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Landslide Analysis of River Bank Affected by Water Level Fluctuation I

저수위 변동에 영향을 받는 강기슭의 산사태 해석 I

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ABSTRACT

The change of water level in reservoirs is an important factor causing failure of bank slopes, i.e. landslide. The water level of Three Gorges reservoir in China fluctuate between 145 m and 175 m, as a matter of flood control. During its normal operational state, the rate of water level fluctuation is supposed to range from 0.67 m/d to 3.0 m/d. Majiagou slope is located on the left bank of Zhaxi River, 2.1 km up from the outlet. Zhaxi River is a tributary of the Yangtze River within the Three Gorges area, of which the water level changes with the reservoir. At the back of Majiagou slope, a 20 m long and 3~10 cm wide fissure developed just after the reservoir water level rose from 95 m to 135 m in 2003. This big fissure was a full suggestion of potential failure of this slope. In this study, unsaturated-saturated seepage analyses were carried out to simulate the change of pore-water pressures in the bank slope subjected to the reservoir water level change. The obtained pore-water pressures were then used to evaluate the change in factor of safety (FS) with reservoir water level. It was found that the phreatic line showed a delayed response with respect to the change of the reservoir water level, because the seepage through soil layer was generally slower than water flows itself. During the rising and drawdown process, the phreatic lines take the shapes of concave and convex, respectively. And the fluctuation of reservoir water level just affected the front part of the bank slope, but had little influence on the back of the slope.

요 지

저수지의 수위변화는 저수지 주변 강기슭 사면파괴의 주요 요인이다. 중국의 삼협댐 저수위는 홍수량 조절을 위해 145m와 175m사이에서 변화한다. 삼협댐 저수위의 정상적 운영상태에서 저수위 변동속도는 0.67m~3.0m의 범위에 있다. 마지아고 사면은 자시강의 2.1km 상류 좌측기슭에 위치한다. 자시강은 삼협지역내에 있는 양츠강의 지류이다. 2003년 저수위가 95m에서 135m로 상승한 직후, 마지아고 사면의 후면부에서 길이 20m, 폭 3~10의 균열이 발생하였다. 지금은 균열 보수 후 특별한 징후는 보이지 않고는 있으나, 이 큰 균열은 마지아고 사면의 산사태 가능성을 암시하고 있었다. 이 연구에서는 저수위 변화와 관련하여 사면내에서 간극수압의 변화를 모의하기 위해 불포화 및 포화 침투해석이 수행되었다. 얻어진 간극수압은 저수위에 따른 안전율 변화를 평가하기 위해 사용되었다. 연구결과 침윤선은 저수위 변화보다 상당히 지연된 반응을 보였고, 저수위의 상승-하강과정에서 침윤선은 각각 요면과 철면의 형상을 나타내었다. 또한 저수위의 변동은 사면의 전면부에만 영향을 미치고 있었고 후면부에는 영향을 미치지 않았다.

Keywords **:** Landslide, Water level fluctuation, Seepage, Pore water pressure

1. Introduction

The change of water level in reservoirs is an important factor causing failure of bank slopes. Jones(1961) investigated the landslides occurred in the vicinity of Roosevelt lake from 1941 to 1953. It was found that 49% of them

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occurred during the first filling period of reservoir from 1941 to 1942, and 30% of them occurred as a result of drawdown of reservoir. In Japan, about 40% landslides around reservoirs occurred during the rising of water level, and 60% of these happened under a drawdown condition. The water level in the Three Gorges reservoir in China fluctuate between 145 m and 175 m, as a matter of flood control. The hydraulic and mechanical loadings changing with the water level will affect the stability of the river bank slope. Majiagou slope is located in Zigui county, Hubei province, China, within the Three Gorges area. The slope lies on the left bank of Zhaxi River which is a tributary of the Yangtze River, 2.1 km up from the outlet. In 2003, a 20 m long, 3~5 cm wide, locally 10 cm-wide fissure developed at the back of the slope just after the reservoir water level rose from 95 m to 135 m. After that, the fissure was stabilized, with no further opening. During the reservoir normal operation state of the reservoir, the rate of water level fluctuation is supposed to range from 0.67 m/d to 3.0 m/d between 145 m and 175 m(Liao, 2005). Even if the new formed fissure was stabilized without further opening, there could be large scale landslide due to the big change of reservoir water level. In this study, unsaturated-saturated seepage analyses were carried out using SEEP/W to simulate the change of pore water pressure in the bank slope subject to the reservoir level change(GEO-STUDIO, 2004). The pore water pressure files obtained from seepage analysis were imported into SLOPE/W program, with fully specified slip surface and limit equilibrium method to evaluate the change in safety factor with reservoir water level change. In this part Ⅰ the results of seepage analyses will be discussed in detail.

2. Geological engineering characteristics

2.1 The geographical position

Majiagou slope is located on the left bank of Zhaxi River, 2.1 km up from the outlet. Zhaxi River is a tributary of the Yangtze River, and the water level changes with the reservoir water level. In 2003, a 20 m long, 3~5 cm wide, locally 10 cm-wide fissure was formed on the back of the slope after the reservoir water level rose from 95 m to 135 m. After that, though the fissure was stabilized, with no further opening, if the water level rise eventually, a big possibility in developing to a landslide could be occurred in the Majiagou slope in view of precedents. As it is shown in Fig. 1, it is part of an ancient large landslide. The ancient large landslide was a bedrock slide and it covered all the left bank of Majiagou Brook, which is a tributary of the Zhaxi River. The slide mass was mostly composed of large sandstone blocks, filled with detritus of purplish red mudstone(Fig. 2). The elevation is range from 130 m to 300 m. It covers an area of 5 km^2 and the volume amount up to 2 billion m^3. A 3~5 m thick

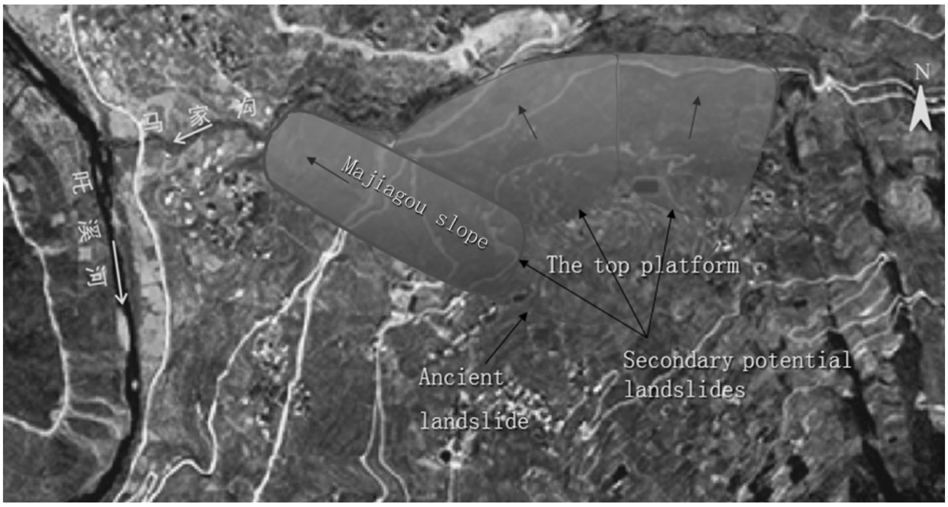


Fig. 1. Plan map of Majiagou slope

Fig. 2. Soil mass of slide zone

Fig. 3. Percolated water in the slide zone

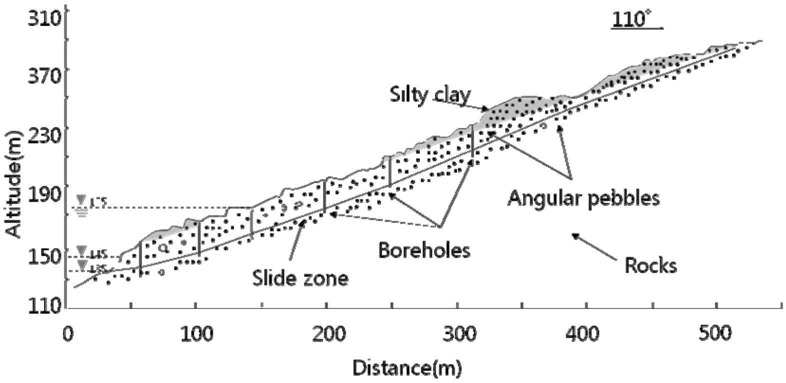


Fig. 4. Geological profile of Majiagou slope

Table 1. Geological parameters of Majiagou slope

Average length (m)	Average width (m)	Maximum thickness (m)	Average Thickness (m)	Area (m^2)	Volume (m^3)	Front elevation (m)	Back elevation (m)
537.9	180	17.5	13.2	96800	1278000	130	280

layer of brown-red clay containing rock blocks covers the top of the slide mass, which is a residual and diluvial deposit and may be deposited after the landslide formed, as the ancient landslide happened at least before the Holocene.

2.2 The geological profile

According to the results of boreholes investigation, an obvious possible slide zone has formed in this potential landslide, taking percolated water(Fig. 3) as a sign. It provided basis to analyze the stability of Majiagou slope on a landslide. The Majiagou slope looks like a narrow tongue in plan, with a movement direction of 290°. The front of the slope is submerged into Majiagou brook, and the back has the new formed fissure, with the elevation are 130 and 280 m respectively. The south and north sides of the slope are bored by two brooks. The slope has a gradient of 20~25° on the surface, a width of 150 m, a length of 538 m, a surface area of 96800 m^2 in plan, and a volume of 1278000 m^3. The mean gradient of the potential slide surface is 18°, and the slide mass has a thickness from 8.9 m to 17.5 m, 13.2 m on average(Fig. 4 and Table 1).

2.3 Material components

The materials of the slope are mainly composed of two types of soil mass. The 3~5 m top layer is brown red, wet and plastic to hard plastic residual silty clay con-

Table 2. Rresults of water injection test

Number	Borehole number	Test depth	Soil type	Permeability coefficient	
				(cm/s)	(m/d)
1	ZK4	0.5~0.67	Slity clay	$1.38e^{-5}$	$1.19e^{-2}$
2	ZK10	4.3~4.5	Angular pebbles	0.064	55.30
3	ZK11	6.1~6.3	Angular pebbles	0.500	432.0
4	ZK1	6.4~6.6	Angular pebbles	1.520	1313.28
5	ZK2	10.0~10.3	Angular pebbles	0.025	21.6
6	ZK6	10.4~10.6	Angular pebbles	0.006	5.18

taining rock blocks. The rock blocks are formed by feldspar quartz sandstones, shale and siltstones, silt mudstones etc, and the size of the blocks is generally 0.5~5 cm with the maximum up to 20 cm in diameter. Besides, the ratio of rock blocks to slity clay is between 6:4 and 7:3. The soil under the silty clay is angular pebbles, which is large sandstone blocks filled with weathered mudstone detritus. The thickness of this layer is 8~11 m. The size of rock blocks is generally 1~2 m, with the largest up to 7~8 m. The ratio of rock blocks to soil of from 8:2 to 9:1, in another words, this layer is formed mainly rocks. The potential slide zone revealed by boreholes is composed of muddy shale and crushed sandstone including a small amount of sandstone pieces. The soil of slide zone appears purple and grey in color, saturated and soft plastic in state. It was observed in the investigation pits in the southwest front, and in the investigation draft in the central part of the slide, that there is a film of crushed muddy materials with polished faces and slick-en-sides. The thickness of the slide zone is 0.5~0.8 m. There is a layer of percolated water within the slide zone. The percolated water can be observed in the draft as overflow and in the boreholes as hanging water and in the east side as down springs. Because the material of the slide mass and the slide bed are similar, the percolated water might be an important indicator of the slide zone. The components of the slide-bed are the sandstone rock blocks filled with the weathered mudstone detritus and fine soil. All the boreholes on the landslide did not reveal intact bedrock, which means the old landslide is a large one with a deep slide zone, and the Majiagou slope is only a relatively shallow part at its front, could be reactivated by the reservoir water.

2.4 Hydrogeological characteristics

Zhaxi River has a prominent effect on the landslide as its water level fluctuates with the reservoir. The grounder water in the slope is mainly the percolated pore water at the potential slide zone which flows out as springs. Based on the permeability tests on the ground surface and in the boreholes, the permeability of the silt clay on the top is 1.38×10^{-5} cm/s; while the angular pebbles below the silt clay has that of 0.006~1.52 cm/s as shown in Table 2. The potential slip zone has the permeability equivalent to the silt clay which is a relatively water tight layer. The Three Gorges rainstorm district has plenty of rainfall. From history data, the average annual rainfall is 1066.92 mm, and the maximum annual precipitation was 1430.6 mm(1963) while the minimum was 733 mm(1966). The rainfall was concentrated from April to October, and monthly mean precipitation was 87.2~147.2 mm, and from May to September it was always over 130mm, which was 67.2% of the total precipitation in a year. The rainy season was popular in storm rain and long term rain.

3. Analysis simulation of the slope

3.1 SEEP/W mode and boundary condition

Fig. 4 was chosen as simulation profile, of which the movement direction is 290°. The elevation of the front and the back is 130 m and 280 m respectively. Fig. 5 shows the finite element mode of the slope.

The soil layer was divided only two layers, those are angular pebbles and rocks layer. The silty clay layer is rel-

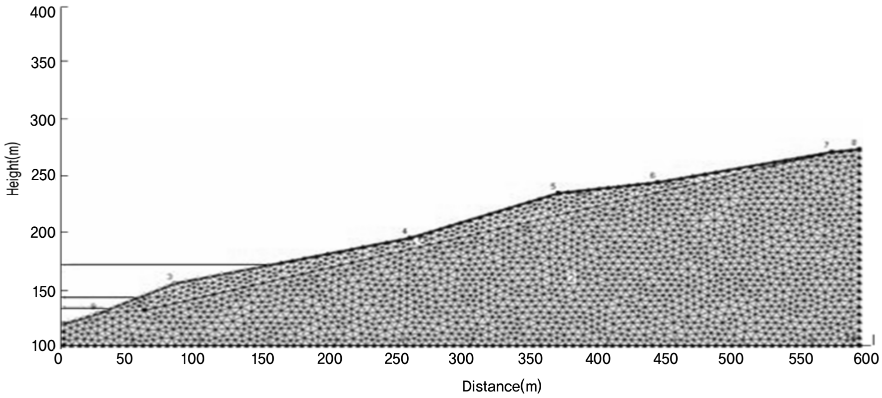


Fig. 5. Finite element mode of the slope

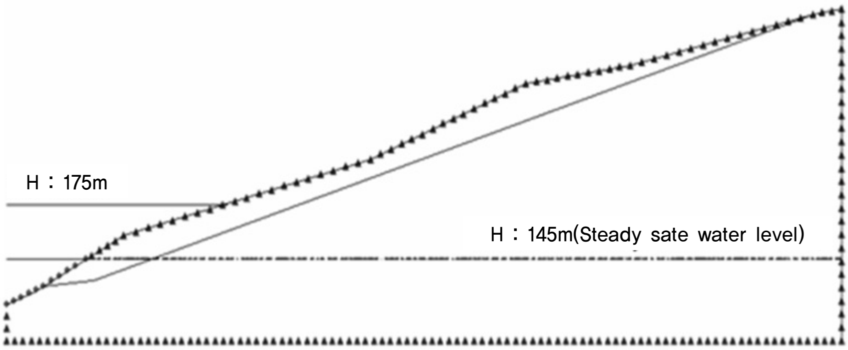


Fig. 6. Initial condition by steady seepage analysis results at 145m water level

atively thin and the thickness is not uniform; so, it can be neglected because it has little effect on the stability assessment. During the analyses, the boundary condition subject to the reservoir water level change is defined as a total head boundary equal to the changing reservoir water level as shown in different time step functions(Fig. 9). During the rise and drawdown process, the boundary is defined as a review boundary, which means that the boundary is adjusted to a zero-flux boundary if the total head of the node is smaller than the corresponding elevation(Desai, 1977). And all the other boundaries are specified as zero-flux boundaries. The initial condition is obtained by a steady state analysis in which the reservoir level maintains at 145 m(Fig. 6). And the total head boundaries time step functions are shown Fig. 9.

3.2 Parameters of the slope

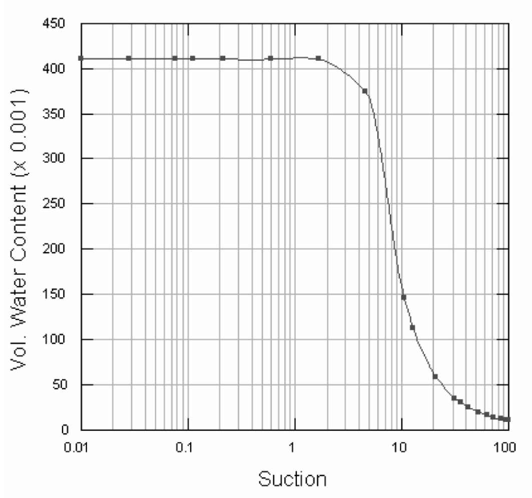
Based on results of laboratory experiments, in situ experiments, the parameters used in the simulation are identified as shown in Table 3. The water content characteristics and permeability function are shown in Fig. 7.

Table 3. Parameters used in the analyses

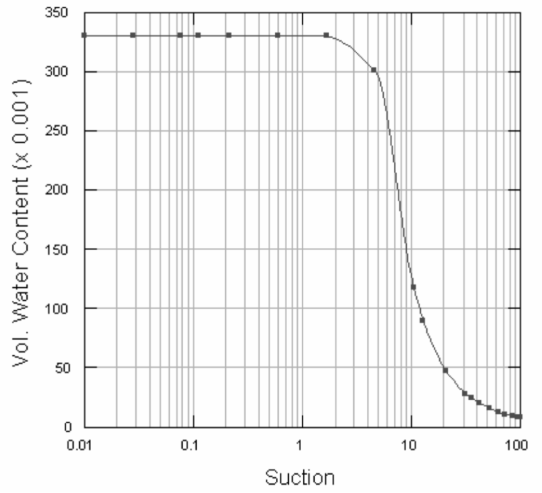
Soil mass	K_{sat} (m/d)	Natural density (kN/m^3)	Saturated density (kN/m^3)
Angular pebbles	5	21.6	22.4
Rocks	0.5	25.0	25.9

3.3 Time step function

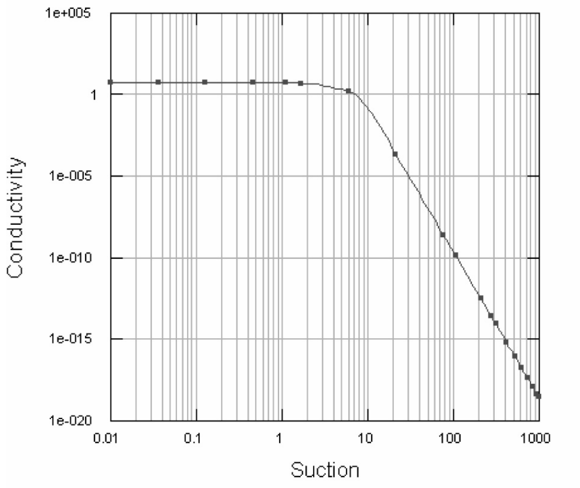
The water level adjustment schedule of the Reservoir in its normal operational state is supposed as shown in Fig. 8. On May, the reservoir water level drops from 175 m to 155m with the rate of less than 1 m/d, average 0.67 m/d; on June, the reservoir water level drops from 155 m to 145 m with the rate of 1.0m/d. The threshold limit for water level is 145 m which is maintained to prevent flooding during the flood season which extends from the



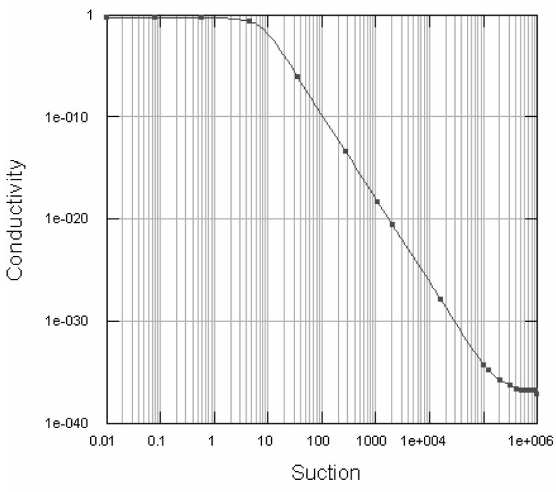
(a) Water content characteristic line of angular pebbles



(b) Water content characteristic line of rocks



(c) Ksat=5 m/d angular pebbles permeability function



(d) Ksat=0.5 m/d rocks permeability function

Fig. 7. Water content characteristic curves and permeability functions

middle of June to the end of September. During this period, if flood occurs, the reservoir water level drops rapidly. The drawdown rate of the reservoir water level depends on how large the flood is and whether the dam can support or not the damage due to the flood. The rate at largest is up to 3m/d as the 100 year flood occurrence. At the beginning of October, the water level rises from 145 m to 175 m, and the 175 m level is maintained until the beginning of the next May unless there is some need for the agricultural irrigation.

In this study, two simulations were carried out. One was accomplished to find out the rules how the water level fluctuations affect the stability of bank slope by comparing the results at different rising and drawdown rates, which is ranged from 1m/d to 3 m/d, and lowing the reservoir water level immediately after rise. The other was completed to find out the influence on the stability of the slope when the reservoir water stays at the lowest and the highest for the longest time, under the condition of neglecting the rainy season flood control and agricultural irrigation.

4. Seepage analysis results

The transient seepage analyses associated with the change of reservoir level shown in next two figures(Fig. 10(a) and 10(b)) were carried out in 60 time steps, as shown in Fig. 9(a)(rising and drawdown at 1m/d)(Jin

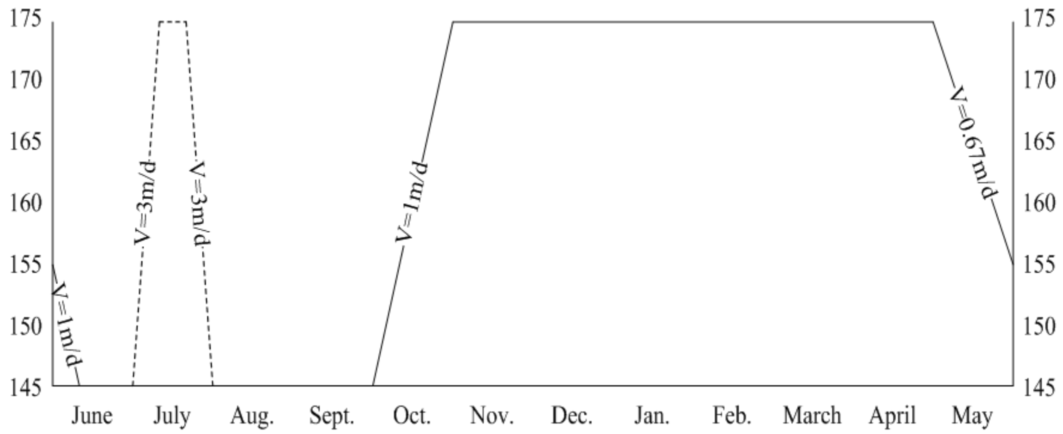
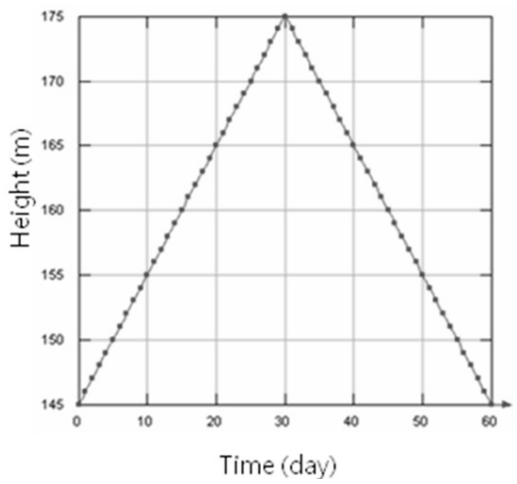
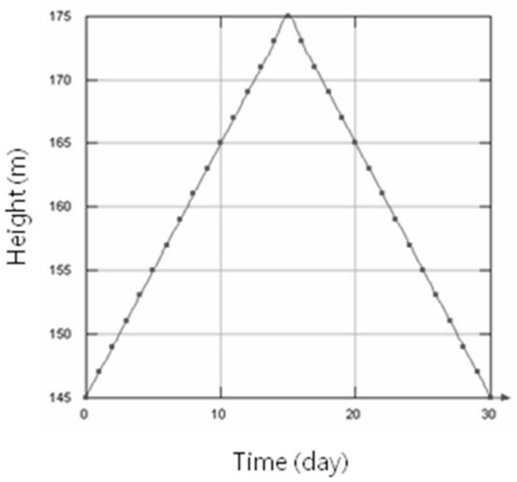


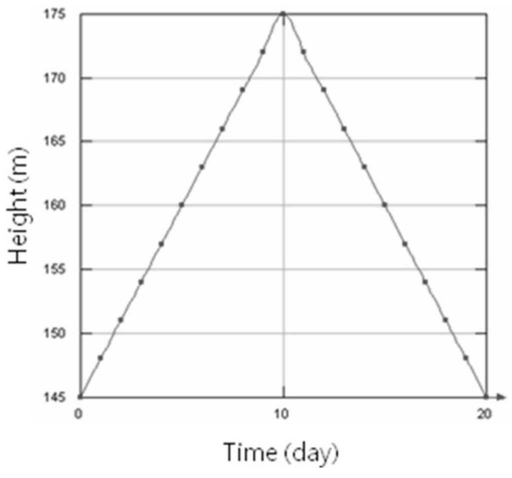
Fig. 8. Water level management schedule of the Three Gorges reservoir



(a) Rise and drawdown at 1 m/day



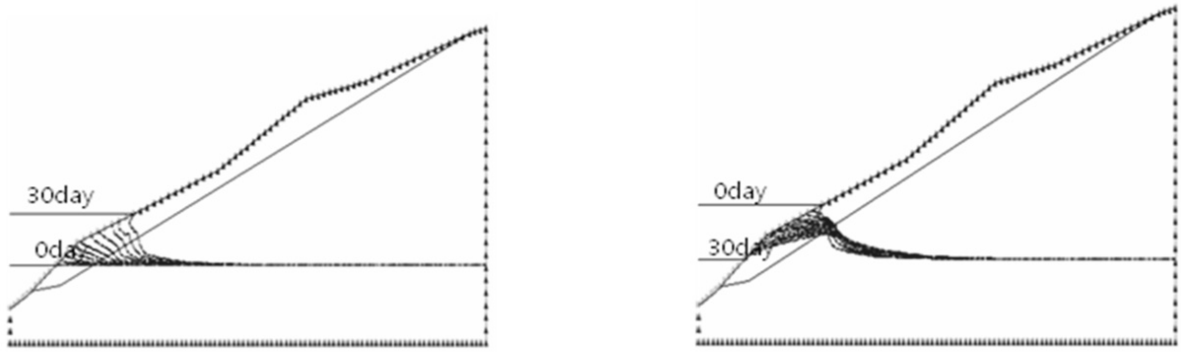
(b) Rise and drawdown at 2 m/day



(c) Rise and drawdown at 3 m/day

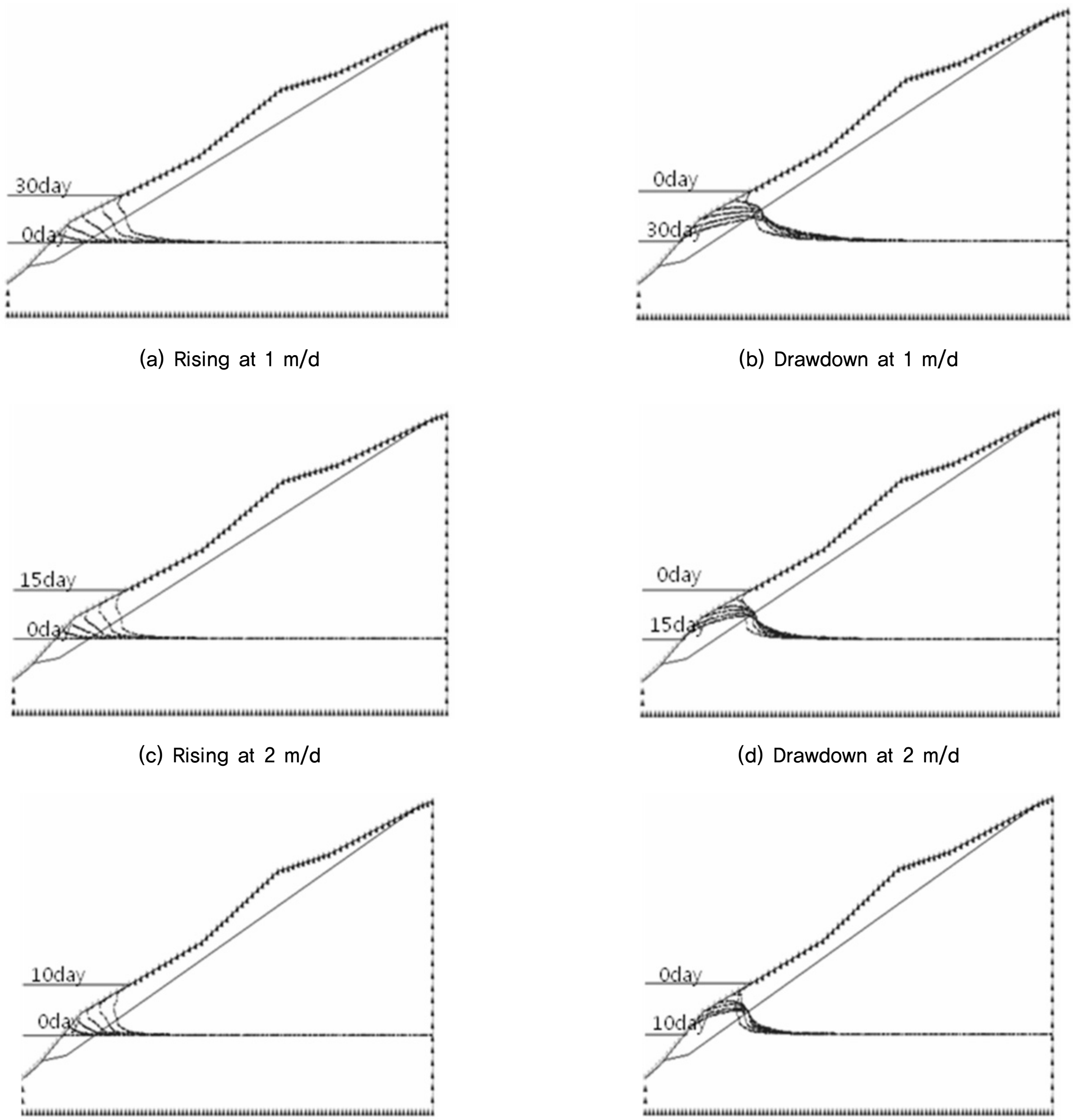
Fig. 9. Time step functiom

Yanli, 2007). Pore- water pressures and phreatic lines in the slope at each time step were obtained from the analyses. Fig. 10(a) shows the change of phreatic lines in the slope with the rising reservoir water level, and Fig. 10(b) shows the change of phreatic lines during the drawdown of reservoir water level just after it gets to 175 m. And the phreatic lines in both figures are shown once every three time steps results. It can be pointed out from



(a) Rising process (b) Drawdown process

Fig. 10. The change of phreatic lines during the rising and drawdown process



(a) Rising at 1 m/d (b) Drawdown at 1 m/d

(c) Rising at 2 m/d (d) Drawdown at 2 m/d

(e) Rising at 3 m/d (f) Drawdown at 3 m/d

Fig. 11. Comparison the changes of phreatic lines during rising and drawdown process

two figures that the phreatic line shows a delayed response with respect to the change of the reservoir water level, because the seepage through a soil is generally slower than water flows itself. During the rising and drawdown process, the phreatic lines take the shapes of concave and convex, respectively. And the fluctuation of reservoir water level just affects the front part of the bank slope, but has little influence on the back of the slope.

Next Fig. 11 is shown the phreatic lines at once every 6m of the reservoir water level (145, 151, 157, 157, 163, 169 and 175 m, respectively) and at different rates during rising and drawdown process. It is founded from those figures that the faster rates of the reservoir water level change, the more concave or convex of the phreatic lines in the slope.

4. Conclusions

(1) The phreatic lines showed a delayed response with respect to the change of reservoir water level because the seepage through a soil is generally slower than water flows itself.

(2) The fluctuation of reservoir water level just affects the front part of the bank slope, but has little influence on the back of the slope.

(3) During the rising and drawdown process, the phreatic lines take the shapes of concave and convex, respectively. And the rates of rising and drawdown are faster, the phreatic lines in the river bank are more concave or convex.

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