a comprehensive well-instrumented field study of rainfall infiltration. The instrumentation included tensiometers, thermal conductivity sensors, moisture probes, earth pressure cells, inclinometers, a tipping bucket rain gauge, a vee-notch flow meter and an evaporimeter. The case study herein focus on the soil-water interactions in the monitored slope, which are based on the in situ measurements of pore-water pressures (or soil suctions), water contents, horizontal stresses, horizontal displacements and vertical displacements (heave), in response to the simulated rainfalls. The monitored results from five different types of instruments located at mid-slope and at a depth of 1.2 m were interpreted in this paper.

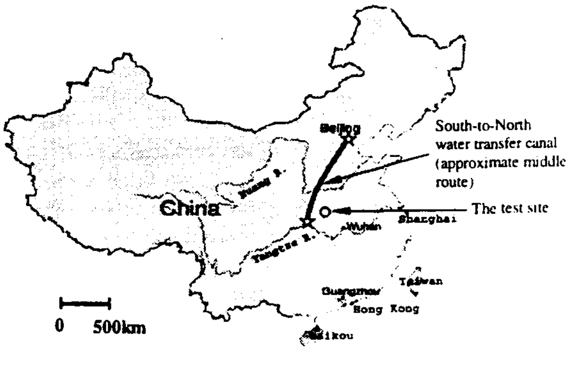

Figure 1 Site location for the field study

2 THE TEST SITE

The test site is located on the intake canal of the Dagangpo second-level pumping station in Zaoyang, Hubei, China (see Figure 1). It is about 230 km north-west of Wuhan and about 100 km south of the intake canal for the SNWTP in Nanyang, Henan, China. The site is in a semi-arid area with an average annual rainfall of about 800 mm and 70% of annual rainfall is distributed from May to September.

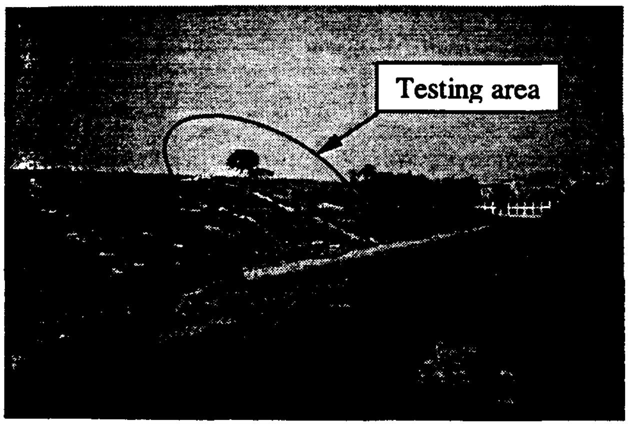

Figure 2 An overall view of the test site

Figure 3 Typical shallow and retrogressive slope failures

The intake canal at the test site was excavated in 1970 with an average excavation depth of 13 m (see Figure 2). The slope angle following excavation was 22°. Several years after construction, a number of slope failures have taken place in succession and parts of a masonry retaining wall have been seriously deflected or destroyed. Most of the mass movement has occurred during wet seasons and the slip surfaces are in the order of 2 m deep.

The testing area selected was located on a cut slope on the northern side of the canal. The area had a uniform slope angle of 22° and a uniform slope height of 11 m (measured from the top of the retaining wall). There was a 1 m wide berm at the mid-height of the slope. The slope surface was well grassed but no trees were present. The area has a significant depth of typical unsaturated expansive soil. Just to the west of the selected testing area, there are a number of typical shallow slips and retrogressive slope failures (see Figure 3). Prior to instrumentation, site investigation was carried out on the slope. The predominant stratum in the slope was a brown-yellow stiff fissured clay. The clay layer was sometimes interlayered with thin layers of gray clay or iron concretions. The brown-yellow clay contained about 15% hard and coarse calcareous concretions (particle size generally from 30 to 50 mm). X-ray diffraction analyses indicated that the predominant clay minerals are illite (31%-35%) and montmorillonite (16-22%), with a small percentage of kaolinite (8%) (Liu, 1997). The natural water content was generally slightly larger than the plastic limit (w_P = 19.5%, I_p = 30) with the exception of a relatively low water content within the top 1 m. Detailed soil profiles and geotechnical parameters are given by Ng, et al. (2002).

3 FIELD INSTRUMENTATION PROGRAMME

An area of 16 m wide by 31 m long with a cleared surface was selected for instrumentation and artificial rainfall simulation tests. The instruments included jet fill tensiometers, thermal conductivity suction sensors (Fredlund et al., 2000), Theta-probes for determining water content (Thetaprobe, 1999), vibrating wire earth pressure cells, inclinometers, a tipping bucket rain gauge, a vee-notch flow meter and an evaporimeter. The layout and locations of the instruments are shown in Figure 4 and the details for each instrument are summarized in Table 1.

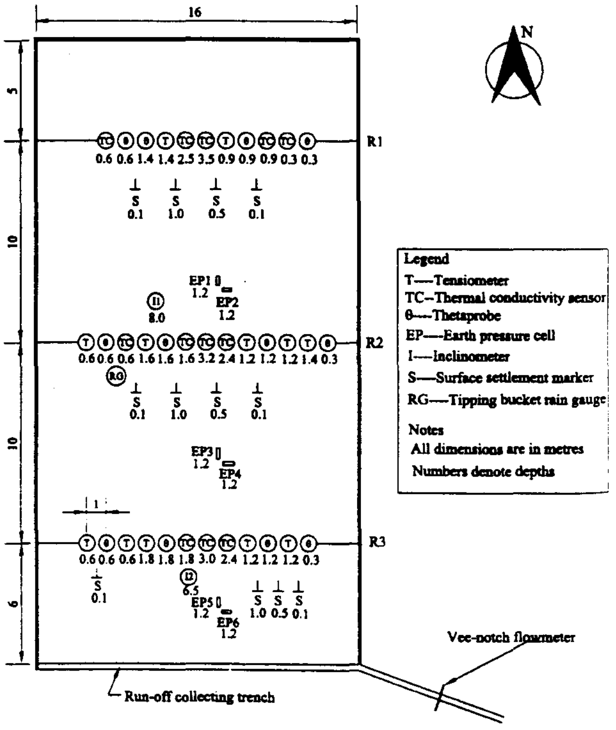

Figure 4 Layout of instruments

Table 1 Summary of Instruments

Item No	Measurement	Type of Instrument	Quantity	Measuring range
1	Soil suction	Jet fill tensiometer (2527A)	12	Less than 90 kPa
		Thermal conductivity sensor	12	20 to 1500 kPa
2	Volumetric water content	Thetaprobe (ML2x/w)	12	0 to 50 %
3	Horizontal stress	Vibrating wire earth pressure cell	6	0 to 1000 kPa
4	Rainfall intensity	Tipping bucket rain gauge	2	0.2 mm/tip
5	Run off	Vee-notch flow meter	1	N/A
6	Horizontal displacement	Inclinometer	2	± 12°
7	Heave / settlement	Movement point	12	N/A
8	Potential evaporation rate	Evaporimeter	1	N/A

3.1 *Monitoring soil suction and water content*

As shown in Figure 4, there were three rows of instrumentation for soil suction and water content monitoring. These were: R1 at the upper part, R2 at the middle part and R3 at the lower part of the slope. In each row, there were 7 to 9 suction sensors (i.e., jet fill tensiometers or thermal conductivity sensors and 4 Theta-probes, which were used for measuring volumetric water content (VWC) indirectly. These probes use the standing wave technique to measure the apparent dielectric constant of a soil, which is then correlated to the volumetric water content in the soil. The sensors at each row were spaced 1 m apart. Most of the sensors were embedded within a depth of 2 m. For each depth, there were generally two soil suction sensors and one Theta-probe, so that the measured data from the three sensors can be verified one again another (Ng et al. 2002).

3.2 *Monitoring horizontal total stresses*

Three pairs of earth pressure cells were installed for monitoring horizontal total stress in two orthogonal directions. As mentioned before, a mid-slope berm divided the slope into two parts. Two pairs of earth pressure cells were embedded 2.5 m above the toe in the upper half portion and the lower half portion of the slope, respectively. The other pair of earth pressure cells was located midway between the former two pairs. For each pair, one earth pressure cell was installed to measure the horizontal stress in the North-South direction (i.e., the inclination direction of the slope), the other was placed in the East-West direction (i.e., parallel to the longitudinal direction of the canal). All 6 pressure cells were installed vertically at a depth of 1.2 m. More details of the instrumentation are given by Ng et al. (2002).

3.3 *Monitoring horizontal movements and surface heave*

Two inclinometers were installed in two orthogonal directions: one (I1) near the toe of the upper portion of the slope and the other (I2) near the toe of the lower portion of the slope. The inclinometers were bottomed at depths of 8.0 m and 6.5 m, respectively (i.e., down to the hard layer with coarse and hard calcareous concretions).

Three rows of movement points were set up near the three main rows of instrumentation (R1, R2 and R3), respectively, to measure the swelling of shallow soil layers due to rainwater infiltration. The movement points were constructed with concrete blocks. Each row has four movement points founded at depths of 0.1, 0.1, 0.5 and 1.0 m, respectively. Two leveling datum points were constructed 20 m outside the artificial rainfall area and founded at a depth of 3 m. These two datum points were checked using a city grid datum located over 100 m away from the site.

3.4 *Monitoring rainfall intensity, run-off and evaporation*

A tipping-bucket rain gauge was installed to record the intensity and the duration of rainfall. Flow meters were installed in the main water-supply line of a sprinkler system to record the total amount water sprinkled onto the slope within a given time interval. A water collection trench was constructed along the toe of the slope to measure surface runoff using an automatic vee-notch flow meter system installed at the end of the channel. An evaporimeter was installed at the middle of the slope outside the monitoring area to measure potential evaporation.

4 ARTIFICIAL RAINFALL SIMULATIONS

Rainfall was artificially produced using a specially-designed sprinkler system. This was done to improve the efficiency of field test monitoring. The sprinkler system comprised a pump, a main water-supply pipe, five branches and 35 sprinkler heads. The system could produce 3 levels of rainfall intensity (i.e., 3, 6 and 9 mm/hr).

The site was fairly dry from November 2000 to April 2001 with a total rainfall of only 60 mm. In May, when the wet season generally begins, there was only about 40 mm of rainfall. From June to the

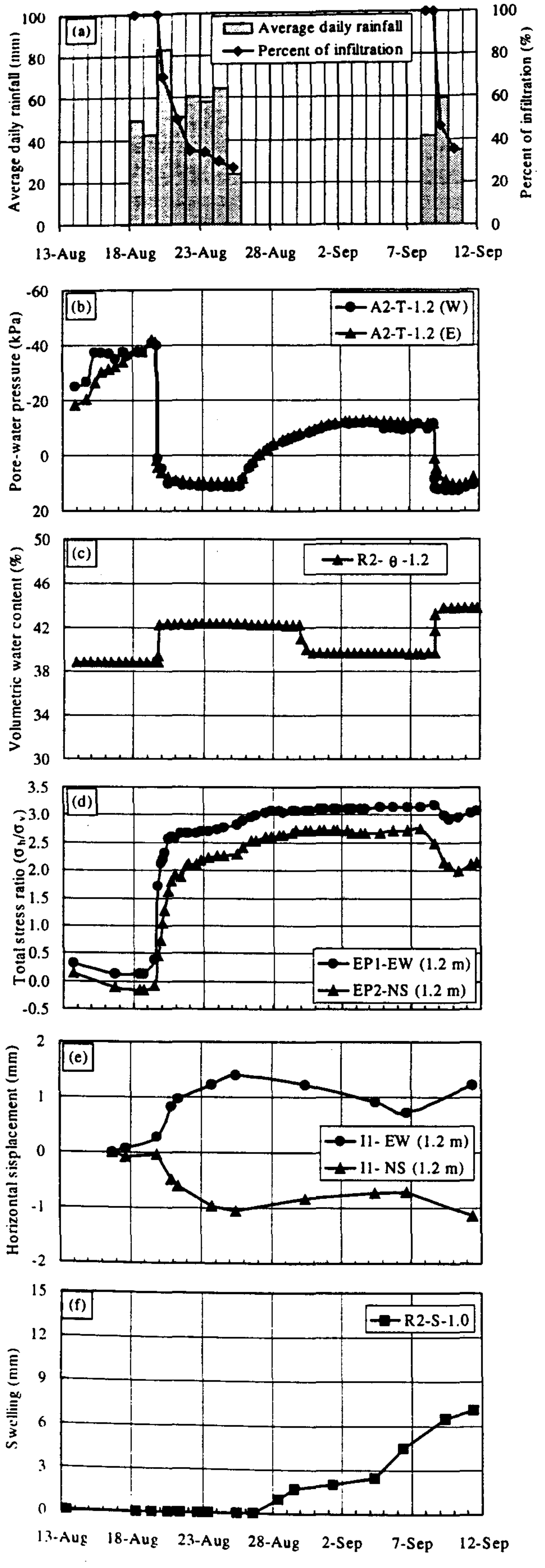

Figure 5. Oberseved responses to the simulated rainfalls

start of the rainfall simulation tests (18 August, 2001), the monitored area was protected against rainfall infiltration with a plastic membrane. The rainfall simulation tests therefore started from a relatively dry soil condition.

Figure 5(a) shows the two simulated rainfall events during the one-month monitoring period, from 13 August to 12 September, 2001. Two rainfall events were simulated. The first rainfall lasted for seven days, from the morning of August 18 to the morning of 25 August, 2001, with an average daily rainfall of 62 mm. The second simulated rainfall was from the morning of 8 September to the afternoon of 10 September, 2001. During both rainfall periods, in the morning of each day, the artificial rainfall was stopped for two or three hours to allow the measurement of horizontal displacements and soil swelling, as well as to auger disturbed specimens for the determination of gravimetric water content (GWC) profiles. Apart from this regular stoppage, the artificial rainfall intensity was maintained constant at 3 mm/hr.

The percentage of infiltration during the two rainfall periods (see Figure 5(a)) is deduced from the measured rain intensity and the surface runoff. During the first one and a half days after the beginning of the artificial rainfall, the percentage of infiltration is equal to 100%, i.e., no runoff. Thereafter, the percentage of infiltration decreased with rainfall duration because of an increase in runoff. After four day of rainfall, the percentage of infiltration tended towards a steady percentage of about 30%, i.e., 70% run off. The decrease in the percentage of infiltration is likely due to the gradual closed-up of opened cracks and fissures as a result of soil swelling upon wetting. This was subsequently verified by the investigation of the previously-identified opened cracks on the slope surface (Ng et al. 2002). For the second rainfall period, during the first twelve hours after the beginning of the rainfall, the percentage of infiltration is equal to 100%. Thereafter the percentage of infiltration decreased significantly with rainfall duration.

5 OBSERVED RESPONSES

Due to page limitation, only the observed responses from the seven instruments located at mid-slope (i.e., at R2 section) and at a depth of 1.2 m are selected to present in this paper. The monitoring period covered from August 13, 2001 to September 12, 2001. More details and explanations of the monitored results are given by Ng, et al. (2002)

5.1 Responses of pore-water pressure (PWP)

Figure 5 (b) shows the changes of *in-situ* PWP obtained from the two tensiometers installed at the same depth of 1.2 m but spaced 2 m apart. It can be seen that the two curves are fairly consistent with each other. This may indicate the PWP was uniformly distributed in the transverse direction during the monitoring period.

Immediately prior to the first artificial rainfall on 18 August 2001, about 40 kPa negative PWP were recorded by the two tensiometers. After the first heavy artificial rainfall started on 18 August 2001, the negative PWP only began to decrease after about one and a half days of rainfall. In the other word, there was a clear delay in PWP response to rainfall infiltration. Once the tensiometers began to response, the recorded negative PWP dropped to zero value in a short period of time, and then a significant positive PWP was observed.

During the two-week no-rain period following the end of the first rainfall, a slight recovery in negative PWP (about 10 kPa) was recorded by the two tensiometers. However, the recovery in negative PWP or soil suction was undermined quickly by the second artificial rainfall started 8 September 2001.

5.2 *Response of volumetric water content (VWC)*

Figure 5(c) shows the monitored results of VWC by the Theta-probe installed at R2 section and at a depth of 1.2 m. The response of VWC to the simulated rainfalls recorded was generally consistent with the corresponding PWP responses shown in Figure 5(b). There was a delay of about two days in changes of VWC, in response to the first artificial rainfall. Then, the measured VWC increased quickly to a steady value (nearly saturated VWC).

After the cessation of the first rainfall, there was about three days more delay in the response of VWC to the cessation than the response in PWP. This difference may be related to the hysteresis characteristic in the relationship between suction and water content. After the commencement of the second rainfall on 8 September, the VWC increased rapidly again to a steady value.

5.3 *Response of horizontal total stresses*

Figure 5(d) shows the monitored total stress ratio (σ_h/σ_v) with time from the two vibrating-wire earth pressure cells (EPCs) just above R2 section. Both the EPCs were installed at a depth of 1.2 m with an estimated total vertical stress (σ_v) of about 23.4 kPa, which corresponded to an average dry density of 1.56 Mg/m^3. Pressure cell EP1 measured the stress changes acting in the East-West (EW) direction (i.e., perpendicular to the inclination of the slope), whereas EP2 recorded pressures acting in the North-South (NS) direction (i.e., parallel to the inclination of the slope). Monitored results from other cells are reported by Ng et al. (2002).

Prior to the first rainfall, the total stress ratios recorded by both the cells were lower than 0.4. Pressure cell EP2 even registered a small tensile horizontal stress, probably resulted from drying shrinkage of the soil (Note: the vibrating-wire type cells are able to record tensile stress).

After the start of the first rainfall, both the EPCs did not register any significant changes of stress for about one and a half days. The delayed response of the pressure cells was consistent with the PWP and VWC measurements shown in Figure 5(b) and 5(c), respectively. Once the EPCs started to response, the ratios (σ_h/σ_v) increase most rapidly and significantly within one day, and then approached a steady value during the first rainfall event. The stress ratio in the EW direction was obviously larger than that in the NS direction after rainfall. The maximum total horizontal stress after the simulated rainfalls was more than three times the total vertical stress. This indicated the possibility of passive pressure failures in the softened clay after the simulated rainfalls.

During the two-week no-rain period, a further increase in σ_h/σ_v was observed from both EP1 and EP2. The continuous increase in σ_h/σ_v, but at a reduced rate, may be due to an ongoing "soaking" of the soil, even after the first rainfall event. After the start of the second rainfall event, the observed σ_h/σ_v at both EP1 and EP2 decreased rather then increased. This may be attributed to the softening of the soil after prolonged swelling during the no-rain period.

5.4 *Horizontal displacements*

Figure 5(e) shows horizontal displacements of the ground at a depth of 1.2 m in response to the simulated rainfalls. The results were calculated from the rotation measured along the inclinometer I1 near R2 section. The interpreted displacements from the South to the North direction (i.e., up-slope direction) and from the West to the East direction are defined as positive. The results indicate that the ground moves toward the down-slope direction and towards the East direction after rainfall. The observed eastern movements of the ground might be attributed to the direction of sub-surface water flow from the West to the East caused by the presence of slightly dipping geological planes. The measured horizontal displacements in the two directions illustrate similar characteristics, and their responses due to the simulated rainfalls were generally consistent with the variations in PWP and VWC shown in Figure 5(b) and 5(c), respectively. The horizontal displacements began to increase after about two days' rainfall, and kept increasing until the cessation of the first rainfall. A recovery of horizontal displacement (i.e., elastic response) is observed with respect to both directions during the two-week no-rainfall period (i.e., from 25 August to 7 September, 2001), due to the increase in soil suctions. The changes in horizontal displacements due to the second rainfall were relatively insignificant when compared with the changes due to the first rainfall.

5.5 *Soil swelling at shallow depths upon wetting*

Figure 5(f) shows the vertical swellings in response to the simulated rainfalls measured from the movement point installed at a depth of 1 m near R2 section. It can be seen that the movement point did not register any movement during the first rainfall period (from August 18 to August 25). In other words, the soil beneath 1 m appeared to show a longer delay in the response of vertical movement than all the other measurements (PWP, VWC, horizontal stress and displacement). The soil beneath 1 m started to swell one day after the cessation of the first rainfall, and continued to swell throughout the reminder of the monitoring period. The substantial delayed soil swelling was somewhat difficult to understand fully.

6 CONCLUSIONS

To improve our understanding on the fundamental mechanisms of rain-induced landslides in an unsaturated expansive clay in Hubei, an extensive instrumentation and monitoring programme was carried out on a 11m high cut slope in Zaoyang. The field instrumentation and monitoring was intended to assist in the design of one of the major infrastructure projects called the South-to-North Water Transfer Project ("Middle-route") in China. Based on the measured and interpreted results, the following conclusions can be drawn:

(1) The percentage of infiltration decreased sharply with rainfall duration (i.e., an increase in runoff). After four days of rainfall, 70% of the simulated rainfall became run off. The decrease in the percentage of infiltration is likely related to the close-up of opened cracks and fissures due to soil swelling upon wetting.

(2) The observed responses in pore-water pressure, water content, horizontal stress and soil deformation were reasonably consistent with one another and generally showed a one- to two-day delay related to the initiation of the rainfall event.

(3) A significant increase in the total stress ratio (σ_h/σ_v) was observed after the simulated rainfalls. The maximum in-situ total horizontal stress after the simulated rainfalls was more than three times the total vertical stress. This indicated the possibility of passive pressure failures in the softened clay after the simulated rainfalls.

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