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Dam Seepage Monitoring Model Based on Dynamic Effect Weight of Reservoir Water Level

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\textbf{Abstract}

For the lag effect of reservoir water level in dam seepage monitoring, through in-depth theoretical analysis, it is concluded that the nature of problem is that seepage field at a certain time is an instantaneous result of all previous reservoir water levels interaction, and effect weight of every reservoir water level not only relates to state properties of dam, but also relates to itself, such as size, change rate etc. By introducing the concept of reservoir water level effect proportion, dynamic effect weight of reservoir water level is obtained and a dam seepage monitoring model based on dynamic effect weight of reservoir water level is put forward, which additionally considers the effect of reservoir water level on effect weight. Examples show that the dam seepage monitoring model based on dynamic effect weight of reservoir water level more tally with the actual and its accuracy is higher.

\textbf{Keywords}: seepage lag; reservoir water level; dynamic effect weight; effect proportion; equivalent reservoir water level;

\section{1. Introduction}

After dam is completed and begins water storage, once its seepage state appears lesions, it becomes abnormal or dangerous. Therefore, it is very important to strengthen dam seepage monitoring and improve the theory and method of monitoring. As is well known, reservoir water level, rainfall, temperature, etc. are all factors that affect dam seepage, of which reservoir water level is main, but its effect has a certain lag\textsuperscript{1,2}. It makes a great difference for improving seepage monitoring theory and

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evaluating dam seepage state to research the reasons of reservoir water level lag effect and how to reflect the lag effect in seepage monitoring.

At present, there are two main ways to reflect the reservoir water level lag effect in seepage monitoring as follows: (1) The previous average reservoir water level method, which uses several previous average reservoir water levels as impact factors of statistical model\(^{[3,4]}\). The method is simple and practical, but in real applications sometimes even the previous month average reservoir water level is elected into statistical model, and finally, it is difficult to explain it. In fact, average is a more general concept. (2) The equivalent reservoir water level method based on the lag effect function, which takes all previous reservoir water levels into account, and through using a lag effect function to measure their effect weight, a equivalent reservoir water level is obtained as a impact factor of statistical model\(^{[5-7]}\). The method not only takes all previous reservoir water levels into account, but also gives the effect amount of every previous reservoir water level. Compared to the former, the method is more reasonable and scientific. However, it is unreasonable to only use a static permanent lag effect function to measure effect weight of previous reservoir water levels all the time.

Based on the above discussion, by introducing reservoir water level dynamic effect weight, a new expression of equivalent reservoir water level is obtained. Therefore, a more rational dam seepage monitoring model is established, which is better able to describe dam seepage process under changing reservoir water level.

2. Basic principle

2.1. Dynamic effect weight

Main reason for seepage lag is that water pressure transfer and water-filling of non-saturated body (or water dissipation of non-pressure saturated body) need time. Because the velocity of water pressure transfer is very fast, the lag time caused by it can be ignored. Water-filling of non-saturated body (or water dissipation of non-pressure saturated body) is caused by unsteady seepage, which is main reason for seepage lag. The time needed by it is decided by the velocity and volume of water-filling or water dissipation. The faster the velocity and the smaller the volume, the shorter the time needed.

The velocity of water-filling or water dissipation mainly relates to anti-seepage properties of seepage media, that is permeability coefficient. Permeability coefficient is mainly decided by the nature of seepage media, but permeability coefficient for the same media is different in different stress conditions. The greater the effective compressive stress in media, the smaller permeability coefficient, Therefore, when considering the lag effect of reservoir water level, fluid-solid coupling should be considered. For seepage media such as dam body or dam foundation that mainly bears compressive stress, when reservoir water level increases, the pore water pressure increases and the corresponding effective stress decreases, which leads to increase of permeability coefficient. Therefore, the higher reservoir water level is, the shorter the lag time is. On the other hand, the volume of water-filling or water dissipation mainly relates to the degree of seepage instability, and seepage instability is mainly decided by the change rate of reservoir water level. The greater the change rate of reservoir water level, the greater seepage instability and the bigger the volume of water-filling or water dissipation. Therefore, the greater the change rate of reservoir water level is, the longer lag time is.

Seepage lag is only a visible phenomenon, whose cause is that seepage field of dam body, dam foundation, bank slope, etc. at a certain time is not a result of reservoir water level alone effect at the same time, but a instantaneous result of all previous reservoir water levels interaction. The interaction can be seen as weighted stack of them, which is same as the equivalent reservoir water level method based on the lag effect function. However, through the above analysis of the reasons for seepage lag, it can be
found that effect weight of every reservoir water level not only relates to state properties of dam body, dam foundation and bank slope, etc. but also relates to itself, such as size, change rate etc. The equivalent reservoir water level method based on the lag effect function ignores the latter, which regards the effect weight of reservoir water level as static and permanent. The method based on dynamic effect weight can consider the effect of reservoir water level on effect weight, and the model that is established by it is more realistic.

2.2. Effect proportion

To reflect the effect of reservoir water level on effect weight, it is necessary to introduce the concept of reservoir water level effect proportion. Reservoir water level at a certain time has effect on all subsequent seepage fields, and this effect should firstly increase and then decrease. The proportion of the effect on seepage field at a certain time in overall effect of the reservoir water level is referred to as effect proportion of the reservoir water level at the moment. The distribution of effect proportion should also be firstly increases and then decrease, with a maximum, and the sum of effect proportion should be equal to 1. The distribution of reservoir water level effect proportion is roughly shown in Figure 1.

\( P_t(t) \)

Fig.1. Distribution of reservoir water level effect proportion

By the distribution of reservoir water level effect proportion, the whole effect process of reservoir water level on dam seepage can be clearly understand, and its lag days and effect days can be also known. Refering to the equivalent reservoir water level method based on the lag effect function, the distribution \( P_t \) of reservoir water level effect proportion at time \( t \) can be taken as normal or Rayleigh distribution, as follows:

(a) Normal distribution

\[
P_t = \frac{1}{\alpha} \frac{1}{\sqrt{2\pi x_2}} e^{-\frac{(t_0-\alpha)^2}{2x_2^2}} \quad (\alpha = \int_0^{+\infty} \frac{1}{\sqrt{2\pi x_2}} e^{-\frac{(t_0-\alpha)^2}{2x_2^2}} dt_0) \tag{1}
\]

Where \( \alpha \) is a coefficient, for reservoir water level at time \( t \), lag days \( x_1 \) and effect days \( x_2 \) are all constants, thus, \( \alpha \) is also constant; \( x_1 \) is lag days of reservoir water level at time \( t \); \( x_2 \) is effect days of reservoir water level at time \( t \).

(b) Rayleigh distribution

\[
P_t = -\frac{2}{\mu^2} \left( \frac{t_0}{\mu} \right)^2 e^{-\frac{t_0^2}{2\mu^2}} \tag{2}
\]
Where $\mu$ is a parameter, $\mu > 0$, the greater $\mu$, the gentler the density distribution curve shown in eq.(2). Physical meaning of $\mu$ is the maximum lag days of reservoir water level at time $t$.

The numeric area of $t_0$ in above two distributions is $[0, +\infty)$, and $t_0 = 0$ in the beginning for every reservoir water level, which means that reservoir water level at time $t$ has effect on all subsequent seepage fields. The parameters $x_1, x_2, \mu$ not only relate to state properties of dam, but also relate to size of reservoir water level this time. When state properties of dam don’t change, these parameters in distribution of effect proportion only vary with size of reservoir water level, that is to say reservoir water levels of different sizes have different distributions of effect proportion. These parameters can be obtained by optimization calculation aiming for maximum multiple correlation coefficient in analysis.

2.3. Equivalent reservoir water level

With reservoir water level effect proportion, following the mechanism of interaction, equivalent reservoir water level can be obtained by stacking all reservoir water level effect proportion at the same time. The equivalent reservoir water level at time $t_0$ is:

$$H_u(t_0) = \int_{-\infty}^{t_0} \alpha(t_0, t) P_t(t_0) H(t) dt$$

(3)

Where $\alpha(t_0, t)$ is correction factor of effect weight of reservoir water level at time $t$ on seepage field at time $t_0$. Correction consists of two aspects. The first is that there are some factors such as reservoir water level change rate which are yet taken into account. The second is that the sum of all weights must be 1; $P_t(t_0)$ is effect proportion at time $t_0$ of reservoir water level at time $t$; $H(t)$ is reservoir water level at time $t$.

The product of $\alpha(t_0, t)$ and $P_t(t_0)$ is effect weight of reservoir water level at time $t$ on seepage field at time $t_0$. $\alpha(t_0, t)$ and $P_t(t_0)$ all vary with reservoir water level, so the product could reflect that effect weight is dynamic. Only considering the effect of reservoir water level size, the effect of every reservoir water level is independent. In addition, if $P_t$ is also permanent, the above equivalent water level degenerates to the expression form by using static effect proportion in the equivalent reservoir water level method based on the lag effect function. Therefore, the equivalent reservoir water level obtained by considering reservoir water level changes is more comprehensive, and can better reflect the nature of the lag effect.

3. Engineering example

There is a roller compacted concrete gravity dam. Its maximum height is 113.0m, and its total capacity is 2.035 billion m$^3$. Bedrock is the early Yanshanian biotite granite with medium-fine-grained texture and massive structure, whose rock is dense and hard. The permeability of bedrock is weak. The two piezometric tubes No.9 and No.19 in dam section No.9 located in the middle of riverbed are selected for analysis. The analysis period is from 2003 to 2008.

Because of the low rainfall at the dam site and the measuring points locating in the middle of the riverbed, the effect of rainfall is tiny and can be ignored in statistical model. The model is as follows:

$$Y = b_0 + b_1 H_u + b_2 H_d + \sum_{i=1}^{2} b_i \sin \frac{2\pi it}{365} + b_2 \cos \frac{2\pi it}{365} + b_3 \theta + b_4 \ln \theta$$

(4)

Where $H_u$ is equivalent reservoir water level; $H_d$ is downstream water level; $t$ is the cumulative days from start date to monitoring date; $\theta = \pi/100$; the others are coefficients.

To simplify calculation, only the size of reservoir water level is taken into account when calculating equivalent reservoir water level. Normal distribution and Rayleigh distribution are respectively used as
the distribution of effect proportion, and static and dynamic effect weights are all used. The static effect weight here doesn’t consider effect of reservoir water level, degenerating to the expression form in the equivalent reservoir water level method based on the lag effect function, and the optimized distribution of effect proportion should belong to the comprehensive water level in analysis period. In addition, to further simplify calculation, when using the dynamic effect weight, reservoir water levels in analysis period are divided into two types by their size, which are high water level and low water level and have respectively a unified distribution of effect proportion. The optimized distributions of effect proportion should respectively belong to the high water level and the low water level. The results are shown in Table 1:

Table 1. Regression analysis results of the two piezometric tubes No.9 and No.19

<table>
<thead>
<tr>
<th>No.</th>
<th>Distribution type</th>
<th>Parameter</th>
<th>Static effect weight</th>
<th>Dynamic effect weight</th>
</tr>
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<td></td>
<td></td>
<td></td>
<td>Comprehensive water level</td>
<td>Multiple correlation coefficient</td>
</tr>
<tr>
<td>9</td>
<td>Nomal</td>
<td>$x_1$</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$x_2$</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Rayleigh</td>
<td>$u$</td>
<td>4</td>
<td>19</td>
</tr>
<tr>
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<td></td>
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<td>$x_2$</td>
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<td>25</td>
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<tr>
<td></td>
<td>Rayleigh</td>
<td>$u$</td>
<td>5</td>
<td>22</td>
</tr>
</tbody>
</table>

Table 1 shows that: (1) The final results is similar, no matter normal distribution or Rayleigh distribution is used as the distribution of reservoir water level effect proportion, which is decided by state properties of dam. However, the multiple correlation coefficient of the former is greater than the latter, which may be due to normal distribution has two adjustable parameters to fit better to the real distribution of effect proportion. (2) The multiple correlation coefficient obtained by using dynamic effects weight is greater than the one obtained by using the static effect weight, which proves that the seepage monitoring model based on dynamic effect weight of reservoir water level is more accurate. (3) There is really great difference between the optimized distributions of high and low water level effect proportion. The effect of the high water level comes faster and goes faster, with greater peak, and the low water level is just contrary. The optimized distribution of the comprehensive water level effect proportion obtained by using static effect weight, regardless of reservoir water level, is just in the middle. So the seepage monitoring model based on dynamic effect weight of reservoir water level more tally with the actual. The optimized distributions are shown in Figure 2-3. The distributions of high and low water level effect proportional shown in solid line corresponds with the method based on dynamic effect weight, and the distribution of comprehensive water level effect proportional shown in dotted line corresponds with the method based on static effect weight.
4. Conclusion

Through analysing the reasons for seepage lag, it is concluded that seepage field at a certain time relates to all previous reservoir water level, and their effect weight not only relates to state properties of dam, but also relates to itself, such as size, change rate etc. and should be dynamic. For the same dam, the distribution of reservoir water level effect proportion should not be permanent, but should vary with reservoir water level. Therefore, the method based on the dynamic effect weight considers the effect of reservoir water level. Examples show that the dam seepage monitoring model based on dynamic effect weight of reservoir water level more tally with the actual and its accuracy is higher.

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