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# Forecasting structural displacement based on geodetic monitoring data

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ABSTRACT

*The article studied the methods of structural displacement forecasting that were calculated by the geodetic monitoring data. The good forecasting of movement not only allows to accurately assess correlation between the displacement and the factors that caused the displacement but also helps operators and managers of the projects determine the suitable time for monitoring. The method that was proposed in the article is done based on determining the delay time of the displacement. If the delay time of the displacement is determined, the period of monitoring is chosen more easily and accurately. This method is feasible and suitable with a large number of constructions. Many experiments were applied and had reliable results.*



## 1. Introduction

Structural deformation monitoring is the high-accuracy geodetic work, so in order to ensure the reliability of the monitoring results, it is necessary to apply suitable technical methods in measuring, data processing for the geodetic networks that were established to survey the deformation of structures.

When the pressure on the structure is varied, it always makes the movement of that structure change, too. Normally, changes of works (shows through the displacement value) happen later after the structure was affected by some factors. Unsychronization about time as mentioned is called the delay time of displacement. Determination of the delay time not only accurately assesses the correlation between the displacement and the factors that cause that displacement but also definites the time of monitoring reasonably (Aitsev A. K. et al., 1991; Yashunn V. R., 1989). There are a lot of methods for predicting such as forecasting based on time models, space models (static and dynamic model). However, determining the delay time of the displacement is more easy to apply. The obtained results are not only forecast the structural displacement but also help to choose the period of monitoring accurately, and it is useful to improve the effect of deformation monitoring and analysis.

## 2. Theory about determination of the delay time of structural displacement

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### *2.1. Determining the delay time of the displacement by the correlation coefficient*

In the document (Aitsev et al., 1991), it proposed the method that was used to determine the delay time based on comparing the correlation coefficient, the content of the method was as follows:

Suppose that in monitoring process it is able to obtain two chains of quantitative values at observation periods: a chain of factors that cause displacement $X=\{x_1, x_2,...,x_3\}$ and a chain of movement value $q=\{q_1, q_2,..., q_n\}$.

The correlation relationship between the displacement ($q$) and causes ($X$) was established through the correlation coefficient $r_{(X,q)}$ and calculated by (1):

$$r_{(X,q)} = \frac{M(X,q)}{M(X).M(q)} \quad (1)$$

In which: $M(X)$, $M(q)$ are corresponding to mean square error of $X$, $q$; $M(X,q)$ is the quadratic correlation moment, calculated through (2):

$$M(X,q) = \frac{1}{n-1}\sum_{i=1}^{n}(X_i - \overline{X})(q_i - \overline{q}) \quad (2)$$

Firstly, on the basis of monitoring data, the graph of fluctuation of factors $X$ that cause the displacement and the fluctuation of displacement $q$ is established. Initially, calculate the correlation coefficient between $X$ and $q$ through the monitoring data. Next, move forward the chart of shift from the chart of agents (period of time for moving forward is $\Delta t$) and calculate the new correlation coefficient between $X$ and $q$. At each time of moving forward, there will be a new correlation coefficient. The delay time of the structural movement is the period of time for moving forward of the chart $\Delta t$, until the correlation coefficient is maximum.

### *2.2. Determining the delay time based on the extremes of regression function*

In fact, on the basis of the chain of monitoring results in periods, the regression function is set up to describe both the displacement and causes of shift. In the document (Le Duc Tinh, 2012), the method is proposed to determine the delay time of the structural movement by analyzing and comparing the time when the extremes are achieved in the displacement regression function and the regression function of causes. This idea was hypothesized on the basis of the linear relationship between the displacement and the causes of shift, then from the phase deviation of the time when reaches the extremes in the regression functions, the delay time is determined.

Suppose that the regression function shows the displacement $q=f(t)$, the function of movement causes (example: the fluctuation of water level in the reservoir $H$) is $H=\varphi(t)$. The time when two above functions reach maximum or minimum is determined through solving two differential equations: $f'(t)=0$ and $\varphi'(t)=0$. The corresponding results of two equations are assigned by $t_1$ and $t_2$. Then the delay time of the movement is calculated by the following formula (Figure 1).

$$\Delta t = t_1 - t_2 \quad (3)$$

Calculation process for determining the delay time of displacement by the method of analyzing the extremes of regression function is shown through the following example:

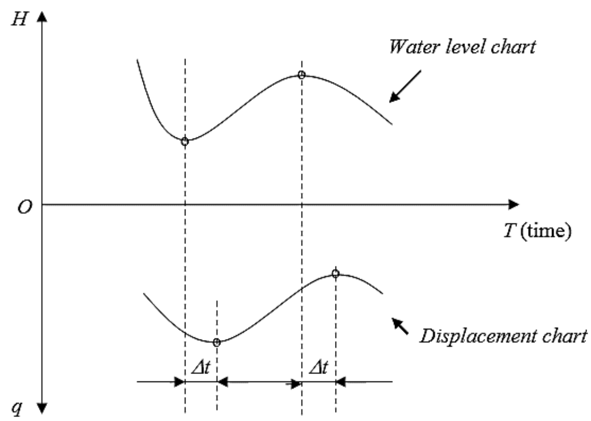


*Figure 1. Structural displacement delay.*

According to the monitoring results in n periods, the displacement ($q$) and the height of water level in the reservoir (H) of a hydropower plant are shown by cyclic regression functions such as (4, 5, 6):

$$q_t = a_0 + a_1.Sin(\omega_1 t) + a_2.Cos(\omega_1 t) + a_3 t \quad (3)$$

$$H_t = b_0 + b_1.Sin(\omega_2 t) + b_2.Cos(\omega_2 t) + b_3 t \quad (4)$$

The function (4) reaches extremes at the time as:

$$t_2 = \frac{\varphi_2 - \alpha_2 + 2k\pi}{\omega_2} \quad (5)$$

With:

$$\alpha_2 = -\frac{b_3}{\omega_2\sqrt{b_1^2 + b_2^2}}; \ Sin\varphi_2 = \frac{b_1}{\sqrt{b_1^2 + b_2^2}}$$

From that, combine with the formula (3) to calculate the delay time:

$$\Delta t = t_1 - t_2 = \frac{\varphi_1 - \alpha_1 + 2k\pi}{\omega_1} - \frac{\varphi_2 - \alpha_2 + 2k\pi}{\omega_2} \quad (6)$$

## 3. The example of calculating the delay time of the hydropower construction displacement

In order to demonstrate for the theoretical basis of the displacement delay determination method in section 2.2, the experiment was made with the displacement monitoring data of an observation point on the Hoa Binh hydropower dam (Hoa Binh hydropower plant, 2005-2011). The horizontal displacements of the monitoring point PVM2 were measured in 59 periods, the monitoring data were shown in Table 1, include: measurement time, the height of water level in the reservoir, the horizontal displacement in the pressure direction (was calculated in comparison with the reference period, shown on 10/1/2005).

*Table 1. The displacement of PVM2 point on the hydropower dam.*

| No | Measurement time | The height of water level | Displacement (mm) | No | Measurement time | The height of water level | Displacement (mm) |
|---|---|---|---|---|---|---|---|
| 1 | 10/1/20005 | 110.29 | 0.0 | 31 | 09/8/2007 | 93.60 | -15.0 |
| 2 | 15/2/2005 | 105.02 | 0.3 | 32 | 29/8/2007 | 111.23 | -11.0 |
| 3 | 8/3/2005 | 101.64 | 0.2 | 33 | 09/10/2007 | 116.46 | -10.3 |
| 4 | 15/4/2005 | 92.39 | 5.7 | 34 | 08/11/2007 | 116.84 | -6.5 |
| 5 | 10/5/2005 | 85.57 | -8.3 | 35 | 10/12/2007 | 116.05 | -7.2 |
| 6 | 2/6/2005 | 78.56 | -9.6 | 36 | 11/1/2008 | 111.80 | -7.2 |
| 7 | 11/7/2005 | 95.12 | -5.7 | 37 | 20/02/2008 | 108.88 | -9.5 |
| 8 | 10/8/2005 | 96.44 | -10.5 | 38 | 20/3/2008 | 104.51 | -13.7 |
| 9 | 31/8/2005 | 113.84 | -4.6 | 39 | 14/4/2008 | 101.47 | -14.4 |
| 10 | 13/10/2005 | 116.59 | -5.2 | 40 | 15/5/2008 | 92.52 | -19.3 |
| 11 | 30/11/2005 | 116.85 | -3.1 | 41 | 12/6/2008 | 85.89 | -20.2 |
| 12 | 17/1/2006 | 116.66 | -3.8 | 42 | 10/7/2008 | 102.07 | -17.2 |
| 13 | 20/2/2006 | 112.22 | -2.3 | 43 | 13/8/2008 | 102.76 | -21.4 |
| 14 | 13/3/2006 | 111.12 | -2.2 | 44 | 03/9/2008 | 106.48 | -13.4 |
| 15 | 6/4/2006 | 94.84 | -4.8 | 45 | 02/10/2008 | 116.65 | -18.7 |
| 16 | 16/5/2006 | 93.95 | -12.3 | 46 | 14/11/2008 | 117.22 | -12.0 |
| 17 | 12/6/2006 | 82.04 | -5.7 | 47 | 11/12/2008 | 116.56 | -11.5 |
| 18 | 13/7/2006 | 98.99 | -4.5 | 48 | 19/01/2009 | 116.13 | -13.0 |
| 19 | 8/8/2006 | 108.00 | -8.9 | 49 | 16/02/2009 | 111.79 | -13.0 |
| 20 | 25/9/2006 | 114.76 | -10.1 | 50 | 05/03/2009 | 109.56 | -16.2 |
| 21 | 09/10/2006 | 116.62 | -4.9 | 51 | 13/4/2009 | 105.62 | -13.6 |
| 22 | 9/11/2006 | 116.64 | -2.5 | 52 | 11/5/2009 | 98.55 | -14.4 |
| 23 | 15/12/2006 | 116.25 | -2.9 | 53 | 11/6/2009 | 90.83 | -17.5 |
| 24 | 16/1/2007 | 114.49 | -1.2 | 54 | 14/7/2009 | 101.15 | -19.0 |
| 25 | 05/2/2007 | 112.10 | 1.0 | 55 | 14/8/2009 | 98.37 | -19.5 |
| 26 | 05/3/2007 | 109.60 | -7.5 | 56 | 15/9/2009 | 110.44 | -20.6 |
| 27 | 09/4/2007 | 101.74 | -11.4 | 57 | 9/10/2009 | 114.22 | -19.7 |
| 28 | 16/5/2007 | 94.84 | -13.6 | 58 | 18/11/2009 | 114.50 | -19.0 |
| 29 | 12/6/2007 | 85.45 | -11.6 | 59 | 7/12/2009 | 116.14 | -21.6 |
| 30 | 09/7/2007 | 97.55 | -13.5 | | | | |

### *3.1. Determining parameters of regression function*

Analyze preliminarily the chart of displacement and the chart of the water level fluctuations in the reservoir through time, and it found that both of two charts are cyclic (Figure 2). The function 4, 5 were used to describe the variation over time of two above components (q and H). On the basis of the monitoring data in table 1, the parameters of regression function (4,5) were obtained by using the least squares method, as following:

*1- The equation shows time-displacement model with parameters:*

$$q_t=-0,81-0,89.sin(0,52.t)+3,59.cos(0,52.t)-0,31.t$$

- Error of model: m = 3.0 mm.
- Amplitude of displacement: T1 = 7.4 mm.
- Period of displacement : P1 = 12.2 months.

*2- The equation expresses time-fluctuation model of the water level height in the reservoir:*

$$H_t=104,07-9,92.sin(0,52.t)+8,94.cos(0,52.t)+0,06.t$$

- The amplitude of water level oscillation: T2 = 26.7m.
- Period of water level oscillation: P2 = 12.15 months.

### *3.2. Determine the displacement delay*

Determination of the delay time of displacement was done by comparison of the time when the function showed the height of water level and the time when the displacement function reached the extremes (Figure 2). Compared data was performed in Table 2 (the time when the function obtained extremes was calculated with unit 'month' and compared relatively with the measurement time of the first period )

Results demonstrated that the delay time of the displacement compared to impact of water pressure in the reservoir in range of 1.2-1.5 months. So it shows that the delay time happens 1.35 months more slowly than the impact of average water level (about 40 days)

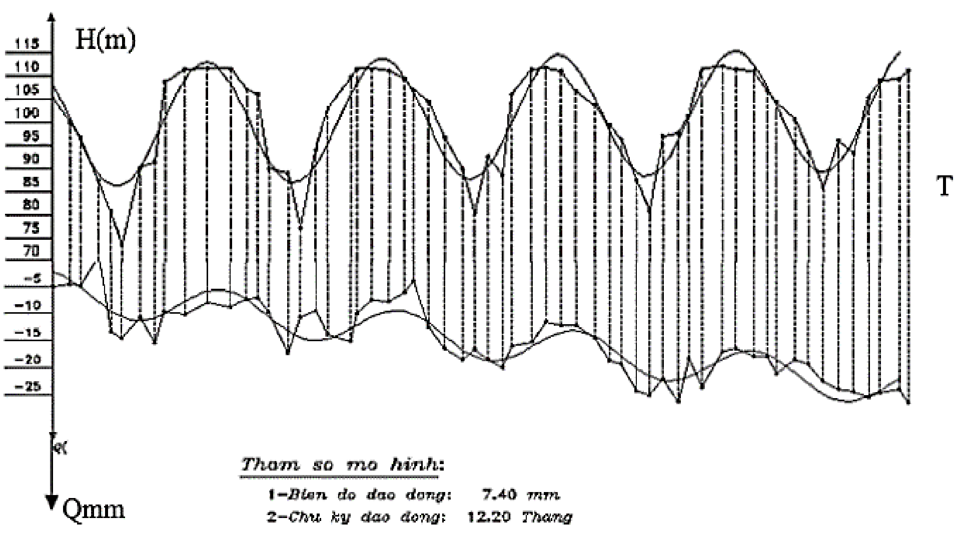


*Figure 2. The displacement graph of monitoring point and the oscilation of water level in the reservoir.*

*Table 2. Compare the extreme time of the displacement function with the cyclic function.*

| Time / Parameter | Time of the model function reaches extremes (month-compared to period 1 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Min | Max | Min | Max | Min | Max | Min | Max | Min |
| Water level | 4.5 | 10.5 | 16.6 | 22.7 | 28.7 | 34.8 | 40.9 | 47.0 | 53.0 |
| Displacement | 5.7 | 11.8 | 17.9 | 24.0 | 30.1 | 36.2 | 42.3 | 48.4 | 54.5 |
| The late time (month) | 1.2 | 1.3 | 1.3 | 1.3 | 1.4 | 1.4 | 1.4 | 1.4 | 1.5 |

## 4. Conclusion

From the results of theoretical studies and examples, some conclusions can be given as following:

- Every construction has its own delay time and the time of monitoring will be determined appropriately based on the delay time. With the Hoa Binh hydropower project, the period of monitoring will be chosen on the 40$^{th}$ day after the dam was affected by the pressure of water in the reservoir. This is the time when the displacement appears and the surveyors are easy to observe the value of movement.

- Research on determination of the delay time that bases on analysis, comparison about the time when reaches the extremes of the displacement regression function and the causes regression function is completely presented in the article and it is comfortable for calculation programming on the computers.

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