Simulation of groundwater flow in the side slopes of a section of the Three Gorges Reservoir, Fengjie, China

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Abstract: The normal impoundment water level of the Three Gorges Dam in Changjiang river is 175 m and it will be limited to 145 m during flood seasons for the purpose of flood control, which means that water levels of the Three Gorges Reservoir will vary between 145 m and 175 m after the whole engineering works are finished. In the process of reservoir water-storing and during the normal operation of the Three Gorges Reservoir after the water-storing process is completed, the discharge basal level of groundwater in Fengjie reservoir banks will rise or decline in accordance with the fluctuation of the reservoir water level, which will result in the groundwater seepage field having a relative variation.Field survey and careful geological work were executed on the Fengjie reservoir bank and its geological and hydrogeological conditions were observed and recorded. Based on these reliable and credible data, a mathematic model of groundwater flow in the Fengjie reservoir bank can be obtained by use of reasonable and scientific simplification. The modelling made use of the well-known simulation software for modelling groundwater flow and pollution - 3D-Modflow, the variation of the groundwater seepage field can be simulated, including the following three kinds of situations: the process of the reservoir water level rise to 145m, the process of the Reservoir water rising from 145m to 175m and declining from 175m to 145m. These simulation results can provide scientific reference for the analysis and evaluation work and disposing project of geological hazards in Fengjie reservoir bank.

Résumé: Le niveau de retenue normal des travaux de trois gorges est de 175m. Le niveau limité à la période de contre l'inondation est de 145m. Le niveau de retenue se varie entre 145m et 175m. au cours de la retenue et après la retenue du réservoir, pendant le fonctionnement normal, Le champ de transfusion de l'eau souterraine du réservoir se varie à la fluctuation du niveau de retenue. Selon le rechrche détaillement sur sîte, on a trouvé la condition de la géologie et de la hydrogéologie. Sur cette base, on a mené le nombre approximatif raisoble et scientifique. On a établi la maquette mathématique du mouvement de l'eau souterraine de la rive du réservoir dans la condition de la retenue. On a utilisé le logiciel de la simulation numérique de l'eau souterraine-3D-Modflow pour prévoir la variation de champ de transfusion de l'eau souterraine dans la condition de la retenue au niveau du 145m au 175m et le retour au niveau de 145m. On a livré le support scientifique pour évaluer la catastrophe géologique et prévoir et traiter la catastrophe géologique de la section du réservoir Fonjie.

Keywords: Three Gorges Reservoir engineering**,** impoundment water level, reservoir bank, 3D-Modflow, Fengjie

INTRODUCTION

The normal impoundment water level of the Three Gorges Dam on the Changjiang River is 175 m. Recently, the water level of the Fengjie section of the Changjiang River during the year ranged from 80 to 110 m. From the beginning, the water level will rise or decline is in accordance with the fluctuation of the Changjiang reservoir water level. Due to its large variation range of hundreds of metres, it will cause many environmental geological problems related to the changes of hydrological conditions to a great extent on the slopes of the reservoir and transportation environment of groundwater. In particular, the obvious problem is the collapse of reservoir bank slopes and the reconstruction of reservoir banks after water storing.

THE SELECTION OF SIMULATION SECTION

The work section is in the new city of Fenjie County, which links Liia Gully to Laolongdong Gully from west to east. According to the subsection principle, it can be divided into 12 sections (Table 1), which can be further categorized into 4 types: matrix rock slope, accumulations of landslide, shallow residual diluvium (<30 m) and thick residual diluvium (>30 m). The reservoir section from Baiyangping Gully to Guihuajingxi Gully contains the four typical types of reservoir bank sections, and has many typical physical geological phenomena, such as the Laofangzi landslide, the Sichouchang landslide, the Dahe Gully deformed mass, and so on. These potentially unstable ancient landslides and deformed masses are wholly or partly located below 175 m of the impoundment water level and above the 145 to175 m of the water level change belt of the Three Gorges Reservoir. The regulating water level fluctuating belt of reservoir level is up to 30 m after the water back and the water infiltrates and seeps into the loose slope, thus, both possess not only have an effect on the water-rock reaction, but also create a static-dynamic hydraulic pressure. Moreover, the slope bank suffers from the weakening effects of external forces such as wind-wave and ship-wave erosion, and its stability will be further reduced. By the influence of water-level-fluctuation, the reservoir water will most probably reactivate, partly or wholly, the landslides, so the safety of roads and cities of the reservoir shore will be threatened directly or indirectly.

Table 1. Subsection of the Three Gorges Reservoir banks in the Feijie section

Location	Types of reservoir banks
Liia Gully to Boyangping Gully	Escarpment slope type of bedrock
Boyangping Gully to Chenjia Gully	Flood plain in the lower (or terrace) + shallow surface slope eluvium in the upper (detritus soil type) (<30 m)
Chenjia Gully to Sunjia Gully	Landslide type (block and detritus soil)
Sunjia Gully to Sichouchang Drain	Backwards (transverse) slope type of bedrock
Sichouchang Drain to Shilipu Gully	Landslide type (block and detritus soil)
Shilipu Gully to Dahe Gully	Terrace in the lower part + backwards slope type of bedrock in the upper part
Dahe Gully	Alluvial-proluvial in the lower part, debris flow (block and detritus soil) + collapse slope eluvium in the upper part (block and detritus soil) type
Dahe Gully to Hejiabaodong Gully	Terrace in the lower part (silty soil) + thick slope eluvium in the upper (detritus soil) (thickness >40 m)
Hejiabaodong Gully to Guihaujingxi Gully to Huangguoshu Gully	Terrace in the lower part (silty soil) + backwards slope type of bedrock in the upper part
Huangguoshu Gully to Tianjiayuanba Gully	Terrace and alluvial-proluvial in the lower part + slope eluvium in the upper part (boulder in the lower part + block detritus soil)
Tianjiayuanba Gully to Dayingpan Gully	Terrace in the lower part (silty soil) + slope eluvium, landslide accumulation and proluvial mixture (detritus soil) (thickness >40 m)
Dayingpan Gully to Laolongdong Gully	Baiyian ancient landslide + Chenjiawan ancient landslide，Terrace in the lower (silty soil) + landslide type in the upper part (detritus soil) (thickness >50 m)

Therefore, the section from Baiyangping Gully to Guihuajingxi Gully was selected to be the typical research objective, and the three-dimensions was used to simulate and study variations in the characteristics of the groundwater dynamic field in the bank slope of Three Gorges Reservoir during the process of impoundment. The result expounded the developing trend and situation of the groundwater dynamic field of the reservoir bank after the operation of the reservoir and provided direct guidance for analysis and forecasting, disaster protection and reduction of landslide stability. Moreover, these simulation results could provide scientific reference for the forecasting and protection of geological hazards in migration settlements in Fengjie, a section of Three Gorge Reservoir bank.

MODEL CONCEPTUALIZATION

The discrete space of the Baiyangping Gully to Guihuajingxi Gully section includes the division into a series of elements in plan and a layered structure vertically. The plan view is divided into 40×31 elements, among which the element dimension of the section strongly affected by the water is 62×30m and the dimension of one less affected is 60×60m (Figure 1), after normal impoundment water levels reach 175 m. Vertical layers can be divided by the borderl between the loose structure and the weathering of bedrock, among which the section of loose deposit on the bedrock, with only one reason to shape, is divided into two layers based on its consolidation and structural types. According to the degree of weathering, bedrock can be divided into three layers: a strongly weathered layer, a weakly weathered layer and fresh bedrock. In order to avoid elements of some sections all becoming dry ones, in this simulation, the elevation of all fresh bedrock bases should be not more than sea level, as the result that the groundwater of the section buried in depth, and the groundwater distribution of fresh bedrock is not the emphasis. As for this simulation, there are five layers totally divided, i.e. two layers of loose deposits, three layers of bedrock; each layer has 1240 elements, 6200 in all (Figure 2).

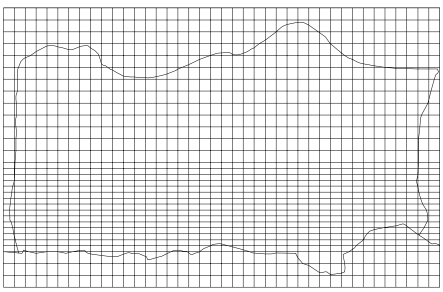

Figure 1. Plan grid of the model

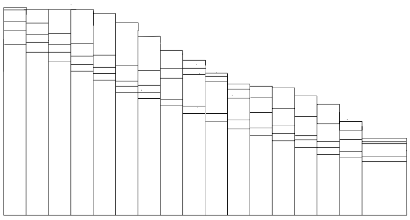

Figure 2. Vertical grid of the model

Hydrological geological boundary conditions of the model are defined to determine the conditions of the water head of each element so as to judge the element types, i.e. the constant water head, changeable water head or the invalid water head. With respect to the section from Baiyangping Gully to Guihuajingxi Gully, the groundwater and reservoir water are regarded as the main source or media. The water level is increased gradually in the process, even the operation of the reservoir under normal conditions, considering the influence of factors such as protection in the flood period and the low level in the dry season, its fluctuation can be up to 20 m. Thus, it is considered that the changeable water head is in accordance with the practical situation relatively. The posterior boundary of the model is in the altitude contour of 320 to 440m, and the horizon range away from current reservoir section is 900 to1200 m. Therefore, it is considered that the change of the reservoir level has not much effect on the posterior boundary of the model and can be defined as the boundary of constant water head; in this simulation, the relation between the recharge and outflow of underground water and the reservoir water should be focused on, while the section from Baiyangping Gully to Guihuajingsi Gully is nearly vertical to reservoir section which can be regarded as the impervious boundary and the other is the element of changeable water head.

Because the computing model is three-dimensional, the elevation of both the top and bottom should be determined in advance, which can be obtained by combining measurements or interpolation of the profile or plan views as well as the analysis of the trend surface. This paper adopted the latter approach.

THE VALUE OF MODEL PARAMETERS

Under the current conditions of reservoir water level, the groundwater of the section is relatively deep, which will directly make many elements in simulation field become dry ones. With the impoundment of water in the reservoir, the water level will gradually increase and part of the dry elements will also change into the potential validate element possessing aquiferous layer characteristics, and even aquifers characterized by confined aquifer after further increase of groundwater level. In this process, when calculating the change of the underground water level in these elements using the model, the available parameters of water feed degree (μ) changes into storage coefficient (S). Therefore, the parameters of model involved include seepage coefficient (k) (divided into horizontal direction (k_x), and vertical direction (k_z), water feed degree (μ) and storage coefficient (S).

With respect to fractures in the rock mass, due to the uneven nature of fracture development, the underground water must be shown as anisotropic. Limited by the adopted measures and available data, this paper regards the rock mass as a kind of continuous and homogenous-like media. The adopted hydrological geological parameter is obtained by the analogical method.

THE DETERMINATION OF INITIAL WATER HEAD

There are three types of method that can be used to determine the situation of the water distribution in the reservoir section: firstly, according to the data on the depth of underground water during the drilling, it can be obtained by the interpolation method or the analysis of trend surface; secondly, determine the hydraulic slope of the section by analogical method, then the depth of each element's underground water by the hydraulic slope obtained and the current reservoir water level can be deducted; thirdly, to realize the stable flux simulation to the model, the result of which can be used as the initial water level. This simulation adopts the latter two methods. Above all, deduct the depth of each element's underground water by hydraulic slope and current water level, regard the depth as the initial water head to assign each element of the computing model, process by stable flux simulation and treat its results as the initial water head of the computed model.

SIMULATION PLAN AND ITS RESULTS

Impoundment water in the reservoir leads to variation of the groundwater dynamic field, and the reactivity of water and rock and soil mass causes the deformation and instability of bank slopes, which is a primary purpose of the evaluation, prediction and consolidated design of Three Gorge Reservoir banks**.** Based on the field investigation of geological and hydrogeological conditions, a mathematic model of groundwater flow in reservoir bank can be acquired by making use of a numerical approach and numerical simulation; the following five kinds of situations can be simulated: under the current reservoir water level (80 to110 m), bank slope seepage field, the dynamic process of bank slope seepage field with reservoir water level rising from 110 to 135 m and the dynamic process of bank slope seepage field with reservoir water level rising from 135 to 175m. The discrete times are shown in Table 2. Figure 3 shows the water level distribution figures under various conditions by simulation.

Table 2. Time distribution of the model

Condition	Border water level	Time section
Under the present water level condition of Changjiang River (80 to 110 m)	80 m	125 days
	80 to110 m	120 days
	110 to 80 m	120 days
sluicing from 110 to 135 m	110 to 135 m	90 days
sluicing 135 to 175 m	135 to 175 m	90 days

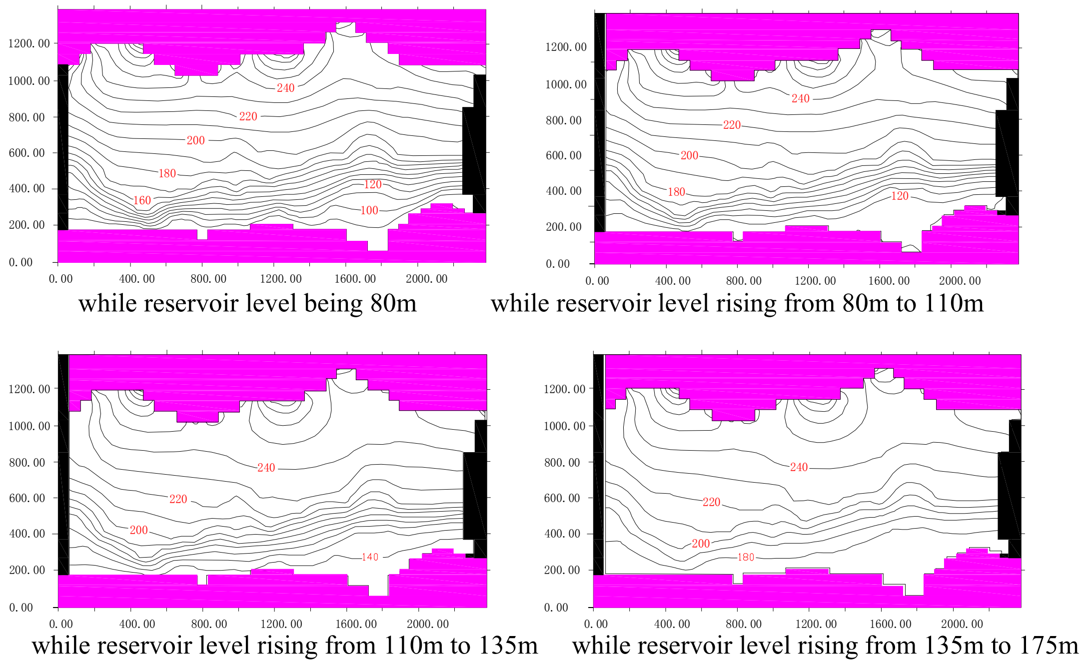

Figure 3. The contours of groundwater levels acorrding to the computed model

CONCLUSIONS

Based on the analysis and studies on geological and hydrologeological conditions of the bank slope, a typical representative section was selected, a vivid hydrogeological conception model and simulation model was built making use of 3D-Modflow software to simulate and study the dynamic variation characteristics of the groundwater seepage field in the reservoir bank slope during the process of impoundment and operation. As a whole, the regulations are as following:

(1) In the simulation section, the distribution of groundwater levels is extremely similar to the terrain; the groundwater level will rise or decline in accordance with the terrain, but its range of variation is slightly less than the terrain.

(2) In the distribution section of water-rock enriched formation (carbonate rocky area, with a thinner cover layer), the groundwater flows rapidly and the distribution of water levels scatters rarely. While in the distribution section of weak permeable water-rock formation and relative aquiclude formation (with thick loose deposits, the bedrock is mainly of mudstone and claystone), the situations are opposite.

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