Experimental study on pore pressure in rock-soil slope during reservoir water level fluctuation

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Abstract A test system was developed for measuring the pore pressure in porous media, and a new model was devised for the pore pressure testing in both saturated and unsaturated rock-soil. Laboratory experiments were carried out to determine the pore pressure during water level fluctuation. The variations of transient pore pressure vs. time at different locations of the simulated rock-soil system were acquired and processed, and meanwhile the deformation and failure of the model are observed. The experiment results show that whether the porous media are saturated or not, the transient pore pressure is mainly dependent on the water level fluctuation, and coupled with the variation of the stress field.

Keywords: landslide, pore pressure, reservoir water level, rock-soil.

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1 Introduction

The effect of seepage flow is a key problem in the investigation on the landslide failure. Water in landslide comes mainly from the infiltration of rainwater and seepage flow of ground water. Rivers and reservoirs are the dominant sources of ground water in landslide. The infiltration of water will cause variations of the ground water level in landslides, which sometimes play a key role in the landslide stability. In particular, the fluctuation of water level varies remarkably in large-scale reservoirs in-service. All these will cause relatively significant changes of seepage field in the landslide bodies within a relatively short time. During water storage of Three Gorges Reservoir, the reservoir water level will change tremendously, which is unfavorable to the stability. So, researchers paid more and more attention to these issues in the recent years. Therefore, the investigation on the mechanics of seepage and the change of seepage field caused by the fluctuation of the reservoir water level are of theoretical and practical significance for analyzing the effect of seepage on the landslide stability.

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Basing on experimental results, Weyman[1] concluded that the infiltration of rainfall made the pressure field pursue an unstable course which casts a serious impact on the stability of landslides. Hurley and Pantelis[2] analyzed the effect of seepage flow on landslides by studying the saturated and unsaturated flows in landslides. Iverson[3] also carried out investigation on the effect of rainwater in inducing the landslide failure. The studies of Kayane and Kaihotsu[4], Johnson and Sitar[5] and Hanenberg[6] showed that the rainfall infiltration will cause the increase of pore pressure in landslides, especially the pressure change in unsaturated zones below the ground surface. The analysis of Montgomery and Dietrich[7] on the stability of landslides suggested that the spatial change of seepage field in landslides was one of the key factors. Angeli et al.[8] made an overview of the testing technique and the research results on landslides, and revealed the important effect of water on landslides. All these investigations comprehensively indicated the importance of water seepage for the stability of landslides, of which the variation of pore pressure caused by water seepage is one of the most important ways of water affecting landslides.

Therefore, scientists have paid much attention to the issue how water seepage causes the change of pore pressure in landslides in a relatively long period of time. However, the measurement of the pore pressure in the unsaturated medium is a nut far from being cracked. Different techniques were attempted to measure the pore pressure in the saturated and unsaturated soil media. Reynolds[9] made a profound study on the *in situ* measurement of the key parameters in the landslide and illustrated the difficulties in measuring pore pressure. Harr[10] found that if the distribution of pore exhibited a step change, the water conductivity in the saturated zone presented a maximum drop difference. Anderson and Burt[11] considered the effect of the landform geometric topological feature on the saturated flow for the first time, and discovered that the horizontal surface flow is proportional to the convergence degree of the slope angle. Torres[12] pointed out that the variation amplitude and frequency of the pore pressure are dependent on the characteristics of unsaturated zone. Simoni[13] gave a preliminary result of pore pressure monitoring in an unstable soil slope. The results suggested that water was the decisive factor causing the change of pore pressure. All the above investigations greatly enriched and improved the level of understanding and observation of how water causes the change of pore pressure. Nevertheless, the majority of past investigations focused on the soil slopes, and few investigations have been conducted on the water seepage within slopes consisting of soil and rock blocks. Iverson[14] studied the fluid flow in a sand and soil mixture on crack bedrock, and discovered that the total flow rate of the mixed slopes is primarily dependent on the components of sand and soil in the slopes. The results by hydraulic monitoring showed that the response of pressure within the slope is an unsteady process. Mesri and Shahien[15] made a preliminary study on the change of stress field in a rock-soil mixture. However, the observation of pore pressure in rock-soil mixtures has not been well solved and the studies on the water seepage in heterogeneous media were very limited. It is necessary to develop test methods and investigate the

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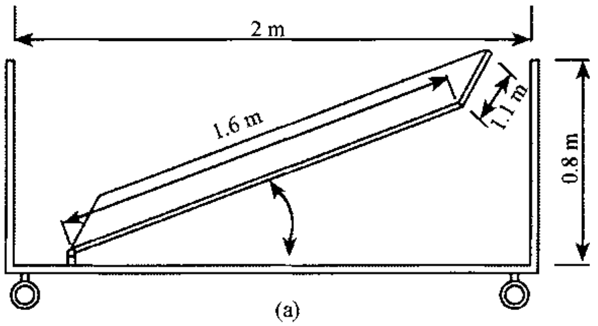
mechanism of seepage flow in heterogeneous porous media.

Most of landslides in Three Gorges Reservoir region would occur on rock-soil mixed slopes and the fluctuation range of the water level in the reservoir varies greatly. It is of significance to develop new experimental and observation methods for investigating the change of pore pressure and the seepage field in rock-soil slopes caused by water level fluctuation and discussing the stability of rock-soil slopes in Three Gorges Reservoir. Therefore, a laboratory model to simulate the rock-soil slopes was devised to study the change of seepage field caused by water level fluctuation. The change of pore pressure in saturated and unsaturated zones, the distribution of water content and the phenomena of slope failure were observed in detail. The coupling mechanism of the stress field and the pressure field affecting the slope failure was analyzed preliminarily. The investigation is of certain importance in understanding the effect of water on the instability of slopes.

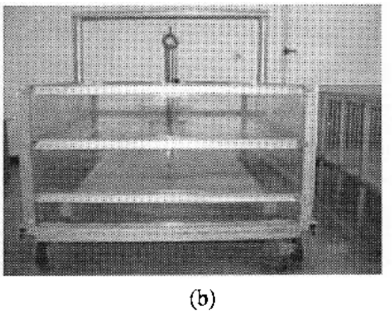
2 Experimental equipment

2.1 Simulation setup

To simulate the effect of the reservoir water level fluctuation on the seepage field in slopes and the stability of landslides, we designed a simulation experiment box in which a working bench with adjustable angle was installed to set the slope congeries (see Fig. 1). The experimental box is 2.0 m long, 1.5 m wide and 0.8 m high, in which a one-side free triangular steel frame is placed as the working bench. The rock-soil model is 1.6 m



(a)



(b)

Fig. 1. Schematic view of the simulation experiment box and the working bench. (a) Sketch of the experimental box; (b) photo of the experimental box.

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long and 1.1 m wide, which is piled up on the working bench. The angle of the working bench can be changed from 0° to 30° by lifting the other side with a pulley fixed on the box. There are two holes at the bottom of the box, one is for injecting water and the other is for drainage.

2.2 Measurement system

The measurement of pore pressure in the simulated slopes is the key point in this study. The measure system consists of pressure sensors, A/D converter and data accumulator (computer) (see Fig. 2).

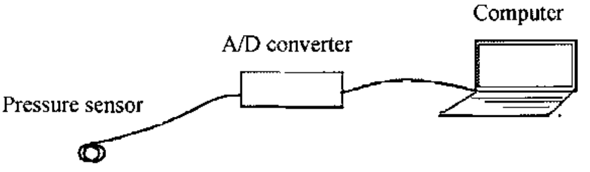

Fig. 2. The pore pressure measurement devices.

Pressure sensors of type 86 manufactured by IC Sensors Company (see Fig. 3(a)) are used in the experiments. The test range of the sensor is 0—5 Psi. The sensor is characterized by small volume, solid structure and good compatibility even with harsh medium, and has high precision, reliability, sensibility and stability.

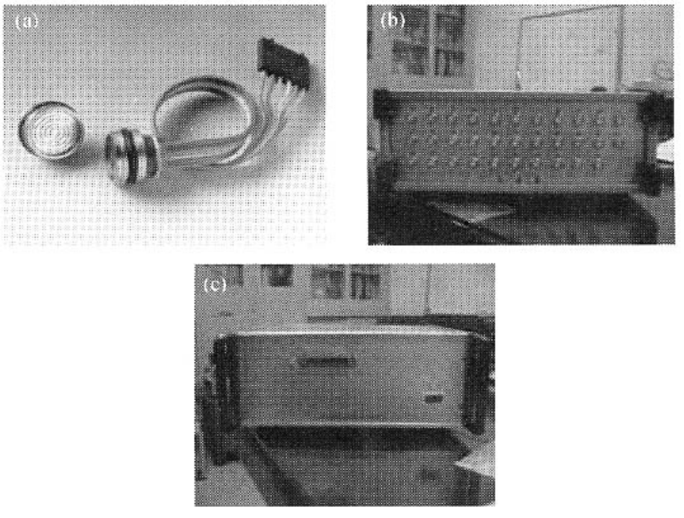

Fig. 3. Components of the pressure measurement device. (a) Pressure sensor of type 86; (b) A/D converter; (c) signal amplifier.

The specific technology used in the experiments is to encapsulate the senor in a little rubber membrane bag filled with the minimal compressible liquid, such as water or oil. When the little bag endures force from any direction, the spherical bag will completely transfer the acting force to the sensor through the internal liquid, so the pressure from

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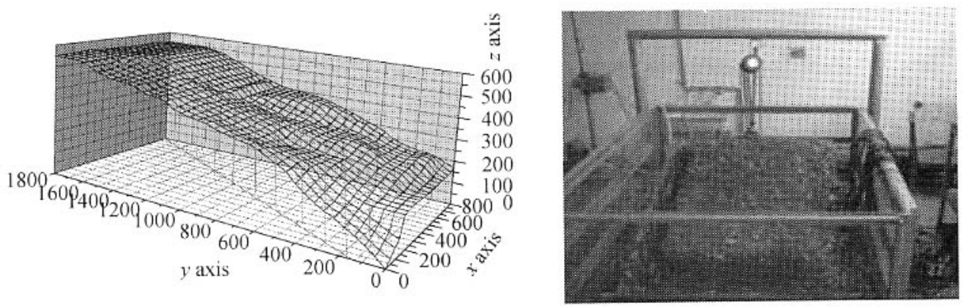
random direction on the measuring point can be reflected immediately. Consequently, the difficult problem to measure the pore pressure due to the sensor directionality in the composite body of rock-soil blocks could be well solved.

By connecting the pressure sensor to A/D converter (see Fig. 3(b)) and signal amplifier (see Fig. 3(c)), test data can be directly collected and stored in the data accumulator (computer).

3 Experimental method

3.1 Model design

Based on the Maoping bank slope of Qingjiang River shown in Fig. 4(a), an indoor simulation model was manufactured in a geometric proportion of 1∶1000. The simulation model is about 1.3 m long, 0.8 m wide and the average thickness is about 0.4 m. In order to simulate the material property of Maoping landslide, the rock-soil model consists of rock blocks and soil with the weight ratio of 1:2. The rock blocks are irregular limestone with the size of about 2 cm in diameter. The soil is the riverbed in which deposited silty clay with the grain size less than 0.005 mm. The shear strength of this kind of soil is relatively low, the cohesive strength (C) is 10.4 kPa, and the internal friction angle (Φ) is 0.57°. According to the actual angle of the landform of Maoping slope (see Fig. 4(a)), the model was established in the angle of 15° by adjusting the working bench (see Fig. 4(b)). The pore pressure sensors were embedded into the rock-soil model with the prearranged site distributions.



(a) (b)

Fig. 4. Sketch of the real landslide and experiment model. (a) Landform of Maoping landslide; (b) experiment model of rock-soil slope.

3.2 Distribution of the testing points

The pressure measurement device used in the experiment was equipped with 32 cables of pressure sensors. In order to use the limited measuring points to reflect the pore pressure of the entire slope, we distribute the pressure sensors into three layers. The relationship among the three sensor layers and the relative position of the sensors in each layer are clearly shown in Fig. 5. This arrangement of the sensors is based on two reasons: one is the limited number of sensors; the other is the fact that pore pressures near

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the bottom of rock-soil blocks are affected greatly by the fluctuation of water level. The sensors located in the third layer will be arranged upwards to the model top, since in this arrangement more widely pore pressure can be tested in the entire slope during the process of water level fluctuation.

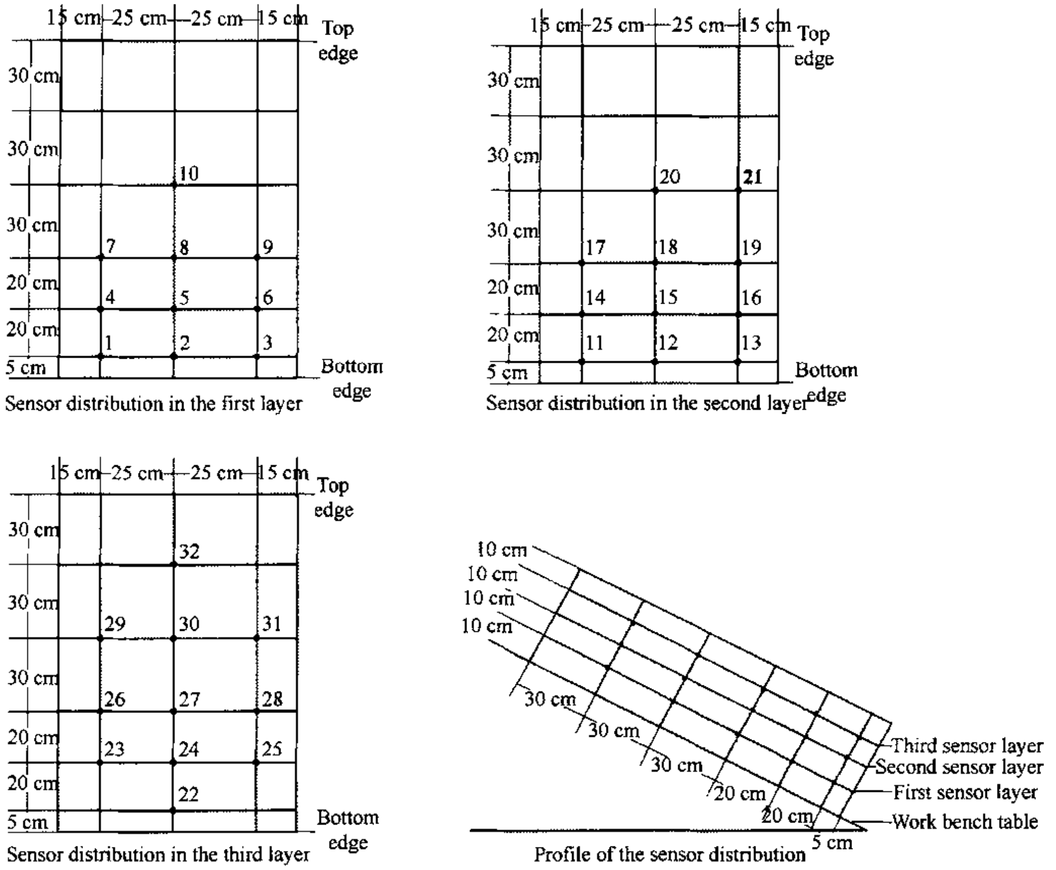

Fig. 5. Distribution of the pressure sensors.

3.3 Experimental method

The experiment was divided into three stages: two stages of water level rising, and one stage of water level dropping. The deformation of slope during the water level fluctuation was observed in all the three stages. The experimental process was shown in Fig. 6.

(1) The first stage: the water level rises gradually to simulate the first phase of water storage of the reservoir during which the injection flux is about 50 cm^3/s. It takes 30 minutes to let the water level reach half of the height. And after 4 hours pressure relaxation, the pressure reaches a relative stable situation.

(2) The second stage: another 30 minutes injection with the same flux. This stage simulates the water storage process of the reservoir in rainy season. After 8 hours relaxation, the pressure reached a relative stable situation again.

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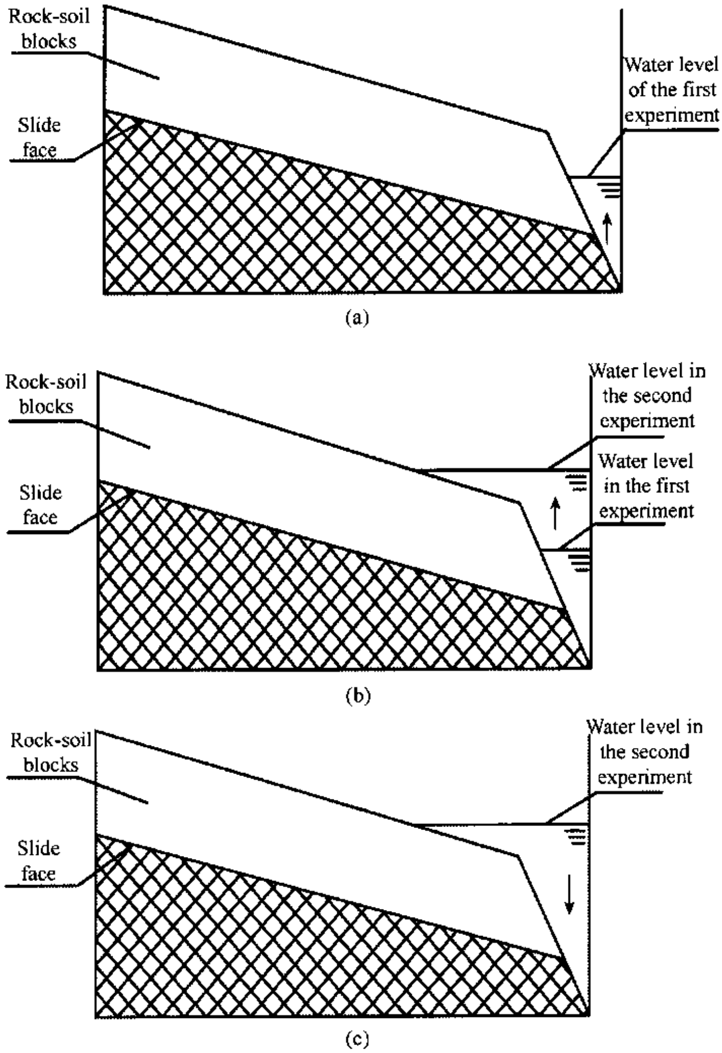

Fig. 6. Schematic of experiment processes. (a) First water level rising stage; (b) second water level rising stage; (c) water level falling stage.

(3) The third stage: this is a water draining stage with the flux of 100 cm^3/s or so. The water level reduces rapidly to simulate the water level suddenly drawdown in the reservoir.

4 Slope deformation in different stages

4.1 The first stage

In this stage, as the water level rose in reservoir, it could be clearly seen that the wetting line gradually moved from the bottom towards the top on the simulated slope surface, but its moving speed was lower than that of water level rising. After the termination of injection, the reservoir water level remained stable, but the wetting line moved continually and then remained relatively stable at a certain height after a long period of

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relaxation. In the injection and the relaxation processes, some cracks appeared near the bottom edge of the simulated slope and extended continuously. After the cracks extended to a certain extent, the part near the bottom edge of the rock-soil blocks collapsed and part of rocks and soils slipped into the experimental box, which caused the partial slope failure. Fig. 7(a) (figure of the partial slope failure near the bottom edge in the later stage of the injection process) and Fig. 7(b) (figure of the partial slope failure near the bottom edge in the relaxation period) show the process of the partial slope failure. In the sequential relaxation period, the widths of the cracks increased no more and reached a relatively stable state.

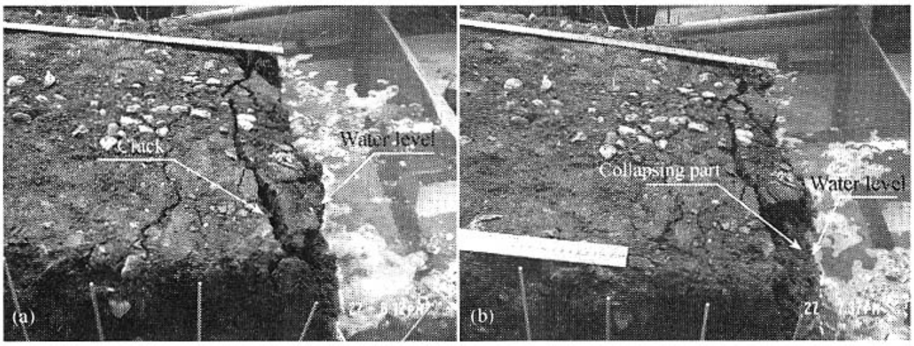

Fig. 7. Slope deformation in the first stage of the experiment. (a) Part slope failure during the injection process; (b) part slope failure during the relaxation period.

4.2 The second stage

During this stage, most phenomena are nearly the same as that of the first stage. The crannies extended and enlarged continuously till part of the rock-soil blocks slipped into the box. In the later injection period and relaxation processes, the cracks widened no more, and reached a relatively stable state again (see Fig. 8).

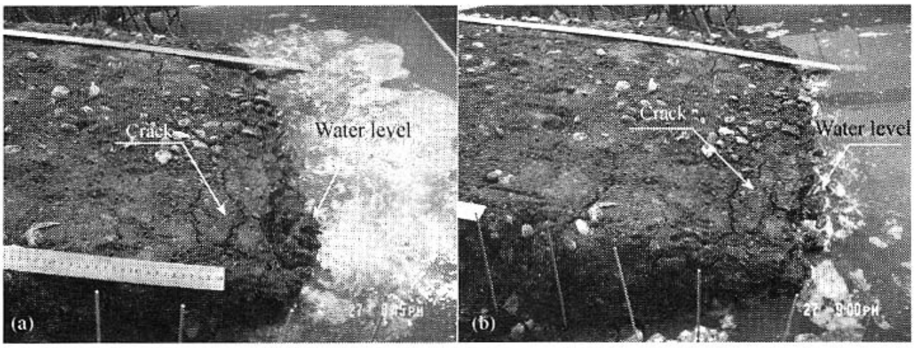

Fig. 8. Slope deformation in the second stage of the experiment. (a) Part slope failure during the injection process; (b) part slope failure during the relaxation period.

4.3 The third stage

In this drainage stage, there are some interesting phenomena after the water level fal-

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ling to the bottom.

After 15 minutes of the water drainage, a large pulling crack parallel to the slope leading edge appeared in the central part of the simulated slope. During the subsequent half an hour, the pulling crack extended continually, and meanwhile a certain amount of water seeped from the simulated slope. Part of the rock-soil blocks in front of the crack slipped slowly to the lower end of the slope.

3 minutes later, the rock-soil blocks in front of the crack suddenly moved towards the bottom edge of the slope and caused the crack width increase rapidly, and then majority of the rock-soil blocks in front of the crack slipped into the box (see Fig. 9).

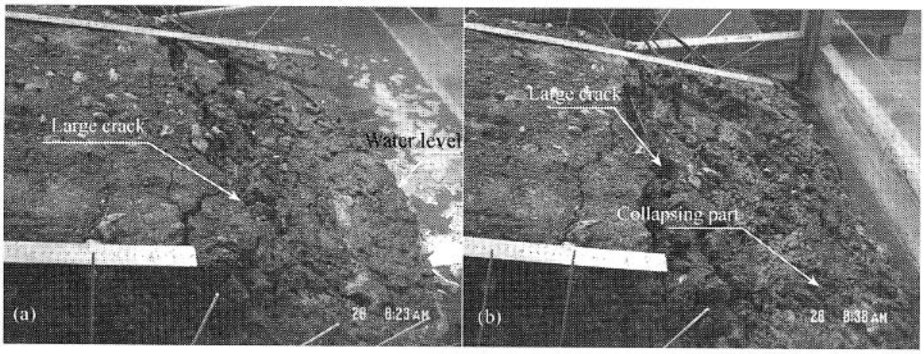

Fig. 9. Slope failure during the third stage of the experiment. (a) Part slope failure at 18 min drainage; (b) part slope failure after the drainage ended.

After 30 minutes of the water drainage, water seeping flow rate became more and more small, and the crack no longer extended and remained relatively stable.

It can be clearly seen from the entire process of water drainage that the water wetting effect causes the lag of water discharge effect in the slope.

5 Experiment results

Large numbers of test data have been acquired for each sensor, amounting to 1.3×10^5 groups, so that the ordinary data processing software is not adequate. Hence, we developed a specified data process program to deal with the test data. The test data are classified as follows. The entire experiment process consisted of 7 periods. From Fig. 10 to Fig. 13, we can see that AB is the period of device installation and other preparation, BC is the period of the first water level rising stage, CD is the period of the first pressure relaxation, DE is the period of the second water level rising stage, EF is the period of the second pressure relaxation, FG is the period of the water level dropping stage, and GH is the period of the last pressure relaxation.

5.1 Pore pressure in the lower part of the model

Fig. 10 shows the test results of the pore pressure acquired by sensor No.2 buried in the first sensor layer in the lower part of the slope, as shown in Fig. 5. It can be seen

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from BC section that the pore pressure remains a constant value for a certain time after the reservoir water level rising and then drops rapidly. This result suggests that there is a part of slope failure near the bottom edge of the slope during the water level rising, as shown in Fig. 7(a). During the first relaxation CD, the pore pressure drops the second time since the partial slope failure hasn't yet stopped as shown in Fig. 7(b). In the second water level rising period, that is DE, the pore pressure acquired by sensor No.2 doesn't reflect the deformation of the slope clearly, but the coupling effect of the stress field with the pore pressure field can be clearly seen in Fig. 10. The fluctuating range of the pore pressure is about 2 Psi. This phenomenon lasted a long time before the water drainage period started at point F. During the second relaxation period, which is EF in Fig. 10, the pore pressure is coupled with the stress field and the fluctuating range of the pore pressure is also 2 Psi or so. In the later phase of relaxation, the pore pressure remains constant for a relatively long time without the effect of the stress. During the water-draining period, which is FG, the stress coupling effect sometimes exhibits. After the water drainage, which is GH section, since the water level falling rate is relatively large, the pore pressure drops sharply, and there is a large crack formed at the same period, and then some part of the slope collapsed into the experiment box as shown in Fig. 9.

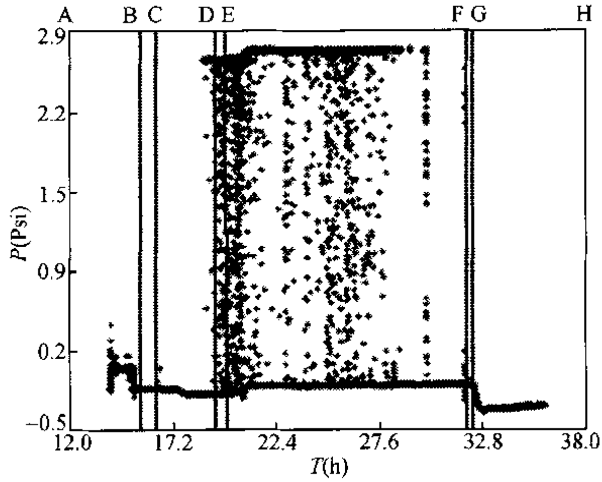

Fig. 10. Pore pressure measured by sensor No. 2.

5.2 Pore pressure in the middle part of the model

Fig. 11 shows the test results of pore pressure acquired by sensor No. 8 buried in the first sensor layer in the medium part of the slope as shown in Fig. 5. It can be seen that the twice water level rising doesn't cast large effects on the pore pressure variation. Most of the test results of sensor No. 8, from point A to G, are just like that of sensor No. 2 shown in Fig. 10. But after the water drainage, the pore pressure changes no more in GH period, as shown in Fig. 11. It suggests that water level falling in the later stage has no clear effect on the pore pressure. The pore pressure is not affected by the partial slope failure near the bottom edge.

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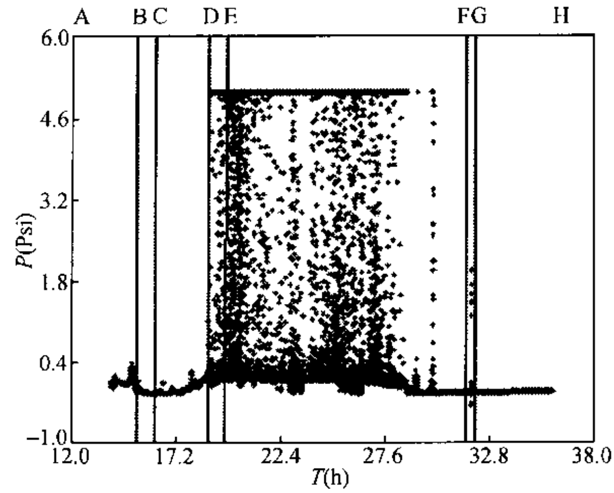

Fig. 11. Pore pressure measured by sensor No. 8.

Fig. 12 shows the pore pressure measured by sensor No. 19 in the second sensor layer in the median of the slope as shown in Fig. 5. The test results show that during the twice water level rising process from point B to E in Fig. 12, the pore pressure measured by the senor is dropping all the times. After the water drainage period, the pore pressure remains a stable constant just like that of the sensor No. 8 shown in Fig. 11. It can be concluded that there is no other factors affecting the pore pressure at point G after the water drainage as shown in Fig. 12.

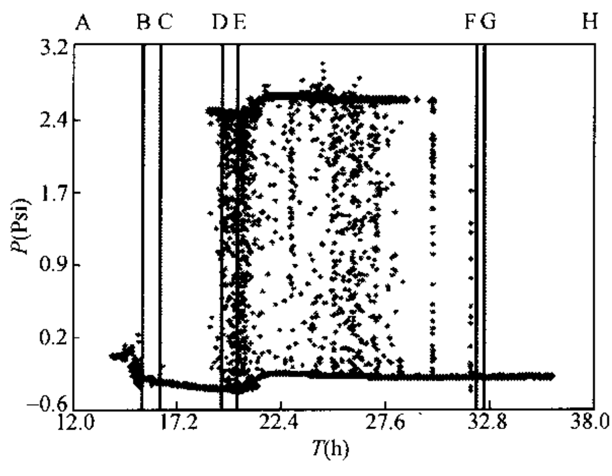

Fig. 12. Pore pressure measured by sensor No. 19.

5.3 Pore pressure in the upper part of the model

Fig. 13 shows the pore pressure variation measured by sensor No. 31 in the third sensor layer in the upper slope. The test results suggest that the pore pressure is little affected by the water level fluctuation in the entire process from point B to H, except that after the water content increases to a certain degree, and the coupling effect of stress field and pressure field made the pore pressure fluctuate.

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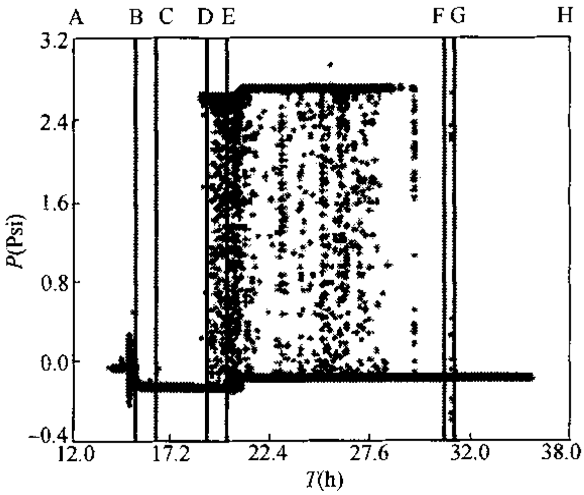

Fig. 13. Pore pressure measured by sensor No. 31.

6 Conclusions

(1) A new test method was developed for measuring pore pressure in both the unsaturated and saturated media. A set of pore pressure test equipment has been built up with specific technologies.

(2) By using the method proposed in this paper, the pore pressures in the rock-soil slope were successfully measured during water level fluctuation, and the phenomena of partial slope failure were observed, which could be reflected in the pore pressure acquired by some sensors.

(3) The test data of pore pressure in every test stage were analyzed by considering the water level fluctuation and the coupling effect with the stress field. The test results showed that the pore pressures at certain positions in the slope were affected by water level fluctuation to different extent and coupled with the stress field.

Finally, it is necessary to point out that although the inherent mechanism of pore pressure variation with the water level fluctuation in reservoir is discovered in laboratory experiments, it is of certain importance in understanding the effect of water seepage on the stability of landslide. This study paved the way for predicting the slope stability by monitoring and analyzing the pore pressure variation in the slope.

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