Geological structure of the dam base as a factor of its reliability during flood periods (Hanoi)

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Abstract. The object of study is a system of protective dams in Hanoi. In the new social and political conditions of Vietnam's transition economy, the transformation of the riverside territories is of great importance for both the city of Hanoi and the country as a whole. A special role is given to the system of dams along the Hanga River (Red), which protect the city from floods. During the long history of construction and operation of the dams in Hanoi, many cases of their damage and destruction are known. The aim of the study is to assess the sustainability of the dams, the possible mechanisms of dam stability loss due to changes in hydrological conditions are examined. By mathematical modeling, the stability of the dam slopes and filtration strength of its base soils are calculated due to an increase in time during flooding hydraulic gradient. This task was solved in the flat setting, meanwhile, filtration modeling was carried out by the finite element method, and the estimation of the dam slopes stability was carried out based on the limit equilibrium method. The mathematical modeling allowed to estimate the dam stability from two positions: 1) change of the dam slope factor safety in time during the flood period; 2) increase of the hydraulic gradient in soils of the dam base during the flood period. The results obtained showed that the reliability of the dam depends both on the thickness of the clay layer at its base and on the duration of flooding. The factors we have identified that affect the stability of dams during flood periods can be used for predicted purposes to assess their reliability.

1. Introduction
In 2005, as part of the VNK05 program, there has been a serious reassessment of the safety of flood protective measures in a changing climate. A number of investment projects were aimed at modernizing existing dam systems in line with the principle of flood risk reduction [1 – 3].

At the same time, special attention was paid to filtration deformations in the dam base soils as one of the main causes (the share of filtration factors influence on the development of dam damage is about 30% [4]), resulting in their destruction [5 – 15].

The object of the study is a system of protective dikes in Hanoi. In the new sociopolitical conditions of Vietnam's transition economy, the transformation and use of riverside territories become very important for the city of Hanoi and the country as a whole. A special role is given to the system of dams along the Hanga River (Red), which protect the city from floods. During the long history of construction and operation of dams in Hanoi, many cases of their damage and destruction are known.
The aim of the study was to assess their stability during flood events. The following tasks have been completed to achieve it:

- mathematical simulation of filtration in the soil of the dam base during the flood period;
- calculation of dam slope stability.

By combining the solutions, it was possible to determine changes in the dam slope factor safety in a non-stationary filtration field over time.

Also, by comparing the obtained as a result of the simulation the value of the pressure gradient with its critical values for soils of the dam base was assessed filtration strength of soils of the dam base.

2. Methods and object

2.1. Object

The territory of Hanoi is located within the dynamic active zone (DAZ) - the "Red River", which is one of the largest tectonic zones in Southeast Asia with a length of more than 900 km. The DAZ in the south of Central Vietnam is covered by sediments of the Bac Bo depression [16, 17], which began to form in the late Miocene.

Typical engineering-geological structure of the riverside territory of Hanoi in the vicinity of the dams is represented by the interchange of sand loams, sands, clay loams, clays, gravel [18,19] (Figure 1).

![Figure 1. Schematic engineering-geological section of the riverside territory of Hanoi near the dam. Engineering-geological elements (figures in white circles): 1 – clay loam, 2 – sand loam, 3 – sand, 4 – clay, 5 – sand, 6 – gravel.](image)

Water consumption in the Krasnaya River at flood peak is quite high, averaging about 30,000 m$^3$/s – 35,000 m$^3$/s with a maximum of 48,000 m$^3$/s. The duration of extreme floods is usually 15-20 days. At the peak of the flood, the river rises to a level of 15 to 20 meters [18].

The Red River dam has a complex and long history and has grown and expanded over hundreds of years (Table 1).

| Years | Dam height (m) |
|-------|---------------|
| 1909  | 10.50         |
| 1915  | 11.20         |
| 1920  | 11.50         |
| 1923  | 12.00         |
| 1924  | 12.80         |
| 1932  | 13.90         |
| 1945  | 15.50         |
| present | 20.00       |
Currently, it is in an unstable condition in many areas due to a lack of substantiation of decisions during its reconstruction. Thus, the body and base of the dam are exposed to the risks of destruction during extreme floods, which is its main function (Figure 2).

![Figure 2. The destruction of the Red River dam](image)

2.2. Dam base fracture mechanism by filtration deformation

It is known that filtration deformations in soil dams can be formed both slowly and extremely rapidly. The fracture mechanism is closely related to water rise, which results are in higher gradients of filtration flow pressure (Figure 3).

The hydrodynamic pressure will increase depending on the flooding time. In the event of a prolonged flood, the filtration pressure in the soils of the dam base may become sufficiently high and then the stability of the dam will be determined by the geological structure of its base [21].

To assess the impact of the geological structure of the dam base on its stability taking into account the impact of filtration flow, it is necessary to combine the theory of groundwater dynamics with appropriate models for calculating the stability of slopes [19, 22].

![Figure 1. Mechanism of dam base collapse during flood. 1 - clay or clay loam 2 – sand](image)

The problem was solved in a flat setting, the filtration modeling was done by the finite element method, and its stability was assessed on the basis of the Morgenstem-Price method [23], which belongs to the class of limit equilibrium methods where the general equilibrium of moments and forces is satisfied [24]. A model of the Coulomb-Mohr soil behavior was used in the calculations, which combines elastic and ideal plastic deformation and linear strength criterion of materials [25].

The final geomechanical scheme used to assess the stability of the dam, taking into account the filtration process, is shown in Figure 4.
As one of the modeling tasks was to estimate the influence of the geological structure of the dam base on its stability, the calculations were performed according to three schemes differing in the clay layer thickness:

- **scheme 1** is clay thickness at the base of the dam - 5m;
- **scheme 2** is clay thickness at the base of the dam - 10m;
- **scheme 3** is clay thickness at the base of the dam - 15m.

### 3. Results and Discussion

The performed mathematical modeling allows to estimate the dam stability from two positions: the first one - based on the analysis of factor safety (Fs) change of the dam slope during the flood period; the second one - based on the analysis of hydraulic gradient increase in the soils of the dam base during the flood period.

#### Change of Fs slope of the dam during the flood.

Analysis of the modeling results showed that with the clay soil thickness of 5 m. (calculation scheme 1), the stability factor (Fs) of the dam slope before the flood is 1.69, that is, it is stable. However, after raising the water level in the river to its maximum level, the dam is destroyed after 4.4 days (Figure 5).

At a thickness of clay soil 10m (calculation scheme 2), Fs slope of the dam before the flood - 1.43. After raising the water level in the river to the maximum mark, the Fs of the dam slope becomes less than 1 for 9 days (Figure 5).

At the power of clay soil 15 m. (calculation scheme 3), Fs slope of the dam before the flood – 1.395. After raising the water level in the river to the maximum level, the dam remains stable for the entire flood period (20 days later Fs=1.060) (Figure 5).

From the results of the performed mathematical modeling, we can see that the stability of the dam depends both on the thickness of the clay layer at its base and the duration of flooding.

Figure 5 shows the dependence of the factor safety on the duration of flooding for a clay layer of different thickness. Its analysis shows that, before the start of flooding, more stability will be provided the slopes of the dam at the base of which there is a low- thickness (5m) clay layer.
During the flood period, the situation will change radically and the durability of the dam will increase as the clay thickness at its base increases.

![Figure 5. Dependence of factor safety on flood duration.](image)

The filtration strength of the dam base was assessed by comparing the characteristics of the filtration fields (pressure gradient) with its critical values for the soils of the dam base.

Figure 6 shows the dependence of hydraulic gradient on flood duration for the clay layer of different thickness. Its analysis shows that at clay thickness of 5 m the value of hydraulic gradient will exceed the critical value in 3.5 days. At clay thickness of 10 m at the base of the dam, the hydraulic gradient will exceed the critical value after 9 days. When modeling according to the third scheme (clay layer thickness at the base of the dam 15 m), the dam will keep stability for the whole period of flooding.

![Figure 6. Change of hydraulic gradient in the soils of the dam base from the flood duration (red line - a critical gradient).](image)

4. Conclusions

1. The geological structure of the soil at the base of the dam plays an important role in ensuring its reliability during flood periods.
2. Changes in the stability of the dam slopes and filtration strength of its base soils, made for clays of different thickness, showed good convergence of results in time.
3. The modeling of the hydraulic gradient showed: a) when clay thickness is 5 m, the hydraulic gradient will exceed the critical value after 3.5 days. The dam slope safety factor will drop below 1 (dam slope will lose its stability) after 4.5 days; b) when clay thickness is 10 m at the base of the dam, the hydraulic gradient will exceed the critical value after 9 days, the dam slope safety factor will drop below 1, also after 9 days; c) when clay thickness is 15 m at the base of the dam, the dam will retain its stability for the whole period of the flood
4. The analysis of the results of the mathematical modeling shows that the stability of the dam depends both on the thickness of the clay layer at its base and on the duration of flooding.
5. Factors identified in mathematical modeling that affect the stability of dams during flood periods can be used for predictive purposes to assess their reliability.

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