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Assessment of the influence of water - level elevation in the reservoir on settlement of the hydroelectric dam

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ABSTRACT

Elevation of the water level in the reservoir is the main reason for the deformation of the hydropower dams. Thus, assessing the influence of this cause on the displacement of construction is extremely necessary, which helps understand the state of dam and evaluate its safety to prevent sudden accidents that damage people and properties. Therefore, the article researches theoretical basis and builds the procedure of data processing in the algorithm of least squares to calculate the subsidence value caused by the influence of water - level elevation on the dam. The monitoring data of Yaly hydroelectric dam at two positions M5 and M26 was used in the experimental calculation. The results indicated that when the highest water level is 515,53 m, the subsidence values caused by this factor at M5 and M26 were 5,2 mm and 0,2 mm, respectively. On the other hand, when the lowest water - level is 491,2 m, the subsidence values caused by this factor at M5 and M26 were -7,7 mm and -1,9 mm, respectively. This demonstrates that the proposed calculating method is entirely feasible, reliable, and suitable for every hydroelectricity dam.

1. Introducion

Deformation monitoring in general and subsidence monitoring is done carefully and elaborately for characteristic and sensitive projects like hydroelectric dams because of the safety of people in the surrounding area. To gain the best effect of monitoring, the complete procedure of observation needs to be given, consisting of designing the monitoring network, choosing of suitable surveying method, measuring accurately and processing data. In all of the above steps, data processing is an essential part of monitoring work, from which the obtained results are used for evaluating the safety of construction projects. However, in reality, data processing is simply an adjustment of network, so the database is insufficiently informative for managers of work to swiftly detect abnormal

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phenomena and early warn potential dangers. Therefore, it is better when the postprocessing, such as analysis of monitoring results is done (Huang et al., 2004; Khanh Tran, Quang Phuc Nguyen, 2010). Assessment of factors' impact on the subsidence of works is one of the primary monitoring results analysis missions.

The external factor that mainly affects deformation is the water - level elevation in the reservoir (Sudip et al., 1995; US.Army Corps of engineers, 2002). Based on this, the article researched the solution of determining the influence of this cause on the subsidence of dams. Investigation of water level effects on the behavior of the dam is a topic in some papers (Leonard and Thayer, 1999; Jean Proulx, 2001). In the past, some documents applied the correlation analysis method to assess the impact of the water - level elevation on the displacement of dams (Dong Ngoc Tran, 2011; Tinh Duc Le, 2012). However, the correlation analysis method showed several disadvantages, such as it only builds the correlation relationship between displacement values and factors causing these movements through a linear function. And if it intends to determine the influence value of each cause on the displacement of works, it is too difficult to calculate. So the application of the correlation analysis method for the above purpose is still limited. It is, hence, necessary to find a comprehensive solution.

To overcome the above limitations, the article proposed an entirely new solution that can be applied all regression functions, even non - linear ones. Using the subsidence polynomial function over time and the available function of the impact rule of the water - level elevation on dams, combining with algorithm of least square, calculating repeatedly many times will find the subsidence value caused by water - level elevation. This solution has not been discussed in any paper. This calculation method allows removing the influent values caused by water - level elevation from the total of the measured subsidence in each cycle. This may help to complete subsidence prediction work more quickly at the cycles when the elevation of water - level unchanged. The practical data of two monitoring points on dam Yaly in Vietnam were tested with a new calculation procedure. The results that are accurate and reliable, further demonstrate the feasibility of the method. It is appropriate for all hydropower dams.

2. Application of correlation analysis method to assess the influence of the water - level elevation on subsidence of dams

To consider the relationship of dependence between the subsidence of work and the water - level elevation in the reservoir, the linear correlation method is used as follows:

2.1. Calculating of correlation coefficient

It supposes that the set of {*Hnuoc*(i), *Si*} (i=1÷n) is two - dimensional random of the subsidence (S) and the water - level elevation in the reservoir (H), so the correlation coefficient (r_{HS}) of these two elements is calculated as the following formula:

$$r_{HS} = \frac{\frac{\sum_i (H_i - \overline{H})(S_i - \overline{S})}{n}}{\sqrt{\frac{\sum_i (H_i - \overline{H})^2}{n}}\sqrt{\frac{\sum_i (S_i - \overline{S})^2}{n}}} \quad (1)$$

$$r_{HS} = \frac{\overline{HS} - \overline{H}\overline{S}}{\sqrt{\overline{H^2} - (\overline{H})^2}\sqrt{\overline{S^2} - (\overline{S})^2}} \quad (2)$$

Where:

$$\overline{H} = \frac{\sum_i H_i}{n}; \overline{S} = \frac{\sum_i S_i}{n}; \overline{HS} = \frac{\sum_i H_i S_i}{n} \quad (3)$$

$$\overline{H^2} = \frac{\sum_i H_i^2}{n}; \overline{S^2} = \frac{\sum_i S_i^2}{n} \quad (4)$$

The correlation coefficient in formula (1) represents the relationship between two random quantities. This coefficient varies between -1 and +1. If S and H exist in the relationship, it is shown by the linear function in form $S = a.H + b$. The nearer the coefficient r_{HS} approaches +1 or -1, the stronger the correlation is. On the contrary, the further the coefficient leaves +1 or -1, the weaker the correlation is. If the coefficient equals zero, then there is no correlation between S and H.

2.2. Assessment of correlation coefficient

Subsidence monitoring for hydroelectric dams is done in periods, so depending on the number of cycles which the data are used for calculating, the reliability of the correlation coefficient is assessed according to two cases:

In the first case, there are fifty cycles and more: the way of evaluation includes two steps as follows:

- Calculate the standard deviation of the correlation coefficient:

$$\sigma_r \approx \frac{1-r^2}{\sqrt{n}} \quad (5)$$

- The relationship between subsidence of dams (*S*) and the water - level elevation (*H*) is established if it satisfies a condition like that

$$|r| \geq 3\sigma_r \quad (6)$$

In the second case, the number of cycles is less than fifty; the way of calculating will be:

- Using the special function that it distributes according to the standard rule, known as Fisher standard:

$$Z = \frac{1}{2} ln \frac{1+r}{1-r} \quad (7)$$

- Variance of quantity Z is calculated as in formula:

$$\sigma_Z \approx \frac{1}{\sqrt{n-3}} \quad (8)$$

With this case, the relationship between subsidence of dams (*S*) and water - level elevation (*H*) is established if it satisfies another condition given as:

$$|Z| \geq 3\sigma_Z \quad (9)$$

2.3. Building of regression function

A single linear regression function is used to display this correlation after assessing the correlation coefficient and establishing a relationship between subsidence values and the water - level elevation. The regression function has the form as:

$$S = aH + b \quad (10)$$

Parameters a, b in regression function (10) are determined through n pairs of observed values (S, H), which are:

$$\{(S_i, H_i)\} = \{(S_1, H_1), \ldots, (S_n, H_n)\} \quad (11)$$

According to the principle of least square, set up n equations like the formula (10) with the condition as follows:

$$\sum_{i=1}^{n} (S_i - aH_i - b)^2 = min \quad (12)$$

Then a linear system of equations is established:

$$\begin{cases} [H^2]a + [H]b - [HS] = 0 \\ [H]a + nb - [S] = 0 \end{cases} \quad (13)$$

Solving the above system of equations (13) and combine with the correlation coefficient r_{HS} in formula (1), two parameters a and b are calculated as follows:

$$a = r_{HS} \frac{\sqrt{\overline{H^2} - (\bar{H})^2}}{\sqrt{\overline{S^2} - (\bar{S})^2}} \quad (14)$$

$$b = \bar{S} - a\bar{H}$$

Comments:

Through theoretical studies about correlation method, it is easy to realize some disadvantages of its as follows:

The correlation method only assesses the dependence between two quantities based on a linear function. Suppose the relationship between the subsidence of dams and the water - level elevation is displayed by a non - linear function. In that case, it is unable to use the correlation method to assess the influence of water - level elevation on the subsidence of works.

The regression function in formula (10) only shows the dependent relationship between the subsidence and the water - level elevation. It means if there is one value of the water - level elevation, a corresponding subsidence value of dam will be calculated. Whereas the measured subsidence of dams is caused by many different factors. Therefore, this method only allows determining the percentage of influence of the water - level elevation on dam. Still, it is impossible to separate the subsidence value caused by the water - level elevation from the total subsidence value. The next section will propose a new calculation procedure that can overcome the correlation method's limitations. This new method allows determining the impact of water - level elevation on dams efficiently, and accurately.

3. Using regression function in determining the influence of the water - level elevation on subsidence of dams

3.1. Theoretical basis

It is assumed that subsidence of hydroelectricity dams is calculated through polynomial function as follows:

$$S_c = a_0 + a_1 t + a_2 t^2 + \cdots + a_n t^n \quad (15)$$

The calculated subsidence is considered to be affected by different factors such as load, temperature, humidity, etc. but without the influence of the water - level elevation. However, the water - level elevation is a primary factor that has the greatest impact on dams. It is necessary to determine this effect. To do this best, we need to know the rule of influence of this element on dams given as follows [US. Army Corps of Engineers, 2002]:

$$S_H = b_0 + b_1 H + b_2 H^2 + \cdots + b_l H^l \quad (16)$$

Where: a_0, a_1, a_2, ...a_n are coefficients in polynomial function that is used to calculate the subsidence of dams; b_0, b_1,..., b_l are coefficients in a polynomial function that is used to calculate the subsidence value caused due to the impact of the water - level elevation; H is the water - level elevation in the reservoir at the time t; n and l are the degree of the polynomial in formula (15) and (16), respectively.

Because the subsidence value that is measured is the sum of the calculated value and subsidence value caused due to the impact of the water level elevation on dams, so it is calculated as follows:

$$S_m = S_c + S_H \quad (17)$$

If the height of water level is approximately equal at different cycles, it will cause a similar subsidence value to each other. When the term "approximate" is mentioned, it means the difference of the water - level elevation among considered cycles is in a range of one meter. To determine the influence of water - level elevation on subsidence of dams, a problem is shown with theory as follows.

It assumes that finding two monitoring cycles i and j at which the height of water level is similar to each other, means:

$$S_{H_i} = S_{H_j} \quad (18)$$

When subtraction between two subsidence values in two cycles is done, the influence of the water - level elevation on subsidence of dams is eliminated, given as:

$$\Delta S_{ij} = S_{c_j} - S_{c_i} \quad (19)$$

Replacing formula (15) with formula (19), the difference of two subsidence values at two periods is given as:

$$\Delta S_{ij} = a_1(t_j - t_i) + \cdots + a_n(t_j^n - t_i^n) \quad (20)$$

If there are several cycles (k) that are bigger than the degree of the equation in formula (20), a system that includes k of equations will be established and solved by the least square principle $[V_{\Delta S}^2] = min$. Coefficients $a_i (i = \overline{1,n})$are easy to be calculated after that. Because at the initial cycle, the subsidence value equals zero, so $a_0 = 0$. Replacing the found values of coefficients a_i in equations like formula (15), the application for all cycles and subsidence (Sc) values are determined. Based on formula (17), the subsidence can be calculated from the impact of the water - level elevation on dams.

After determining S_H, all coefficients b_i are found by using the formula (16). Based on the theory of the above problem, the procedure of calculation will be detailed in the next section.

3.2. Procedure of calculation

From the mentioned theoretical basis, the calculation procedure is built clearly to help the application of the method easier in reality. The two stages below describe the application. It is necessary to calculate repeatedly (usually from two to three times) in each stage until coefficients a and b nearly unchanged.

3.2.1. The first stage: approximate calculation

In the total of cycles that are used to calculate and assess the influence of the water - level elevation on subsidence of dams, choose some processes at which the height of water level is approximately equal to each other, and then doing in the following order:

- Firstly, calculate the difference of measured subsidence values among chosen cycles, determine equations like the formula (20).

- Next, solve a system of equations that were established in the first step with condition that $\left[V_{\Delta S}^2\right] = min$, all coefficients $a_i(i = \overline{1,n})$ are found.

- Then, Replace $a_i(i = \overline{1,n}), a_0 = 0$, in formula (15), the calculating subsidence values Sc are determined in all cycles.

- Finally, the subsidence values that were caused by the impact of the water - level elevation on dams (S_H) are determined. There is a system of equations like formula (16) which is easy to find out coefficient b_i.

Due to approximate calculation, subsidence values obtained from the impact of the water - level elevation on dams have a difference from each other, whether the height of water level in cycles is similar. Therefore, the procedure of calculation has not been finished yet. After a circle of analysis from the four steps, return to do subtraction between the measured subsidence values among chosen cycles firstly and continue other steps. The procedure of calculation is repeated like that until all coefficients a_i and b_i are nearly convergent.

3.2.2. The second stage: standard calculation with condition of $[V_S^2] = min$

This stage includes some steps of calculation as follows:

- After finishing the first stage, there are approximate values of b_i. In each cycle, the subsidence caused by the impact of the water - level elevation on dams S_H is calculated in the formula (16)

- From the formula (17), calculate the values of (S_c) in all cycles

Solving a system of equations like the formula (15), coefficients a_i are determined.

- Similarly, find coefficients b_i after calculating S_c in formula (15), S_H in formula (16). The procedure of calculation is repeated about 2÷3 times.

Note:

The way to determine the degree of a polynomial is as follows:

- Choose the degree of the polynomial in turn, the smallest initial degree equals one (n = 1, l = 1)

- Each time of choosing the degree of a polynomial, it is necessary to do two above stages to determine the coefficients a_i and b_i.

- The selected polynomial is the one whose error of the model is equal to the error of measurement.

4. Experiment of calculating the subsidence caused by impact of the elevation of water - level on dam at yaly hydroelectricity works

To illustrate the theoretical basis and procedure of calculation in the above section, the data of subsidence monitoring of two points on Yaly hydroelectricity dam were used to calculate. Two monitoring points that belong to the Yaly hydroelectricity dam are called M5 and M26. This dam is one of the items of the Yaly hydroelectricity project located in Gia Lai province, Vietnam. Dam Yaly is a kind of rock dam, the waterproof core is clay, the elevation of the peak is 522 m. It includes six flood outlets (Figure 1).

Monitoring data of two points M5 and M26, in fourteen cycles are used for experimental calculation and listed in the Table 1.

Application of calculation procedure in section 3.2 for determining the subsidence value that was caused by the impact of the water - level elevation on monitoring points M5 and M26. With each source of data, the calculation are in two stages ofapproximation and accuracy.

4.1. Results of calculation for M5

4.1.1 Approximate calculation

The iterative process of the calculation was performed three times. The last results are listed in Table 2.

Polynomial functions and error of model given as

$$S_c = -0{,}0416t - 0{,}001t^2 + 0{,}0006t^3 - 0{,}00003t^4$$

$$m_o = 7{,}9\ (mm)$$

$$S_H = 0{,}002 + 0{,}000001t - 0{,}00003t^2.$$

$$m_o = 5{,}7\ (mm)$$

Figure 1. Hydroelectricity dam Yaly.

Table 1. Monitoring data of two monitoring points M5 and M26.

Cycles	Measurement time	Time difference from cycle 0 (year)	The measured subsidence of point M5 (m)	The measured subsidence of point M26 (m)	Elevation of water level
0	08/12/1999	0,0000	0,0000	0,0000	508,66
1	25/04/2000	0,3799	- 0,0185	- 0,0037	514,87
2	27/09/2000	0,8021	- 0,0305	- 0,0069	510,50
3	12/05/2001	1,4276	- 0,0521	- 0,0112	501,02
4	02/12/2001	1,9836	- 0,0730	- 0,0171	515,10
5	15/06/2002	2,5192	- 0,1127	- 0,0247	491,20
6	25/12/2002	3,0466	- 0,1256	- 0,0267	514,15
7	15/08/2003	3,6858	- 0,1514	- 0,0330	510,10
8	29/02/2004	4,2242	- 0,1598	- 0,0336	513,02
9	30/08/2004	4,7269	- 0,1790	- 0,0389	510,00
10	20/11/2005	5,9495	- 0,1988	- 0,0440	515,53
11	01/04/2007	7,3142	- 0,2206	- 0,0480	505,46
12	18/12/2008	9,0274	- 0,2502	0,0000	512,62
13	19/01/2010	10,1135	- 0,2588	- 0,0037	508,48

Table 2. Results of approximate calculation.

Cycles	Subsidence was calculated through the time function (m)	Subsidence from the impact of the water - level elevation (m)	The measured subsidence (m)
0	0,0000	0,0000	0,0000
1	- 0,0159	- 0,0026	- 0,0185
2	- 0,0338	0,0033	- 0,0305
3	- 0,0602	0,0081	- 0,0521
4	- 0,0831	0,0101	- 0,0730
5	- 0,1042	- 0,0085	- 0,1127
6	- 0,1239	- 0,0017	- 0,1256
7	- 0,1458	- 0,0056	- 0,1514
8	- 0,1626	0,0028	- 0,1598
9	- 0,1767	- 0,0024	- 0,1790
10	- 0,2047	0,0059	- 0,1988
11	- 0,2268	0,0062	- 0,2206
12	- 0,2467	- 0,0035	- 0,2502
13	- 0,2601	0,0013	- 0,2588

Comment:

Results in the third iteration are nearly unchanged when compared to the ones in the second iteration. It means all coefficients of two polynomial functions for calculating S_c and S_H are convergent. The degree of the polynomial for S_c and S_H are 4 and 2, respectively.

4.1.2. Standard calculation

After finishing the first stage, it only needs to be calculated two iterative times. Coefficients are swiftly convergent, and influence the water - level elevation on dam that are similar to each other. These will be illustrated clearly by the results in Table 3.

Polynomial functions and error of model given as

$$S_c = -0{,}0403t - 0{,}0023t^2 + 0{,}0008t^3 - 0{,}00005t^4$$

$$m_o = 7{,}4\ (mm)$$

$$S_H = 0{,}002 + 0{,}00003t - 0{,}00002t^2.$$

$$m_o = 5{,}6\ (mm)$$

4.2. Results of calculation for M26

To illustrate the procedure of calculation more clearly and emphasize the effect of the method, monitoring data of the point M26 was used as another test.

The calculation process is similar to the way of M5; results are given as follows (Table 4, 5).

Table 3. Finally results of the second calculation stage.

Cycles	Subsidence was calculated through the time function (m)	Subsidence from the impact of the water - level elevation (m)	The measured subsidence (m)
0	0,0000	0,0000	0,0000
1	- 0,0156	- 0,0029	- 0,0185
2	- 0,0335	0,0030	- 0,0305
3	- 0,0602	0,0081	- 0,0521
4	- 0,0835	0,0105	- 0,0730
5	- 0,1050	- 0,0077	- 0,1127
6	- 0,1250	- 0,0006	- 0,1256
7	- 0,1472	- 0,0042	- 0,1514
8	- 0,1638	0,0040	- 0,1598
9	- 0,1776	- 0,0015	- 0,1790
10	- 0,2040	0,0052	- 0,1988
11	- 0,2239	0,0033	- 0,2206
12	- 0,2438	- 0,0064	- 0,2502
13	- 0,2618	0,0030	- 0,2588

Table 4. Results of approximate calculation.

Cycles	Subsidence was calculated through the time function (m)	Subsidence from the impact of the water - level elevation (m)	The measured subsidence (m)
0	0,0000	0,0000	0,0000
1	- 0,0038	0,0001	- 0,0037
2	- 0,0080	0,0011	- 0,0069
3	- 0,0137	0,0025	- 0,0112
4	- 0,0185	0,0014	- 0,0171
5	- 0,0229	- 0,0018	- 0,0247
6	- 0,0269	0,0002	- 0,0267
7	- 0,0312	- 0,0018	- 0,0330
8	- 0,0346	0,0010	- 0,0336
9	- 0,0376	- 0,0013	- 0,0389
10	- 0,0438	- 0,0002	- 0,0440
11	- 0,0491	0,0011	- 0,0480
12	- 0,0531	0,0002	- 0,0529
13	- 0,0543	- 0,0005	- 0,0548

Table 5. Finally results of the second calculation stage.

Cycles	Subsidence was calculated through the time function (m)	Subsidence from the impact of the water - level elevation (m)	The measured subsidence (m)
0	0,0000	0,0000	0,0000
1	- 0,0038	0,0001	- 0,0037
2	- 0,0079	0,0010	- 0,0069
3	- 0,0137	0,0025	- 0,0112
4	- 0,0184	0,0013	- 0,0171
5	- 0,0228	- 0,0019	- 0,0247
6	- 0,0267	0,0000	- 0,0267
7	- 0,0312	- 0,0018	- 0,0330
8	- 0,0346	0,0010	- 0,0336
9	- 0,0376	- 0,0013	- 0,0389
10	- 0,0438	- 0,0002	- 0,0440
11	- 0,0491	0,0011	- 0,0480
12	- 0,0531	0,0002	- 0,0529
13	- 0,0543	- 0,0005	- 0,0548

4.2.1. Approximate calculation

Polynomial functions and error of model given as

$$S_c = -0{,}0103t + 0{,}0005t^2 + 0{,}0000001t^3$$

$$m_o = 1{,}5 \text{ (mm)}$$

4.2.2. Standard calculation

$$S_H = 0{,}0002 + 0{,}00004t$$

$$m_o = 1{,}3 \text{ (mm)}$$

The calculation test for two monitoring points on hydroelectricity dam Yaly shows that:

- At different elevation, the water level in the reservoir affects dissimilarly the dam. With each water - level elevation, will determine the subsidence due to this cause's influence, respectively.

- Although water level is in the same elevation, it affects dissimilarly different monitoring point of dam, like when the highest water level is 515,53 m, then the subsidence values caused by this factor at M5 and M26 were 5,2 mm and - 0,2 mm, respectively. On the other hand, when the lowest water - level is 491,2 m, then the subsidence values caused by this factor at M5 and M26 were - 7,7 mm and - 1,9 mm, respectively. These results also show that the water - level elevation affected the subsidence of M5 more than the one at M26.

5. Conclusion

The research of the theory and calculation test gives some conclusions as follow:

- It needs to emphasize that the analysis of monitoring results is extremely important and necessary. This aspect helps to improve the effectiveness of data processing. Moreover, the operator and manager of the projects will have a database to assess the state of works better, especially projects are hydroelectricity dams - a kind of characteristic ones that influence the economy and society of the country. Understanding the status of a dam can predict potential risks, and prevent sudden accidents that are dangerous for people and properties.

- Assessment of the influence of factors that cause displacement is one of the main missions of analysis. Many elements affect the displacement of dams, such as temperature, humidity, load, the water - level elevation, etc. However, the water - level elevation is the factor that impacts the biggest on the displacement of the dam. It not only influences the horizontal displacement, but also affects subsidence of the dam. This article answers the question of whether the water - level affects subsidence of dams. Results of tests that are based on a reliable process of calculation clarified this. When this subsidence influence value is determined, finding the way to limit the impact and stop the consequence is easy. So determining the subsidence value due to the effect of the water - level elevation is also convenient to guess the subsidence of the dam in later cycles.

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