Investigation and analysis of the suction of unsaturated soils in a landslide

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Abstract: Although, we know that rainfall is the main factor that affects the stability of slope, we do not always know the exact reason or processes involved. With greater use of unsaturated soil mechanics, a new way is coming to solve how suction and temporary water pressure affect the stability of slope. During a period of rainfall, the water level in the slope will change, at the same time the suction and the temporary water pressure will also change with time and rainfall. In order to know the characteristic of change, an experiment to observe the change of suction and temporary water pressure is described here. The well has a depth of twenty meters and a diameter of two meters. It is the largest observation well for the observation of suction in the world. The well was put into action and the dates of the suction, temporary water pressure and rainfall was observed between October 2002 and December 2004. By analyzing the large number of dates and records, we found out the characteristics of the change of suction and temporary water pressure. The hypothesis that the distribution of suction is decided by the materials and structure of slope was supported. If the suction doesn't change promptly after the rain; there is time difference of the suction's change and rainfall. These conclusions will direct us to make further scientific studies on how rainfall affect slope.

Résumé: Bien que, nous sachions que les précipitations sont le facteur principal qui affecte la stabilité de la pente, nous ne savons pas toujours la raison ou les processus exacts impliqués. Avec une plus grande utilisation de mécanique insaturée de sol, une nouvelle manière vient pour résoudre comment l'aspiration et la pression provisoire de l'eau affectent la stabilité de la pente. Pendant une période des précipitations, le niveau d'eau dans la pente changera, en même temps la succion et la pression provisoire de l'eau changeront également avec du temps et les précipitations. Afin de savoir la caractéristique du changement, une expérience pour observer le changement de succion et de la pression provisoire de l'eau est décrite ici. Le puits a une profondeur de vingt mètres et un diamètre de deux mètres. C'est la plus grande observation bien pour l'observation de succion dans le monde. Le puits a été mis dans l'action et les dates de succion, de la pression de l'eau et des précipitations provisoires ont été observées entre octobre 2002 et décembre 2004. En analysant le grand nombre de dates et d'informations enregistrées, nous avons découvert les caractéristiques du changement de succion et de la pression provisoire de l'eau. L'hypothèse que la distribution de succion est commandée par les matériaux et la structure de la pente a été convenue avec. Le changement de succion est lié à : les précipitations, le temps, la profondeur, et la saison. Si succion ne change pas promptement après la pluie ; il y a un retarder entre le changement de succion et les précipitations. Ces conclusions nous dirigeront effectuer encore d'autres études scientifiques sur la façon dont les précipitations affectent la pente.

Keywords: suction, unsaturated zone, soil mechanics, monitoring, climate change, data analysis

INTRODUCTION

As we all know, rainfall is one of the main causes of slope failure, and according to the recent studies, it is during the rainy seasons that landslides occur in natural slopes, artificial slopes, (caused by the digging of the railway roads, road foundations, hydroelectric projects as well as opencast mine) and those in underground caves. From recent research, we know that the rainfall will affect the hydrogeology of the inner part of the slope (when viewed macroscopically), and it will also change the physical-chemistry character of the materials which in the slope at the microscopic scale. However these are seen as very completed random processes.

Due to the factors we mentioned above, we need to use unsaturated soil mechanics related theory, to analyze and discuss the unsaturated soil suction changes in the slope that occur during different levels of rainfall. This research enabled further analysis of such affects on the slope during rainfall-progress and to provide scientific observations on such behaviour. The correct measurements and the correct recognition of changing characteristics showed that the changing characteristics of the environment play key roles in the engineering use of unsaturated soil mechanics theory. The works showed that site observation of suction was absolutely necessary for this type of research.

In order to observe the characteristic of slope changes, we carried out an experiment to observe the change of suction and temporary water pressure. An observation well was built on the Xietan slope of The Three Gorges of the Changjiang River in May 2002 to observe suction. The well has a depth of 20 meters and a diameter of 2 meters. It is probably the largest well for suction observation in the world. The well was is put into use and measurements of suction, temporary water pressure and quantity of rainfall were observed from October 2002 until the end of 2004. Other workers have carried out similar experiments (Sweeney 1982, Ching & Fredlund 1984, Biwei Gong et al, 1999), but this is the first time that observations have been made on this scale and over such a long period of time. The following article will show the elementary analysis and discussion on the findings of the site observation experiment.

UNSATURATED SOIL MECHANICS BASIS

Unsaturated soil effective stress principle

Unsaturated soil is comprises soil grain, water, air, contractile skin. Due to the gas phase form, it is more complicated than saturated soil mechanics. The contractile skin (the intersect interface between the unsaturated soil's gas phase form and fluid phase form), it is different from water and air, and apparent an independent phase. It is named "contractile skin" in the surface chemistry. It is the unsaturated soil's forth-phase. Nowadays, the most persuasive and popular unsaturated soil effective stress principle among the unsaturated soil theories is Bishop' theory (Bishop and Blight 1961):

$$\sigma_0 = (\sigma - u_a) + x(u_a - u_w)$$

where σ is normal stress on the broken surface when broke, u_a is pore air pressure, u_w is pore water pressure, $(u_a - u_w)$ is suction in the soil, x is suction coefficient of efficiency and x is different with the different strength and capacity's alteration, u_a is the relative air pressure in the soil grain's pore space, u_w is the relative water pressure in the soil grain's pore space.

The difference between pore water pressure and pore air pressure in one of the soil's unit body $(u_a - u_w)$ is called suction, it represent the hydrophilic ability of the soil grain.

Unsaturated soil's shear strength formula

Unsaturated soil's shear strength formula can be expressed by the independent stress condition variable (Fredlund et al 1978). We can use two of the three stress condition variables in the shear strength formula. It has been proved that the stress condition variables $(\sigma - u_a)$ & $(u_a - u_w)$ is the most favorable association. We can use these variables to form the following formula:

$$\tau = C' + (\sigma - u_a)_f \, tg\phi' + (u_a - u_w)_f \, tg\phi^b$$

where C′is the intercept of Mohr-Coulomb broken envelope line and the shear stress axes, σ is the total normal stress when the surface broke, u_a is pore air pressure on the broken surface, when analyze we can precept the pore air pressure as the standard atmosphere pressure, ϕ' is internal friction angle which relate to the net normal stress condition variable $(\sigma - u_a)_f$, u_w is pore water pressure when the surface broke, ϕ^b is represent the friction angle which change with the shear strength vary as the suction alteration.

$$\Delta c' = (u_a - u_w)_f \, tg\phi^b$$

Δc′ is effective cohesive strength's increment when the $(u_a - u_w)_f$ change, $(\sigma - u_a)_f$ is net normal stress condition when the surface broke, $(u_a - u_w)_f$ is suction on the broken surface.

Unsaturated soil's effective stress principle and shear strength formula are both extended from the saturated soil related theory, for the sake of continuity. Bishop suggests that the relation between the x value and $tg\phi^b$ & $tg\phi^t$ which in the unsaturated soil's effective stress principle formula can be showed as:

$$x = tg\phi^b \big/ tg\phi^t$$

Unsaturated soil's related theories are not perfect to some states, but the existing research achievements and theories have already provided a direction to make further study on the unsaturated soil.

THE SUCTION AND THE PORE WATER PRESSURE’S SITE TESTING

The purpose of the site testing

We can come to a conclusion from the above analysis and equations, when study the slope’s stability and deforming damage’s influence, we need to involve a most elementary parameter—suction. The suction parameter also plays a key role in the identification of the unsaturated soil theory and the saturated soil theory. Therefore, it is necessary to do special study and experiment on such issue.

Any survey must be made with reference to the original suction of the slope, and we should conclude the changing rules of suction on the basis of robust experiment. During the process of the observation, our main job is to obtain the suction of different depths in the slope body, the pore water pressure, the amount of rainfall in slope region and the changing features with time, season and depths. The aims of this observation are listed as below:

- How the suction in the Xietan ancient slope body’s unsaturated zone changed with the depth changing
- How the suction in the Xietan ancient slope body’s unsaturated zone changed with time and seasons
- How the suction in the Xietan ancient slope body’s unsaturated zone changed with rainfall
- How the suction in the Xietan ancient slope body’s unsaturated zone changes=d during the process of the moisture absorption
- How the suction in the Xietan ancient slope body’s unsaturated zone changed during the process of moisture loss

The well is built on the cover of Xietan ancient slope body, and located in the middle inclined to right of the slope body. Its well mouth elevation is 100m. It is a diameter of 2 m and 20 m deep up to the sliding belt. We build a layer made of bricks and leave a small opening for the slope body’s vadose zone. The layer is 0.24 m thick. In the well we have equipped with 30 pull tension gauge and 20 pore water pressure meters-feeler searches, the feeler is 1m to1.5m away from the sidewall and the vertical interval between instruments are 0.5 m to1.0 m. There is a ladder in the well bringing observation members up and down to read the data.

The pull tension gauges are distributed in three vertical rows, mostly in the direction of S75ºE, the distribution condition and the general extending direction is as the following Figure 1. The feeler search is paralleled with pull tension gauge, and horizontally 0.2 m away from the vacuum gauge, as presented in Figure 1. The pull tension gauge and feeler search extend downward till the ground of the well.

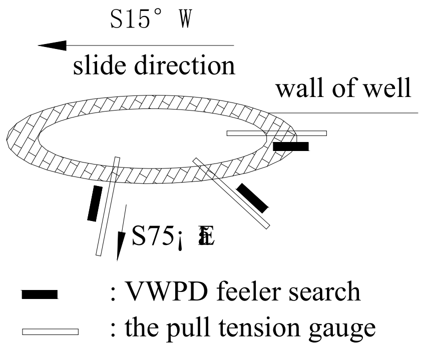

Figure 1. Cross section of instalment of equipments

OBSERVATIONS OF SUCTION AND TEMPORARY PORE WATER PRESSURE

The distribution patterns of suction and temporary pore water pressure in different depth and slope structure

The measurement of suction was carried out by manual observation of the pull tension gauges, which is a convenient technique, but one that couldn’t be used repeatedly. Because of the limited space of writing, here we only select three days at a monthly interval to draw reported curves as in Figure2. These reflect the different distribution patterns of suction from slope surface to lower bedrock.

The measurement of pore water pressure used VWPD feeler search (which is also called vibrating string uplift pressure gauge). Its features are fast, sensitive, but the cost is comparatively high. Because of the location of the instrument is unsaturated zone, most of the pressures are below zero, expressed as minus pore water pressure. Part of the slide body was found to be temporarily saturated due to rainfall, thus the result is above zero. Figure 3 shows the results of observations made on three separate days, at a two-month interval. It reflects a set of distributive patterns of pore water pressure along with the depth and the component of the rock-soil mass.

The distributive patterns of suction and pore water pressure are listed below:

- The suction and temporary pore water pressure of Xietan ancient slope are closely related to the material and feature of the slide body.
- The temporary pore water pressure in unsaturated areas is mostly below zero, and it presents different changing tendencies along with rainfall and with the time, some parts of it will temporarily show a saturated water pressure; the more the negative value is, the more moisturized the slope body is. But the moisture absorption ability is comparatively weak.
- Xietan slope talus is mainly composed of crushed rock and rocks. Because of the gravity-selecting effect, the slope body materials are partially sorted. The distribution of suction and pore water pressure in the unsaturated zones was related to the amount of fine particles, density and moisture content. Figure 2 and Figure 3 show that the actual suction and pore water pressure cut plane also show a zoning distribution. This has not been mentioned in the past researches and works.
- The observation well can be divided into *I, II, III, and IV,* four zones form top to foot. Particle size of material changes from coarse to fine, as the sandy and silty clay increases in proportion; but the natural water content changes from low to high.
- Layers of different substances, where suction becomes much less and pore water pressure is comparatively high, hinder water migration. The particle size of zone *II* is finer than that of zone *I*, but its permeability is lower. The relative rate of water content is higher near the contact plane of zone *I* and zone *II*, where the suction value is smaller. The main sliding belt and the secondary sliding belt have formed a layer that is relatively impermeable. In the raining seasons, water cannot penetrate this, so the soil body above becomes saturated and the host suction close to zero.

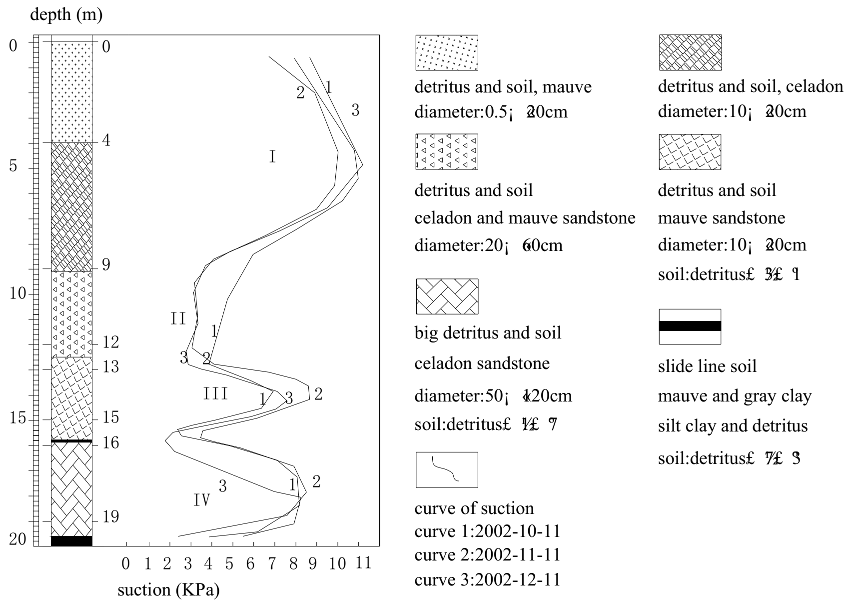

Figure 2. Characteristic curve of suction change with depth

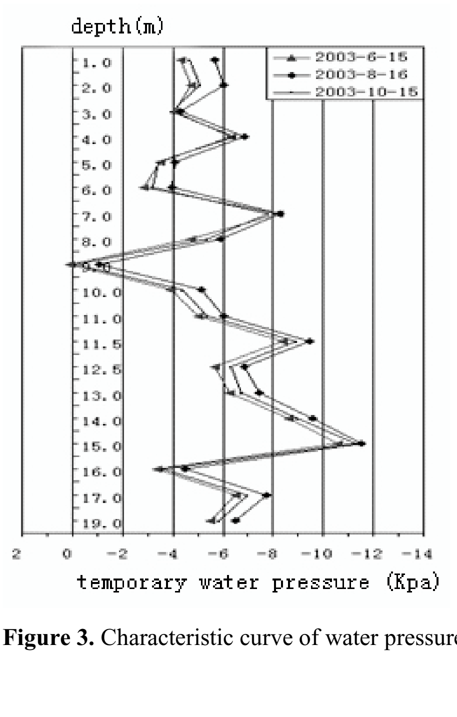

Figure 3. Characteristic curve of water pressure change with depth

Changes in suction and temporary pore water pressure with the time and rainfall

According to the alteration of the seasons and the climate change, the water in the slope body will present different changing tendencies. The changing conditions and the changing tendencies are shown in Figure 4. This shows the variation in suction with rainfall at depths of 1.0 m, 6.8 m, and 1.8 m.

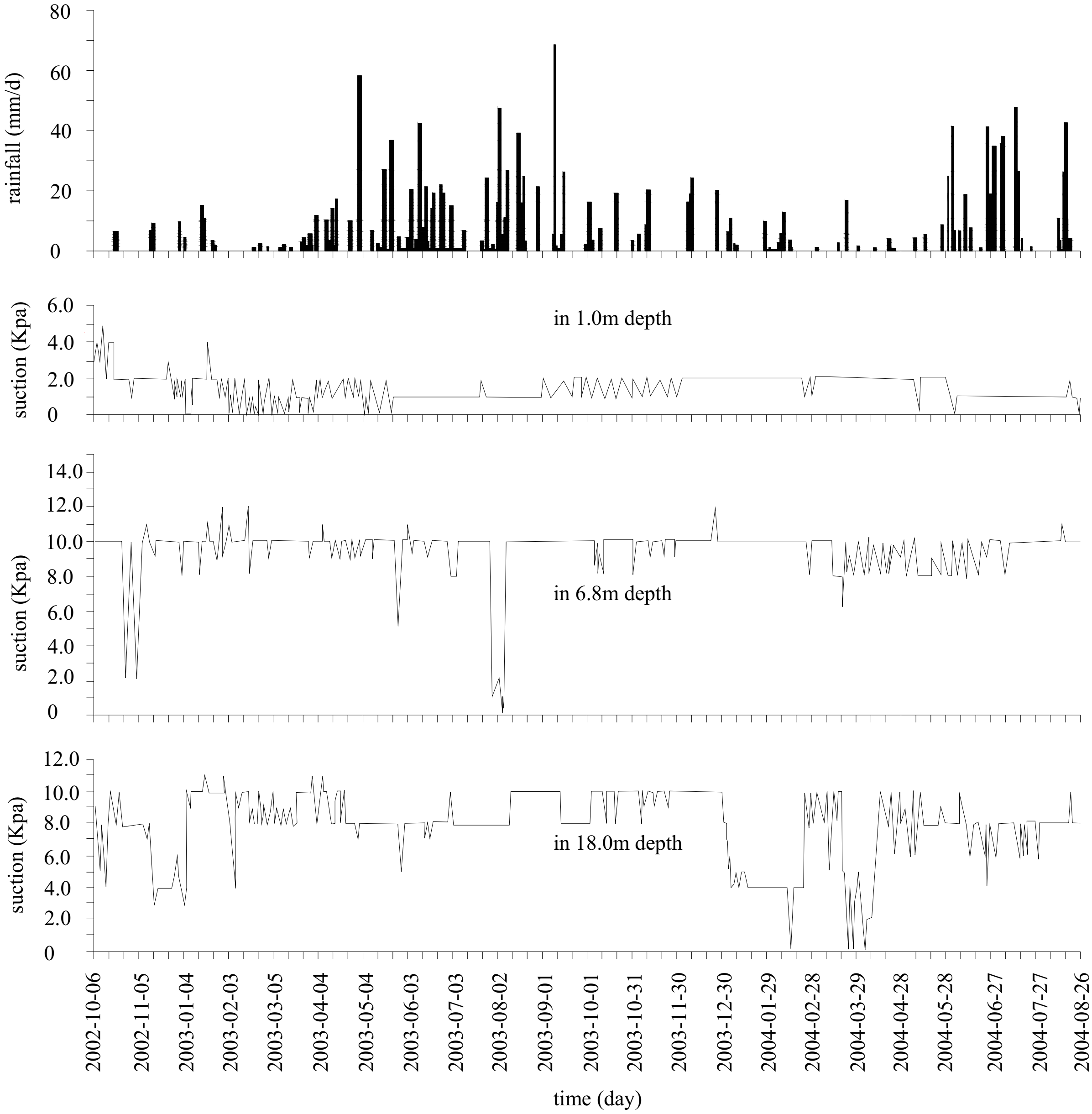

Figure 4. Monitoring curve of suction change with the quantity of rainfall variation and time passing by

The quantity of rainfall will raise the moisture content in the slope body directly, so the pore water pressure in the slope will present different changing tendencies with the alteration of the seasons and the progress of rainfall, the changing characters are shown Figure 5. This shows the variation in water pressure over time, again at depths of 1.0 m, 6.8 m, and 1.8 m.

We can get some information from the detailed analysis of the great amount of observation data and monitoring curves, the Xietan ancient slope body's suction and the pore water pressure changing characters with the quantity of rainfall variation and time passing by.

- The fluctuation of the monitoring data indicates that when the time and weather change, the monitoring curve will react sensitively. When the quantity of rainfall reach to the 10mm/d, 80% of the pull tension gauges' data reading will change, apparent declining tendency; 100% of the feeler searches data reading will change, apparent rising tendency, due to the minute change which in the water pressure and the temperature, it will provoke the feeler search's vibrating string shock excitation, and make the data reading changed.
- In the one year, the rainfall present an obvious Gaussian distribution, and centralize in the period of May to October; the water in the slope body will change with the rainfall in an obvious cyclicity, and present the

hysteresis quality (time difference) when related to the rainfall time. The slope body's moisture absorption and drying time always apparent after the rainfall, there is also an obvious difference between the rainy seasons and dry seasons. The suction's average value which in the October to the next May observation period is larger than the average value; measured in the next May to the next October.

- Because of the initial state's limitation, the monitoring curve began to reflect the changes in water condition of the in the slope from 2002/10/6, stabilising towards 2002/10/15, after which the water in the slope returned to normal conditions.
- The weather in autumn and winter is always dry, and the quantity of rainfall will reduce as well as the rainfall time (the appearance on the curve is the limited height difference), the rain is greater during spring and summer, and the suction is small in general, while the pore water pressure is higher than in autumn and winter.
- The change in the rainfall and weather which reflect on the curve will present certain hysteresis quality, the delayed time is related to the geologic bodies components and the character of the rock-soil mass. After the rain falls on the ground surface, the suction in the slope will change. The change will appear on the curve 1~2 days later.
- When the quantity of rainfall reaches above 8 mm/d, the pull tension gauge's monitoring curve will present a decline tendency, the water pressure, measured by the feeler search will present a rise tendency. It indicates that the suction will become small while the water pressure will rise during the period of the water in the slope body raising.
- When the weather is fine in a whole week, the pull tension gauge's monitoring curve will present an obvious rising tendency, the water pressure, measured by the feeler search will present a decline tendency. It indicates that the suction will become large while the water pressure will decrease during the period of the water in the slope body decreasing.
- The rainfall strength and the quantity of rainfall will affect the suction and the pore water pressure directly. When the quantity of the rainfall above 15 mm/d, the pull tension gauge data reading will decrease. For example: after two days (November 13, 14, 2002) it rained for three days, 80% of the pull tension gauge data readings reduced, even decreasing to zero, at the same time most feeler searches change significantly. When the quantity of the rainfall is between 15 mm/d and 10 mm/d, some of the pull tension gauge data reading will decrease, some of the feeler searches will change significantly, and the pore water pressure will rise obviously.
- The changes of the reading of the pull tension gauge are closely related to the permeating process of the rainfall, i.e. the closer the pull tension gauge is to the earth's surface (h<3m), the shorter the lagging time will be; on the contrary, the reading of the vacuum meter in the well bottom changes relatively slowly as regards to the changing of the rainfall. The reading of the meter that is closer to earth's surface (less than 3m) drops on the day of the rainfall (within 12hours), whereas the meter that is further from the surface (more than 5m) lags behind of time for 18-24 hours. During the rainfall, the pressure of the temporary saturation water normally below 2kPa.
- When discontinuities are large, or, as in the lower zone it is impermeable stratum due to high clay content, suction may be high and it will not be easy for the water seep through (e.g. the 3.2m-7.5m section) and the reading of the meter is relatively small and so does the suction of materials. When the tension meter is located/installed in the impermeable stratum or suction stratum, the reading will obviously become smaller. But in the thick clay stratum and sliding belt, it is difficult for the water to evaporate in the vacuum tube, so the reading might not change noticeably. Therefore, we usually come across with the cases in which the cloudburst after long-time of drought caused the soil suction in the sliding belt attraction suddenly fall down which consequently resulted in slope.
- When the weather is fine, the water in the non-saturated region drains off mainly by gravity, and secondly by evaporation. Through the observation records we find out that the reading of the meter at the bottom of the observation well increases first.

CONCLUSIONS AND PERCEPTIONS

According to the 2-year observation and experimentation of soil suction in Xietan ancient slope in the Three Gorges area, we can come to a conclusion that: The rainfall and its permeating process will directly influence the suction and temporary pore water pressure in the slope body. The following conclusions can be drawn from analyses.

Xietan ancient slope body's suction, the distribution and variable features of pore water pressure are related to the depth, materials and structure of the slope body, the amount and time of rainfall and the climate; and they also have hysteresis quality as regards to the time and degree of the rainfall.

Xietan ancient slope body's suction and pore water pressure have changing tendencies with the season, and they are also closely related to the humidity change of the whole region.

The distribution of the Xietan ancient slope body's suction by depth is similar to the testing result on the side slope of Sweeney (1982).

Our predecessors' studies on the suction which is in unsaturated region and pore water pressure's transient state are mostly stopped at the theories, which have their limitations, lacking of verification and analyzing on practical information. These test results are formed comprehensively on large amount of actualized information, thus revealing the changing conditions of water inside the slope. The results are practical and reliable.

Application of the theory of unsaturated soil mechanics to a real slope and construction an observation well of this scale to measure suction is unprecedented in our country and even unusual in the foreign countries. After the Three Gorge's construction and commence with water storing, because of the rising of the water level, it might cause the decreasing of stability in some parts of the side slope and incline to critical condition. And they lose their stability or not are decided by the rainfall. Therefore, this study has significant meaning for the safe operation and the prevention of geological disasters of the Three Gorge area.

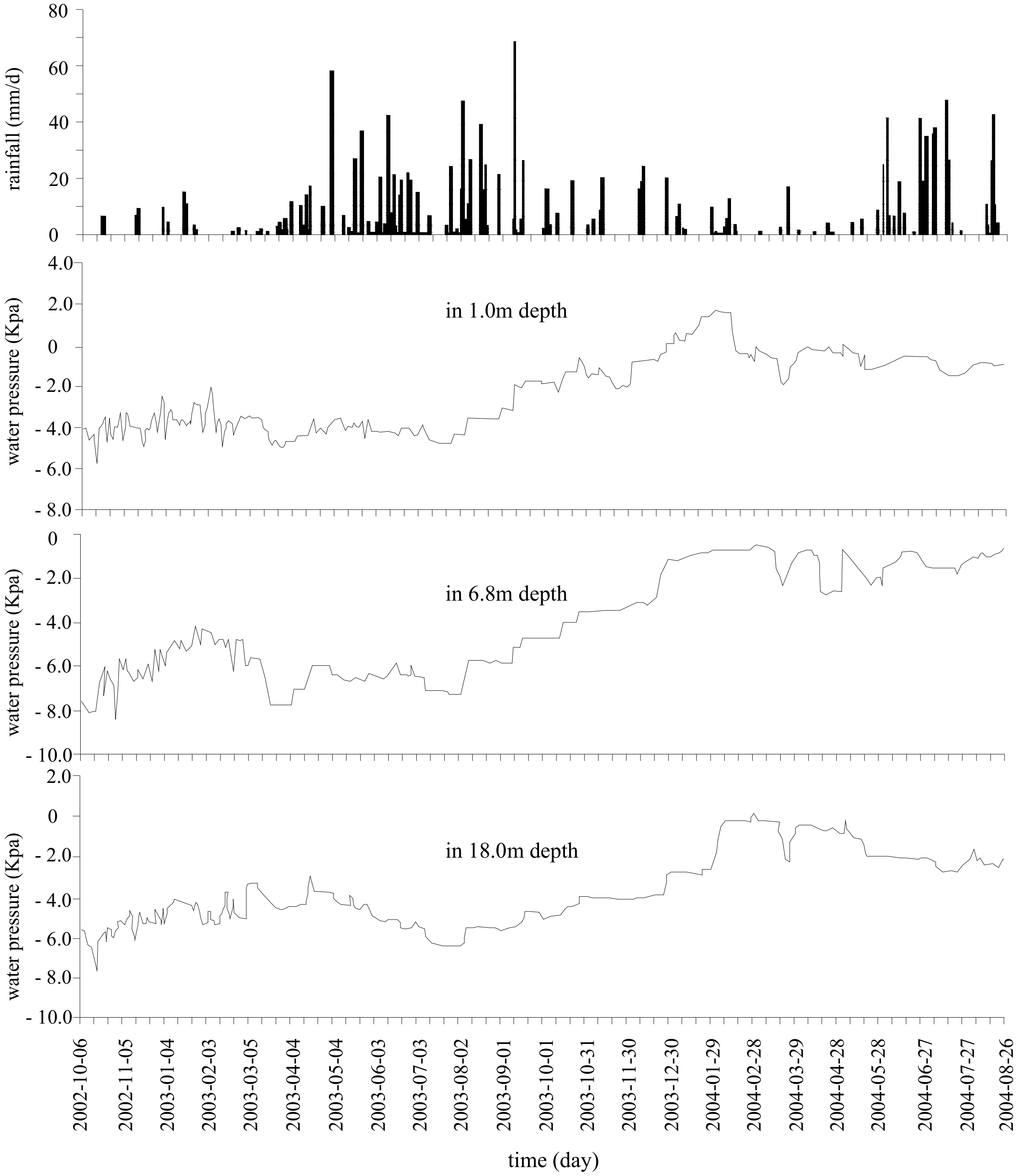

Figure 5. Monitoring curve of pore water pressure change with the quantity of rainfall variation and time passing by

DISCUSSIONS

Unsaturated soil pressure suction's influence upon the stability of the slope is very complicated and it is affected by the soil texture, suction's distribution and the interaction of the rainfall and the soil etc... And the application of the theory of unsaturated soil strength to solve problems in actual projects is largely confined by the strength theory of unsaturated soil and parameter testing technology, and the relationships between the suction, temporary pore water pressure transient state, soil shear strength and the stability of the slope especially require further investigation. However, the works concerning this aspect will greatly promote our understanding and comprehension about the complexity of the rainfall on the side slope projects as slope and foundation trench, and further understand the reconstructing procedure by the storing and transmission of water which in the geologic body, thus quantize the rainfall's influence and effect on the slope. Therefore, this research has significant value, theoretically and practically, for the geotechnical engineers to improve their designs and works to economically and effectively govern the slope.

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