Analysis and Peak Value Prediction of Rainfall Component Factors Influencing Seepage Flow for Homogeneous Earth Dams

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Abstract: The rainfall component of seepage flow is an important indicator for monitoring earth dam safety. Compared with previous practice of only analyzing rainfall, this paper divides the analysis dimensions into three categories according to the seepage process in the process of rainfall: the saturation permeability coefficient of the soil receiving the rainfall, the rainfall intensity and rainfall duration. This paper conducted FE simulation according to the principle of unsaturated seepage flow, and it is concluded that: the influence of different rainfall intensity on seepage flow is roughly linear and can be expressed by a first power factor; the influence of different saturation permeability coefficient and rainfall duration on seepage flow is obviously nonlinear, and should be expressed by multiple powers. Based on the above law, the model expression of peak seepage flow prediction was established, and both the fitting effect and prediction accuracy were good. The results show that the law of influence factors has been summarized correctly, and the research result can provide effective theoretical support for the seepage flow monitoring and early warning and safety monitoring for homogeneous earth dams.

1. Introduction
There are 98,002 reservoir dams in China, more than 90% of which are earth dams. According to statistics, since the first record of dam failure in 1954, there have been over 3,500 dam failures in China. As shown in the National Register of Reservoir Dam Failures, the number of earth dams collapsed in China accounted for more than 98% of all dam types. The causes of earth dam failure include overtopping, seepage failure and insufficient foundation shear strength. Among them, accidents caused by seepage damage accounted for 37.1%. The safety of earth dams is the key to the safety of reservoir dams, and the seepage flow analysis and peak prediction for earth dams are one of the main ways to monitor and judge the seepage safety of earth dams[1, 2].

The origins of peak seepage flow can be divided into three categories: rainfall[3], upstream water level rise[3], and dam body damage[4]. The study on the rainfall component of seepage flow is very important to the seepage safety of dams. At present, the calculation mechanism of rainfall seepage flow peak value is not clear[5], and the method used to calculate such peak value is mainly to establish a prediction model based on the current day and multi-day average rainfall. The disadvantage of this
method is that the influence of multi-dimensional elements of rainfall on seepage flow has not been taken into account. Rainfall processes of the same amount may produce seepage flows that differ significantly due to different rainfall intensity and duration, and different saturation permeability coefficient of the soil receiving the rainfall.

Based on the above background, the unsaturated seepage theory and FE method were used in this paper to deeply study the influencing factors and influencing laws of the seepage flow process caused by rainfall, and to establish the prediction expression based on the influencing laws, providing reliable theoretical support for the seepage flow monitoring and early warning and safety monitoring of earth dams.

2. Preliminary analysis

The unsaturated Darcy's law is substituted into the seepage continuity equation, with the water density taken as constant. The saturation-unsaturated seepage differential equation expressed by the pressure water head can be obtained as follows:

$$\frac{\partial}{\partial x_i} \left[ k_{ij} (h_c) \frac{\partial h_c}{\partial x_j} + k_{ij} (h_c) \right] + Q = \left[ C(h_c) + \frac{\theta}{n} S_w \right] \frac{\partial h_c}{\partial t}$$

(1)

Where $k_{ij}$ is saturation permeability tensor, $h_c$ the pressure head, $k_r(h_c)$ the ratio relative to saturation permeability coefficient, $Q$ the source sink term, $C(h_c)$ the water capacity, $\theta$ the water content, $n$ the porosity, and $S_w$ the water storage per unit. In the calculation in this paper, the source sink term only includes rainfall.

The process of rainfall producing seepage flow can be divided into two stages: the first stage is the surface infiltration of rain, in which the infiltration rate, rainfall intensity and rainfall duration are the decisive factors affecting the amount of rain infiltrated into the soil body; the second stage is the infiltration within the soil body, in which the permeability coefficient is the main influence factor of seepage flow. The influencing factors of the whole process include infiltration rate, rainfall intensity, rainfall duration and permeability coefficient. The value of infiltration rate is related to the infiltration boundary, which can be divided into flow boundary and head boundary. When the rainfall intensity is less than the saturation permeability coefficient of the dam body, the rainfall will increase the saturation of the surface of soil body, but will not saturate it, the infiltration rate is always equal to the rainfall intensity, and the infiltration boundary condition is the flow boundary. When the rainfall intensity exceeds the saturation permeability coefficient of the dam body, the rain begins to infiltrate fully into the soil body, and then the surface soil body reaches saturation in a short time, part of rainwater flows into the soil body, the remaining forms surface runoff, some water remains on the surface, and the infiltration boundary condition becomes the head boundary[6]. In the examples selected in this paper, the local maximum rainfall intensity of the earth dam of the area is less than the permeability coefficient of the dam body, so the flow boundary was selected, that is, all rainwater penetrates into the soil body. Therefore, in this paper, the influence law of saturation permeability coefficient, rainfall intensity and rainfall duration on the peak value of seepage flow rainfall component was studied, and a quantitative refined prediction model expression based on the relevant law was established.

3. Multi-dimensional analysis of influencing factors of rainfall component

3.1. Engineering overview and calculation model

In order to study the influence mechanism and law of multi-dimensional influencing factors of rainfall on seepage flow, a FE element model of foundation and dam body is established in a generalized way with a homogeneous earth dam as prototype.

The dam body section is 6m at the top and 247m at the bottom in width, and 24m high. The upstream slope ratio is 1:5 and 1:6, and the downstream slope ratio is 1:4 and 1:5. The foundation thickness is 20m, as shown in Figure 1. The dam has a head of 18m upstream, and no water
downstream. The maximum rainfall intensity at the site of the dam is 50mm in 12h, the permeability coefficient of the dam is taken as $2.32 \times 10^4$ cm/s, and the permeability coefficient of the foundation is taken as $4.87 \times 10^4$ cm/s, as the rainfall intensity is constantly less than the permeability coefficient, flow boundary was taken as the rainfall boundary, which means that all rainwater penetrates into the soil body. According to the typical section of the dam body, the FE numerical model was established. The upstream dam slope bc and upstream dam slope df were set as the boundary of water level, bagf was set as the impermeable boundary, and that above the infiltration line set as the rainfall boundary. The calculation model was divided into 2357 nodes and 2212 units, as shown in Figure 2.

3.2. Influencing factors
The influencing factors of dam seepage flow mainly include permeability coefficient, rainfall intensity and rainfall duration, so simulation calculation and analysis were carried out respectively for them.

3.2.1. Influence of saturation permeability coefficient.
According to Darcy's law, there is a linear relationship between the seepage flow and permeability coefficient in the saturated and unsaturated soil water. The saturation permeability coefficient is a constant value, while in unsaturated soil water, the permeability coefficient changes dynamically with water content. In order to simplify the prediction model factor, the relationship between seepage flow and saturation permeability coefficient in unsaturated soil water was studied in this paper. Therefore, unsaturated seepage theory and FE method were used to calculate the seepage flow variation of the earth dam under different saturation permeability coefficients. The combination of permeability coefficients is shown in Table 1. The variables rainfall intensity and duration were selected as 35mm (12h rainfall) and 12h, respectively. The seepage flow variation curves of the combinations are shown in Figure 3. Rainfall increases the water content in the soil body, and the dynamic change of permeability coefficient with water content can be simulated by a nonlinear function. Suppose the permeability coefficient of unsaturated soil water is in nonlinear relation of saturation permeability coefficient, that is, the seepage flow $q$ and saturation permeability coefficient $k$ are in a power relationship, as shown in Equation (2).

$$q = f \cdot k^j$$

Table 1. Combinations of permeability coefficients.

| Combination Application Ratio | Saturation permeability coefficient ($\times 10^4$ cm/s) |
|-----------------------------|--------------------------------|
| Dam body                    | Foundation                     |
| a:b                         | 1:5                            |
| c:d                         | 1:4                            |
| e:f                         | 1:5                            |
|     |     |     |     |
|-----|-----|-----|-----|
| 1   | 1   | 2.32| 4.87|
| 2   | 0.5 | 1.16| 2.44|
| 3   | 0.75| 1.74| 3.65|
| 4   | 0.9 | 2.09| 4.38|
| 5   | 1.2 | 2.78| 5.85|
| 6   | 1.5 | 3.48| 7.31|
| 7   | 1.8 | 4.18| 8.77|
| 8   | 2   | 4.64| 9.74|
| 9   | 0.8 | 1.86| 3.90|
| 10  | 1.6 | 3.71| 7.80|
| 11  | 1.1 | 2.55| 5.36|

Figure 3. Comparison of seepage flow with permeability coefficients of all combinations

3.2.2. Influence of rainfall intensity.
To study the influence of rainfall intensity on seepage flow, the intensity of 12h rainfall of 15mm, 25mm, 35mm, 45mm and 50mm was selected, the variables saturation permeability coefficient and rainfall duration were selected as combinations 1 and 12h in Table 1, respectively, to calculate the seepage flow under different conditions of rainfall intensity. The comparison of the calculated values is shown in Figure 4. The differences between seepage flows are shown in Figure 5. Comparison of the trend lines in the figure shows that, the differences of rainfall intensity between 25-15, 35-25 and 45-35 are almost the same, roughly 2 times the difference between 50-45. This indicates that in unsaturated soil water, the seepage flow $q$ and rainfall intensity $\alpha$ are in the first power relation, as shown in Equation (3).

$$q = \lambda \cdot (\alpha - \omega)$$  \hspace{1cm} (3)

where: $\lambda$ is the correction factor to the rainfall intensity, and $\omega$ the rainfall intensity factor.
3.2.3. Influence of rainfall duration.

To study the influence of rainfall duration on seepage flow, the rainfall durations of 8h, 12h, 16h, 20h and 24h were selected, the variables saturation permeability coefficient and rainfall intensity were selected as combinations 1 and 35mm (rainfall of 12h) in Table 1, respectively, to calculate the seepage flow under conditions. The comparison of calculated values is shown in Figure 6. The differences between seepage flows are shown in Figure 7. The comparison of calculated values and difference trend curves shows that the seepage flow and rainfall duration are in obvious non-linear relation. Therefore, the seepage flow $q$ and rainfall duration $t$ in unsaturated soil water can be assumed to be in a power relation, as shown in Equation (4).

$$q = r \cdot t^s$$  \hspace{1cm} (4)

where: $r$ is the correction factor to the rainfall duration, and $s$ the rainfall duration factor.

From the above analysis, it can be concluded that the influence of different rainfall intensity on seepage flow is roughly linear, and the seepage flow $q$ can be expressed by the first power of rainfall intensity $\alpha$; the influence of different saturation permeability coefficients and rainfall duration on seepage flow is obviously nonlinear, and it can be expressed by the power of saturation permeability coefficient $k$ and rainfall duration $t$. Therefore, the peak value of seepage flow $q$ caused by rainfall can
be expressed as a function of the above influencing factors as independent variables, as shown in Formula (5).

\[ q = m \cdot k' \cdot t' \cdot (\alpha - \omega) \]  

(5)

Where: \( m = f \cdot \lambda \cdot r \), being the correction factor; and the meanings of \( f, j, \lambda, \omega, r, s \) are the same as above.

4. Seepage flow peak value prediction model

4.1. Establish expression

On the basis of the law summarized above and the function model, 25 sets of data of seepage flow peak value, saturation permeability coefficient, rainfall intensity and rainfall duration of the homogeneous earth dam model were used to establish the prediction model expression. The data are shown in Table 2. The nonlinear fitting of data was realized by using the least square method, to establish the prediction model as shown in Equation (6). The value of seepage flow calculated by this formula is shown in the right-most column of Table 2. Correlation analysis was carried out for this model, and the regression coefficient is 0.9995. It can also be seen from the comparison of the two curves in Figure 8 that the expression has produced a good fitting effect.

\[ q = 0.003665886 \cdot k^{0.9871} \cdot \alpha^{0.0897} + 450.06825 \]  

(6)

Table 2. Comparison of the seepage flow peak value of an earth dam and the fitted values.

| S/N | Combination of saturation permeability coefficients | Rainfall intensity (mm/12h) | Rainfall duration (h) | Seepage flow (×10^3 L/s) | Seepage flow of fitting formula (×10^3 L/s) |
|-----|---------------------------------------------------|-----------------------------|-----------------------|--------------------------|--------------------------------------------|
| 1   | 1                                                 | 35                          | 8                     | 1.62                     | 1.69                                       |
| 2   | 1                                                 | 35                          | 12                    | 1.70                     | 1.75                                       |
| 3   | 1                                                 | 35                          | 16                    | 1.71                     | 1.80                                       |
| 4   | 1                                                 | 35                          | 20                    | 1.77                     | 1.84                                       |
| 5   | 1                                                 | 35                          | 24                    | 1.84                     | 1.87                                       |
| 6   | 1                                                 | 15                          | 12                    | 1.62                     | 1.68                                       |
| 7   | 1                                                 | 25                          | 12                    | 1.66                     | 1.72                                       |
| 8   | 1                                                 | 45                          | 12                    | 1.74                     | 1.79                                       |
| 9   | 1                                                 | 50                          | 12                    | 1.76                     | 1.81                                       |
| 10  | 2                                                 | 35                          | 12                    | 0.85                     | 0.89                                       |
| 11  | 3                                                 | 35                          | 12                    | 1.27                     | 1.32                                       |
| 12  | 6                                                 | 35                          | 12                    | 2.55                     | 2.62                                       |
| 13  | 8                                                 | 35                          | 12                    | 3.39                     | 3.48                                       |
| 14  | 1                                                 | 35                          | 10                    | 1.65                     | 1.73                                       |
| 15  | 1                                                 | 35                          | 14                    | 1.70                     | 1.78                                       |
| 16  | 1                                                 | 35                          | 18                    | 1.74                     | 1.82                                       |
| 17  | 1                                                 | 35                          | 22                    | 1.79                     | 1.85                                       |
| 18  | 1                                                 | 5                           | 12                    | 1.59                     | 1.65                                       |
| 19  | 1                                                 | 10                          | 12                    | 1.61                     | 1.66                                       |
| 20  | 1                                                 | 20                          | 12                    | 1.64                     | 1.70                                       |
| 21  | 1                                                 | 30                          | 12                    | 1.68                     | 1.74                                       |
| 22  | 1                                                 | 40                          | 12                    | 1.72                     | 1.77                                       |
| 23  | 4                                                 | 35                          | 12                    | 1.53                     | 1.58                                       |
| 24  | 5                                                 | 35                          | 12                    | 2.03                     | 2.10                                       |
| 25  | 7                                                 | 35                          | 12                    | 3.05                     | 3.13                                       |
4.2. Check of expression

The saturation permeability coefficient, rainfall intensity and rainfall duration not having appeared in the modeling process were randomly combined into three sets of parameters, which were then substituted into the prediction formula (6) established above to calculate the predicted values, and also to compare with the real values to check the accuracy of the model. It has been shown in practice that the relative error between the predicted values calculated from three sets of random parameters and the true values is within 3.9%, so the expression established in this paper can accurately predict the seepage flow values.

| Test No. | Combination of saturation permeability coefficients | Rainfall intensity (mm/12h) | Rainfall duration (h) | Seepage flow ($\times 10^3$ L/s) | Seepage flow of fitting formula ($\times 10^3$ L/s) | Relative error (%) |
|----------|---------------------------------------------------|-----------------------------|----------------------|---------------------------------|---------------------------------|-------------------|
| 1        | 9                                                 | 32.5                        | 9                    | 1.32                            | 1.36                            | 3.5               |
| 2        | 10                                                | 26.5                        | 10.5                 | 2.61                            | 2.71                            | 3.6               |
| 3        | 11                                                | 48.5                        | 13                   | 1.92                            | 2.00                            | 3.9               |

5. Conclusions

(1) To analyze the influence of rainfall on the seepage flow of homogeneous earth dams, compared with previous practice of only analyzing rainfall, this paper has, according to the process of seepage flow produced in the rainfall process, divided the analysis dimensions into: the saturation permeability coefficient of the soil receiving the rainfall, the rainfall intensity and rainfall duration.

(2) With a homogeneous earth dam as the prototype, a FE element model of foundation and dam body was established in this paper, to study the influence mechanism and law of saturation permeability coefficient, rainfall intensity and rainfall duration on seepage flow: The influence of different rainfall intensity on seepage flow is roughly linear and can be expressed by a one power factor; the influence of different saturation permeability coefficient and rainfall duration on seepage flow is obviously nonlinear, and should be expressed by multiple powers.

(3) On the basis of the influence law of relevant factors on seepage flow summarized in this paper, 25 sets of seepage flow peak values were selected to establish a prediction model. Calculation and verification showed that the prediction model in polynomial form has good accuracy, and is concise form and convenient for application. It can provide effective theoretical support for seepage flow monitoring, early warning and safety monitoring of homogeneous earth dams.
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