MINISTRY OF EDUCATION AND TRAINING
UNIVERSITY OF MINING AND GEOLOGY

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RESEARCH SOLUTIONS FOR IMPROVING THE EFFICIENCY OF DATA PROCESSING IN MONITORING SETTLEMENT AT HYDROELECTRIC DAMS

MAJOR: GEODETIC–CARTOGRAPHIC ENGINEERING
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SUMMARY OF TECHNICAL PHD THESIS

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The thesis has been completed at**: Department of engineering surveying, Faculty of Geodesy-Cartography and Land Management, University of Mining and Geology, HaNoi**

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INTRODUCTION

1. The urgency of the study

Settlement monitoring has been conducted regularly at hydroelectric dams to supervise the state of structures. However, the obtained result is only settlement of hydroelectric dams in each cycle. To improve the efficiency of supervising the dams safety and warn early potential risks, the managers need to be updated more related information such as influence of external factors on settlement of dams or displacement trend of dams in the space and over time. With the request like that, analyzing the observed results is the solution which is proposed to conduct with a view to improving the efficiency of data processing and adapting to the urgent requirement in reality.

2. Target, subject and scope of the study

The target of the study is to establish the scientific basis of the solutions of data processing for improving accuracy and reliability of the subsidence observed results which support efficiently in early warning to prevent and reduce risks of hydroelectric dams. The studied subject is settlement monitoring at hydroelectric dams in Viet Nam. The scope of study is data processing and analysis of the observed results in settlement monitoring at hydroelectric dams.

3. The research contents

Research on building the procedure of data processing of the base network in monitoring the settlement of hydroelectric dams; Determining the settlement caused by the impact of the elevation of water level in reservoir on dams; Study about appliability of Kalman filter in predicting the settlement of hydroelectric dams.

4. Research methodology

Statistical method, analytical method, experimental method, comparative method, mathematical method and computer applications

5. Scientific and practical significance

The thesis contributes to building the theory of processing data of settlement monitoring network system at hydroelectric dams. The obtained results can be used in teaching, researching and production reality.

6. The defended points

- *The first point:* Procedure of processing data based on the stability standard of benchmarks is the effective solution which makes a contribution to handle flexibly the network positioning in settlement monitoring for hydroelectric dams.
- *The second point*: Assessment of the influence of elevation of water level in the reservoir on the settlement of hydroelectric dams and prediction of settlement by Kalman filter help supervision of dams safety better, warn about potential incidents

7. New contributions

– Proposal of standard for assessing the stability of the benchmarks and build the procedure of data processing of the base network in hydroelectric dams settlement monitoring.

– Build the process for calculating the influence of elevation of water level on the settlement of hydroelectric dams.

– Build the process for predicting the settlement by Kalman filter.

8. Structure of the thesis: The thesis consist of three parts: Introduction, 4 chapters of content and conclusion.

Chapter 1

OVERVIEW OF SETTLEMENT MONITORING AT HYDROELECTRIC DAMS

1.1. Characteristics, content and requirements of settlement monitoring at hydroelectric dams

1.1.1. The structural characteristics of hydroelectric works

1.1.2. Requirements of settlement monitoring at hydroelectric dams

1.1.3. Height-measuring methods in settlement monitoring at hydroelectric dams

1.1.4. Overview of processing the settlement monitoring data at hydroelectric dams

1.2. Overview of researches about processing the settlement monitoring data at hydroelectric dams in the world

1. Research about processing data of the network system of settlement monitoring: methods of network adjustment and analyzing the stability of benchmarks.

2. Research about analyzing the observed results

- The statistical analysis was conducted by models such as graph, HST, EDF…with a view to assessing the influence of external factors on subsidence of hydroelectric dams.
- Predicting settlement by the modern methods: Gene Expression Programming, Neuro-Genetic, Empirical Mode Decomposition…

1.3. Overview of researches about processing the settlement monitoring data at hydroelectric dams in VietNam

1. Researches about processing data of the settlement monitoring network, in which they focus on analyzing the stability of benchmarks: a large number of studies mentioned application of free network adjustment in processing data of the base network.

2. Automating the calculation process through programming.

5. Analyzing settlement with the statistical models, the subsidence models in space and over time.

1.4. Assessing the research status and orientating for the thesis

1.4.1. Achievements

- Processing the settlement observed data of hydroelectric dams is always cared both in research and reality. This is the potential and open research direction, studies about this topic were quite diverse.

- The studies about processing the settlement observed data of hydroelectric dams have high applicability, which adapts to the urgency of production reality.

- The most modern methods and technologies have been applied for data processing in settlement monitoring at hydroelectric dams.

1.4.2. Disadvantages

- In Vietnam, regulations for determining the accuracy requirement of settlement monitoring at hydroelectric dams have not been unified and published, only are proposed by designing consultants, therefore data processing and analyzing the observed data have difficulties.

- At present, in Vietnam, processing the observed data of hydroelectric dams is agreed to use the free network adjustment for analyzing the stability of benchmarks, but there is no an unified opinion about the standard of analysis as well as selecting the positioning principle for the base network.

- Analysis, assessment of settlement of hydroelectric works are hardly cared properly in Viet Nam, analysis of settlement combines with different influence factors has not been conducted carefully.

1.4.3. The main research direction of the thesis

- Establishment of the network system of settlement monitoring and processing the observed data of hydroelectric dams, especially focusing on research about data processing of the base network

- Analysis and assessment of the influence of external factors on the settlement of hydroelectric dams.

- Research about application of Kalman filter for predicting the settlement of hydroelectric works.

Chapter 2

SOLUTIONS OF DATA PROCESSING FOR NETWORK SYSTEM OF SETTLEMENT MONITORING AT HYDROELECTRIC DAMS

2.1. Characteristics of establishing the network system of settlement monitoring at hydroelectric dams

2.2. Accuracy estimation

2.3. Standard for assessing the stability of benchmarks

2.3.1. Some technical requirements for the base network

The benchmarks must be absolutely stable so it is necessary to survey and analyze the stability of benchmarks in all cycles.

2.3.2. The stability standard

Proposals of stability standards of benchmarks

a. Standard for the case of positioning by all of stable benchmarks

$$|S| \leq 1.5m_{S_1} \tag{2.20}$$

b. Standard for finding the most stable benchmark, the network is positioned by this point

$$\left[\Delta h_{ij}\Delta h_{ij}\right] = min \tag{2.22}$$

2.4. The method of free network adjustment

2.4.1. Concept of free elevation networks

2.4.2. Algorithm of free network adjustment

2.4.3. Properties of free elevation network adjustment

2.4.4. Positioning of free elevation network

The sum of squares of elevation deviations of the stable points in the network is the smallest, so:

$$[\delta H^2] = \delta H_i^2 + \delta H_j^2 + \delta H_k^2 = min \quad (2.33)$$

Because of $[pvv] = min$, so $[\delta H] = \delta H_i + \delta H_j + \delta H_k = 0$

Choose: - Positioning points: C = 1

- The remaining points in the network: C = 0

2.5. Application of free network adjustment for processing data of the base network in structural settlement monitoring

2.5.1. Rationale

2.5.2. Procedure of processing data of the base network in settlement monitoring

a. Adjustment and positioning of the base network according to the stable points

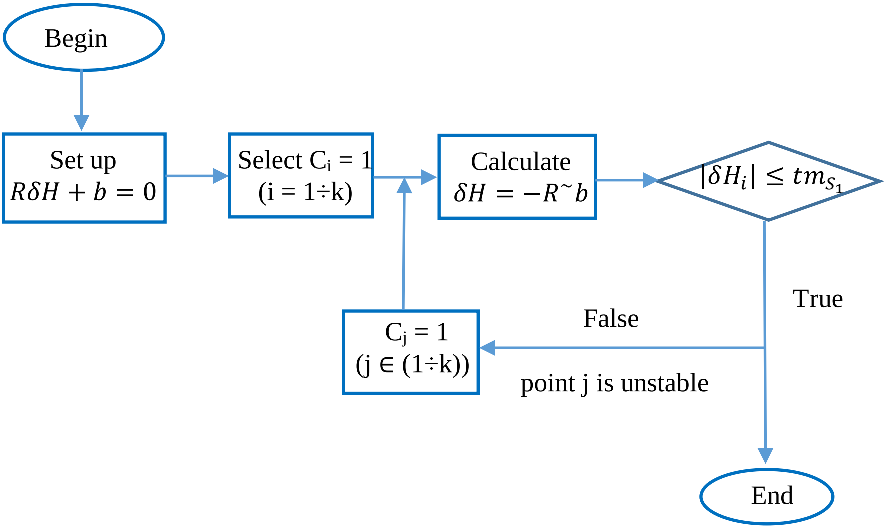

Figure 2.1: Calculation diagram

b. Adjustment and positioning of the base network according to the most stable point

In the stable group of benchmarks, determining the most stable benchmark that satisfied (2.22) for positioning the network

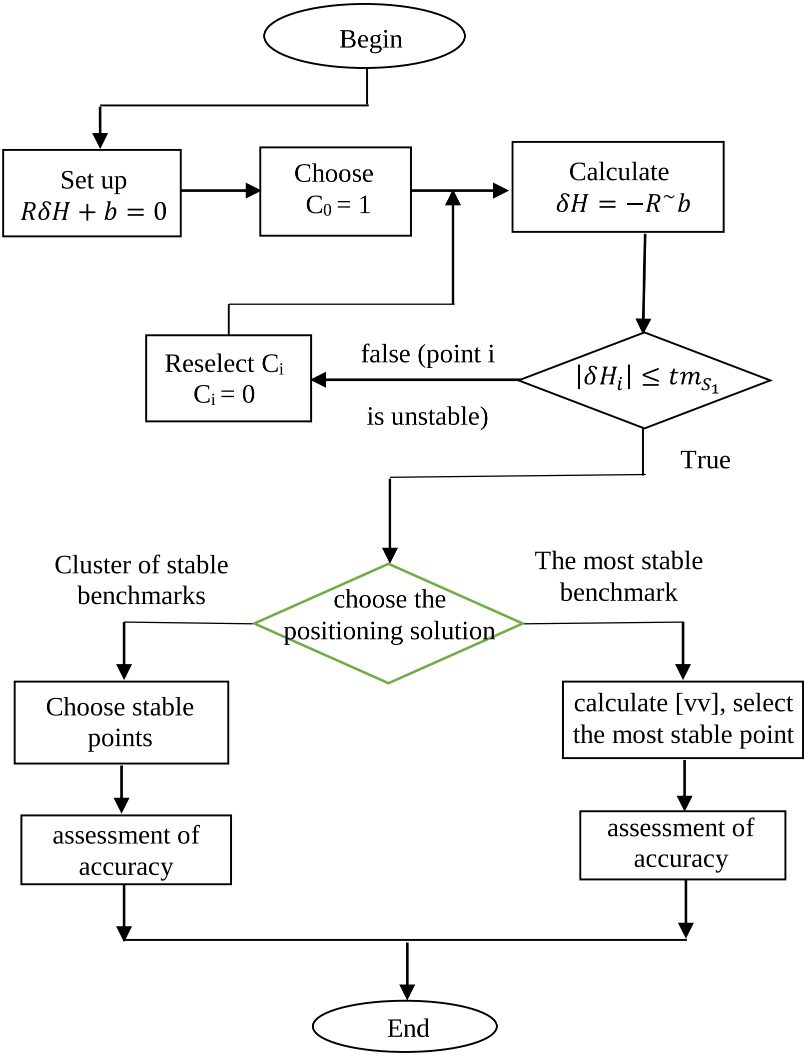

Figure 2.8: Procedure of processing data of the base network

2.6. Adjustment of the observation network and calculation of settlement

Conclusion of chapter 2

Proposal of stability standard and establishment of procedure of data processing for two different cases of network positioning

Chapter 3

ANALYSIS OF SETTLEMENT OF HYDROELECTRIC DAMS

3.1. Geometric analysis of settlement

Describing the geometric status (changes in shape and size), determining trend of structural displacement in space as following methods:

3.1.1. The probability straight line

3.1.2. The curve method

3.1.3. The probability plane

3.2. Analysis of settlement according to time

3.2.1. Theoretical base

The subsidence model in time as follows

$$S = f(t) \tag{3.21}$$

with vector of parameters

$$Z = (z_1 \;\; z_2 \;\; \dots \;\; z_k)^T \tag{3.22}$$

Parameters are determined by least square method

3.2.2. Some of time subsidence models

There is exponential function, polynomial function, Asaoka function, hyperbolic function. In which, the polynomial function can represent for any function when the rule of displacement is not determined [52], so the thesis has used the polynomial function for analyzing and predicting settlement of hydroelectric works.

$$S_t = a_0 + a_1 t + a_2 t^2 + \cdots + a_n t^n \qquad (3.27)$$

3.3. Proposal of solution for calculating the dams settlement caused by elevation of water level in the reservoir

3.3.1. The rationale of the problem

The time settlement of hydroelectric dams

$$S_t = a_1 t + a_2 t^2 + \cdots + a_n t^n \qquad (3.30)$$

The settlement caused by elevation of water level in the reservoir is calculated as follows [49]:

$$S_H = u_0 + u_1 H + u_2 H^2 + \cdots + u_m H^m \qquad (3.31)$$

The observation values are sum of the time settlement and the settlement caused by elevation of water level

$$S = S_t + S_H \qquad (3.32)$$

The elevation of water level has periodic changes so it is able to find observation periods having the same elevation of water level. It means that settlement caused by elevation of water level are similar.

Considering two cycles i and j with the same elevation of water level ($S_H^i \approx S_H^j$), calculating difference of settlement between two cycles, the obtained value is not affected by elevation of water level.

$$\Delta S^{ij} = \left(S^j - S^i\right) = S_t^j - S_t^i \qquad (3.35)$$

$$\Delta S^{ij} = a_1\left(t_j - t_i\right) + a_2\left(t_j^2 - t_i^2\right) + \cdots + a_n(t_j^n - t_i^n) \qquad (3.36)$$

Coefficient a in (3.36) is determined by least square method, then calculation of S_t, S_H is calculated as the following formula:

$$S_H = S_{đo} - S_t \qquad (3.41)$$

3.3.2. Calculation process

Step 1: Approximate calculation of coefficient u in equation (3.31) with condition as $\left[V_{\Delta S}^2\right] = min$. Choose cycles with the same elevation of water level, determining (a) in the time settlement function and S_t; calculating $S_H = S_{đo} - S_t$ for all cycles; then (u) is determined.

Step 2: Calculation of (u) with the condition as $[V_S^2] = min$ *(using all cycles).* Determining (a), calculating S_H and (u). Repetition of calculation is conducted until a and u converging

3.3.3. Choosing the degree of polynomial

- In each polynomial, degree is sequentially replaced, start at 1.
- Degree of polynomial is chosen when the error of modeling (polynomial) equals to the observation error.

3.4. Application of Kalman filter for predicting settlement of hydroelectric dams

3.4.1. Overview of Kalman filter

The mathematical form of the Kalman filter consists of two models: a prediction model and a filter model. These two models are related and shown in the calculation procedure as follows:

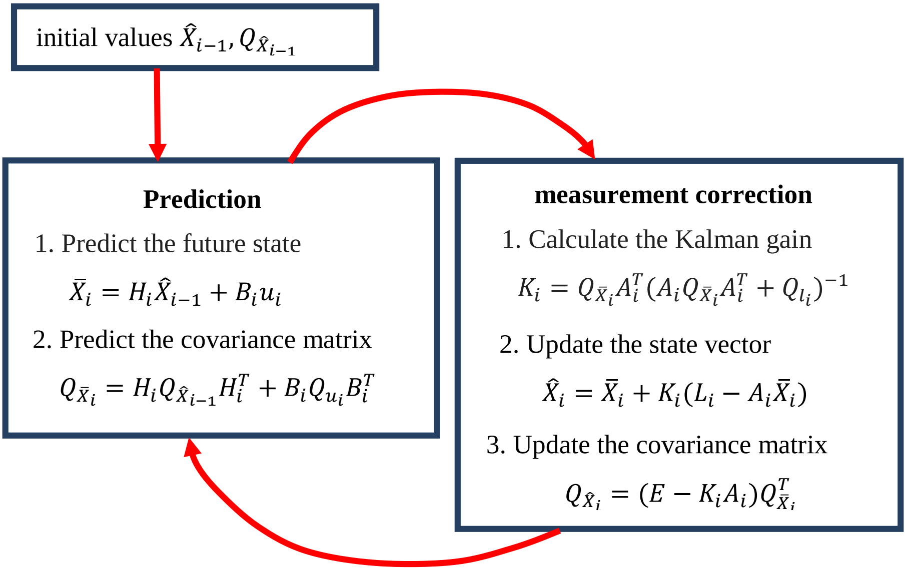

Figure 3.7: Calculation diagram of Kalman filter method

3.4.2. Application of Kalman filter for predicting the settlement of hydroelectric dams

a. Establishment of the prediction model

According to section 3.3, the observed settlement of dam is that

$$S_i = S_{t_i} + S_{H_i} \qquad (3.56)$$

- The settlement is calculated according to time

$$S_{t_i} = a_1 t_i \qquad (3.57)$$

Coefficient a_1 is the subsidence speed

$$v_{t_i} = \frac{\partial S_{t_i}}{\partial t} = a_1 \qquad (3.58)$$

Calculating the difference of settlement in two cycles i and (i-1), the settlement of dams at cycle i is determined as follows:

$$S_{t_i} = S_{t_{i-1}} + \ (t_i - t_{i-1}) a_{1(i-1)} \qquad (3.60)$$

- The settlement is calculated according to elevation of water level

$$S_{H_i} = u_0 + u_1 H_i \qquad (3.61)$$

The elevation of water level at the time t (between two cycles i and (i-1) changes linearly and is determined by formula

$$H_t = \frac{(H_i - H_{i-1})}{(t_i - t_{i-1})}(t - t_{i-1}) + H_{i-1} \qquad (3.62)$$

Speed of settlement caused by elevation of water level

$$v_{S_H} = u_1 \left(\frac{\Delta H_{i,i-1}}{\Delta t_{i,i-1}} - \frac{\Delta H_{i-1,i-2}}{\Delta t_{i-1,i-2}} \right) \qquad (3.63)$$

Based on (3.61), calculate difference of settlement caused by elevation of water level in two cycles i and (i-1), S_H at cycle i as follows:

$$S_{H_i} = S_{H_{i-1}} + u_1 (H_i - H_{i-1}) \qquad (3.64)$$

Speed of settlement caused by elevation of water level at the time t:

$$v_{S_{H_i}} = \frac{\partial S_{H_i}}{\partial t} = u_1 \frac{(H_i - H_{i-1})}{(t_i - t_{i-1})} = u_1 \frac{\Delta H_{i,i-1}}{\Delta t_{i,i-1}} \qquad (3.65)$$

Symbol of the filter state vector at time (i-1) is $\hat{X}_{i-1} = [\hat{s}_{i-1} \quad \hat{a}_{i-1}]^T$

Symbol of the prediction state vector at time i is $\bar{X}_i = [\bar{S}_i \quad \bar{a}_i]^T$

From formulas (3.56), (3.60), (3.64), the settlement at cycle i is that

$$\bar{S}_i = \hat{S}_{i-1} + \hat{a}_{1(i-1)}(t_i - t_{i-1}) + u_1(H_i - H_{i-1}) \tag{3.66}$$

From (3.58), (3.65), detemining the subsidence speed

$$\bar{a}_i = \hat{a}_{i-1} + u_1\left(\frac{\Delta H_{i,i-1}}{\Delta t_{i,i-1}} - \frac{\Delta H_{i-1,i-2}}{\Delta t_{i-1,i-2}}\right) \tag{3.67}$$

The state transition matrix H is calculated as formula:

$$H = \begin{bmatrix} \frac{\partial \bar{S}_i}{\partial \hat{S}_{i-1}} & \frac{\partial \bar{S}_i}{\partial \hat{a}_{i-1}} \\ \frac{\partial \bar{a}_i}{\partial \hat{S}_{i-1}} & \frac{\partial \bar{a}_i}{\partial \hat{a}_{i-1}} \end{bmatrix} = \begin{bmatrix} 1 & \Delta t_{i,i-1} \\ 0 & 1 \end{bmatrix} \tag{3.69}$$

The inputs control matrix B of parameters in vector u is calculated as

$$B = \begin{bmatrix} \frac{\partial \bar{S}_i}{\partial u_1} \\ \frac{\partial \bar{a}_i}{\partial u_1} \end{bmatrix} = \begin{bmatrix} \Delta H_{i,i-1} \\ \frac{\Delta H_{i,i-1}}{\Delta t_{i,i-1}} - \frac{\Delta H_{i-1,i-2}}{\Delta t_{i-1,i-2}} \end{bmatrix} \tag{3.70}$$

b. Establishment of the measured value model

$$l_i = S_i \tag{3.71}$$

Conclusions of chapter 3

- *Establishment of calculation process for determining the influence of elevation of water level on settlement of hydroelectric dams.*
- *Based on the theory of the dynamic model of Kalman filter, the calculation process is established suitably for predicting the settlement of hydroelectric dams.*

Chapter 4

EXPERIMENT OF DATA PROCESSING IN SETTLEMENT MONITORING AT HYDROELECTRIC DAMS

4.1. Design of the base network of settlement monitoring at Son La hydroelectric dam

4.1.1. Design of the base elevation network (figure 4.2)

4.1.2. Accuracy estimation

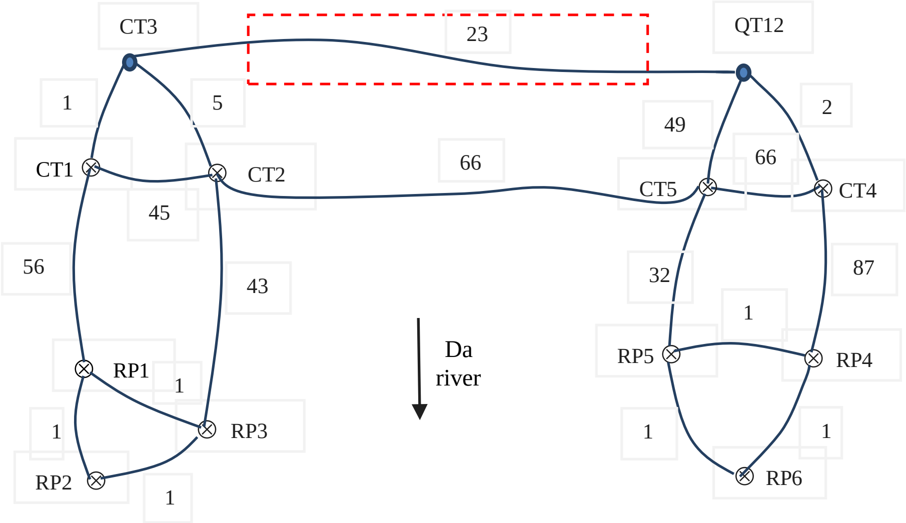

Figure 4.1:The base network in settlement monitoring at Son La dam

Table 4.1: Results of network accuracy estimation

No	Points	Design elevation H (m)	Error of height m_H (mm)
1	CT3	231.24	0.3
2	QT12	229.78	0.3
3	RP1	141.18	0.4
4	RP2	141.30	0.4
5	RP3	141.32	0.4
6	RP4	189.92	0.4
7	RP5	190.30	0.4
8	RP6	190.40	0.4
9	CT1	218.84	0.3
10	CT2	142.13	0.3
11	CT4	261.80	0.4
12	CT5	193.89	0.3

Mean square error of unit weight $m_{h/tr}$ = 0.08 mm

4.2. Processing data of the base height network at SonLa dam

m_S = 2mm, the stability standard is calculated as follows:

$$|\delta H_i| \le \frac{tm_S}{\sqrt{1+K^2}} = \frac{1{,}5.2}{\sqrt{1+9}} = 0{,}95(mm) \qquad (4.1)$$

Table 4.2: Procedure of adjustment

No	Point	first iteration		second iteration		third iteration		forth iteration	
		C	settlement (m)	C	Settlement (m)	C	Settlement (m)	C	Settlement (m)
1	RP3	1	0.0000	1	-0.0001	1	-0.0004	1	-0.0002
2	RP4	1	0.0007	1	0.0005	1	0.0003	1	0.0005
3	RP5	1	0.0006	1	0.0004	1	0.0002	1	0.0004
4	RP6	1	0.0004	1	0.0002	1	0.0000	1	0.0002
5	CT1	1	-0.0002	1	-0.0003	1	-0.0005	1	-0.0004
6	CT2	1	-0.0014	1	**-0.0015**	0	**-0.0018**	0	**-0.0016**
7	RP1	1	0.0014	1	0.0013	1	**0.0011**	0	**0.0012**
8	CT4	1	**-0.0016**	0	**-0.0018**	0	**-0.0020**	0	**-0.0019**
9	CT5	1	0.0001	1	0.0000	1	-0.0002	1	-0.0003
10	RP2	1	0.0000	1	-0.0002	1	-0.0004	1	-0.0003

Solution of positioning according a cluster of stable benchmarks

Table 4.3: The adjusted elevation of benchmarks

No	points	Elevation (m)	Error (mm)	No	points	Elevation (m)	Error (mm)
1	RP1	141.18601	0.34	6	RP6	190.40105	0.25
2	RP2	141.30924	0.34	7	CT1	218.84400	0.3
3	RP3	141.32258	0.33	8	CT2	142.13229	0.3
4	RP4	189.92176	0.25	9	CT4	261.80053	0.32
5	RP5	190.30305	0.25	10	CT5	193.89632	0.24

Solution of positioning according to the most stable benchmark

Table 4.4: Detemining the most stable benchmark

No	points	$[\Delta h_{ij}\Delta h_{ij}]$ (mm^2)	assessment	No	points	$[\Delta h_{ij}\Delta h_{ij}]$ (mm^2)	assessment
1	RP2	1.104	ổn định	5	RP6	**0.690**	Ổn định nhất
2	RP3	0.984	ổn định	6	CT1	1.769	ổn định
3	RP4	2.098	ổn định	7	CT5	0.808	ổn định
4	RP5	1.515	ổn định				

Table 4.5: The adjusted elevation of benchmarks

Số TT	Tên điểm	Độ cao (m)	Sai số (mm)	Số TT	Tên điểm	Độ cao (m)	Sai số (mm)
1	RP1	141.18600	0.34	6	RP6	190.40104	0.25
2	RP2	141.30923	0.34	7	CT1	218.84399	0.3
3	RP3	141.32257	0.33	8	CT2	142.13228	0.3
4	RP4	189.92175	0.25	9	CT4	261.80052	0.32
5	RP5	190.30304	0.25	10	CT5	193.89631	0.24

Comments:

- The calculation process in fig 2.8 can flexibly solve the network positioning according to cluster of points or the most stable point.
- The adjusted elevation of benchmarks in two positioning solutions have no significant differences, thus, two solutions have the similar reliability and applicability.

4.3 Experiment of establishing the subsidence model for Son La dam

The form of subsidence model is straight line: S = -0.00000554X – 6.4

Declination angle: α = arctg (- 0.00000554) = -1.14”

error of modeling: $\mu = \pm 0.0033\ (m)$

4.4. Experiment of determining the influence of elevation of water level on the settlement of hydroelectric dams

Figure 4.2: Location of PVM8 and SM8 on Hoa Binh dam

The observed data that was used belongs to monitoring cycles in period of 2000-2003 and 2013-2015 at point PVM8 (located on the dam crest and SM8 (at route on dam body).

a. At the observation point *PVM8 (2000-2003).* Settlement function:

$$S_H = -0.058625 + 0.0005905H$$

Table 4.6: Settlement is caused by elevation of water level

cycles	obsevation time	water level (m)	S_H (m)	**cycles**	obsevation time	water level (m)	S_H (m)
79	10/1/2000	115.07	0.0000	**89**	01/2/2002	111.53	-0.0018
80	15/2/2000	110.31	-0.0024	**90**	02/4/2002	100.08	-0.0076
81	03/4/2000	100.92	-0.0072	**91**	07/5/2002	87.82	-0.0139
82	10/5/2000	86.77	-0.0144	**92**	09/8/2002	90.64	-0.0124
83	03/8/2000	90.61	-0.0125	**93**	7/11/2002	116.28	0.0006
84	10/11/2000	116.36	0.0007	**94**	11/2/2003	114.84	-0.0001
85	01/2/2001	112.87	-0.0011	**95**	15/5/2003	85.89	-0.0149
86	10/5/2001	90.87	-0.0123	**96**	01/8/2003	92.19	-0.0116
87	06/8/2001	90.15	-0.0127	**97**	6/11/2003	116.24	0.0006
88	2/11/2001	116.73	0.0008				

Figure 4.3: Chart of settlement caused by elevation of water level

b. At the observation point SM8 (2000-2003)

$$S_H = -0.028348 + 0.0002464H$$

Table 4.7: Settlement is caused by elevation of water level

cycles	obsevation time	water level (m)	S_H (m)	**cycles**	observation time	water level (m)	S_H (m)
79	10/1/2000	115.07	0.0000	**89**	01/2/2002	111.53	-0.0009
80	15/2/2000	110.31	-0.0012	**90**	02/4/2002	100.08	-0.0037
81	03/4/2000	100.92	-0.0035	**91**	07/5/2002	87.82	-0.0067
82	10/5/2000	86.77	-0.0070	**92**	09/8/2002	90.64	-0.0060
83	03/8/2000	90.61	-0.0060	**93**	7/11/2002	116.28	0.0003
84	10/11/2000	116.36	0.0003	**94**	11/2/2003	114.84	-0.0001
85	01/2/2001	112.87	-0.0005	**95**	15/5/2003	85.89	-0.0072
86	10/5/2001	90.87	-0.0060	**96**	01/8/2003	92.19	-0.0056
87	06/8/2001	90.15	-0.0061	**97**	6/11/2003	116.24	0.0003
88	2/11/2001	116.73	0.0004				

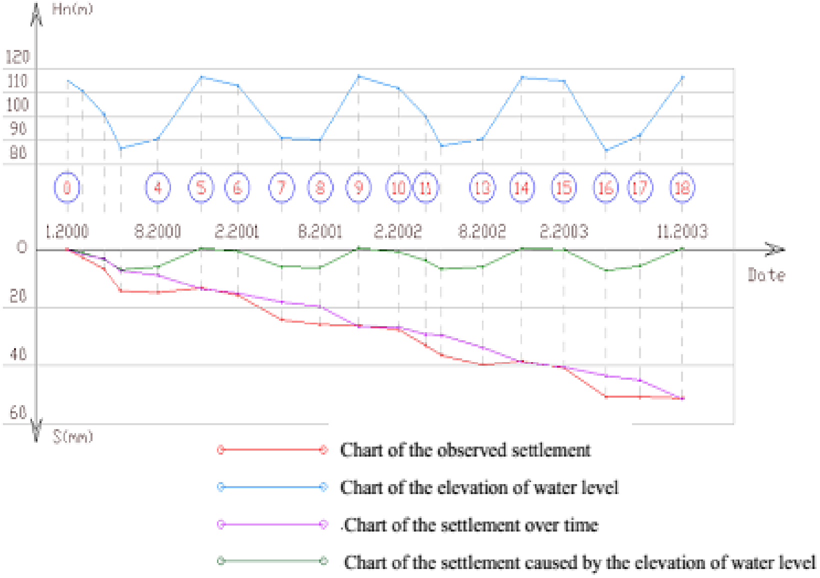

Figure 4.4: Chart of settlement caused by elevation of water level

c. At the observation point PVM8 (2013-2015)

$$S_H = -0.047032 + 0.0004218H$$

Table 4.8: Settlement is caused by elevation of water level

cycles	obsevation time	water level (m)	S_H (m)	**cycles**	observation time	water level (m)	S_H (m)
159	29/1/2013	111.51	0.0000	**171**	15/8/2014	107.59	-0.0017
160	22/2/2013	102.71	-0.0037	**172**	26/9/2014	115.40	0.0016
161	2/5/2013	101.82	-0.0041	**173**	10/11/2014	116.72	0.0022
162	11/6/2013	89.62	-0.0092	**174**	2/2/2015	114.32	0.0012
163	15/8/2013	109.80	-0.0007	**175**	10/4/2015	111.60	0.0001
164	19/9/2013	117.20	0.0024	**176**	11/5/2015	109.11	-0.0010
165	`12/11/2013	116.41	0.0021	**177**	19/6/2015	85.83	-0.0108
166	14/2/2014	101.86	-0.0041	**178**	5/8/2015	104.68	-0.0029
167	28/3/2014	109.91	-0.0007	**179**	3/9/2015	110.82	-0.0003
168	13/5/2014	101.85	-0.0041	**180**	6/10/2015	115.85	0.0018
169	25/6/2014	86.84	-0.0104	**181**	13/11/2015	116.38	0.0021
170	31/7/2014	104.09	-0.0031				

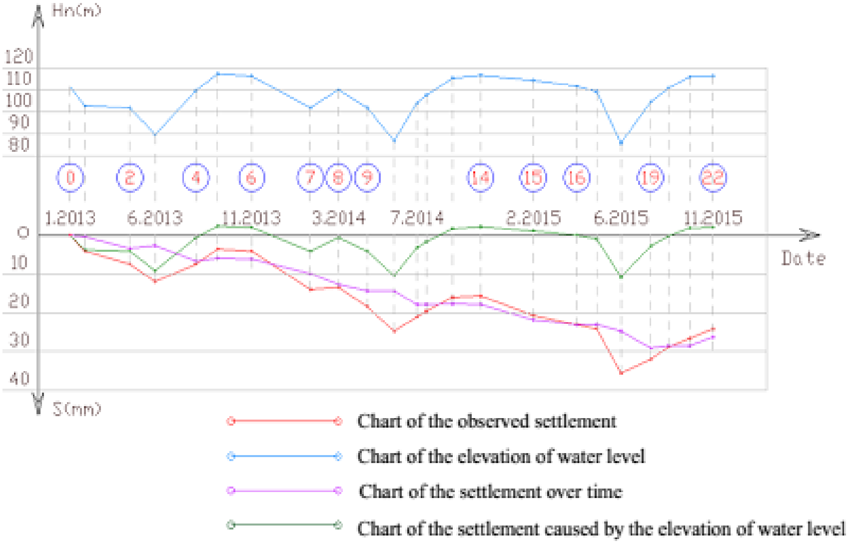

Figure 4.5: Chart of the settlement caused by elevation of water level

d. At the observation point SM8 (2013-2015)

$$S_H = -0.008495 + 0.0000762H$$

Table 4.9: Settlement is caused by elevation of water level

cycles	obsevation time	water level (m)	S_H (m)	**cycles**	obsevation time	water level (m)	S_H (m)
159	29/1/2013	111.51	0.0000	**171**	15/8/2014	107.59	-0.0003
160	22/2/2013	102.71	-0.0007	**172**	26/9/2014	115.40	0.0003
161	2/5/2013	101.82	-0.0007	**173**	10/11/2014	116.72	0.0004
162	11/6/2013	89.62	-0.0017	**174**	2/2/2015	114.32	0.0002
163	15/8/2013	109.80	-0.0001	**175**	10/4/2015	111.60	0.0000
164	19/9/2013	117.20	0.0004	**176**	11/5/2015	109.11	-0.0002
165	`12/11/2013	116.41	0.0004	**177**	19/6/2015	85.83	-0.0019
166	14/2/2014	101.86	-0.0007	**178**	5/8/2015	104.68	-0.0005
167	28/3/2014	109.91	-0.0001	**179**	3/9/2015	110.82	-0.0001
168	13/5/2014	101.85	-0.0007	**180**	6/10/2015	115.85	0.0003
169	25/6/2014	86.84	-0.0019	**181**	13/11/2015	116.38	0.0004
170	31/7/2014	104.09	-0.0006				

Figure 4.6: Chart of the settlement caused by elevation of water level

Comment: The elevation of water level in the reservoir affects different points on dam in each cycle with the different settlement.

4.5. Experiment of applying Kalman filter for predicting the settlement of hydroelectric dams

The used data are settlement that were calculated according to time at two points PVM8 and SM8 after the settlement caused by elevation of water level was filtered out of the observed values.

1. At the point PVM8 (2002-2003)

Equation of the time settlement: $S = -0.0164t$

Table 4.10: Predicted settlement in 4 cycles in 2003

Cycles	Monitoring time	Predicted settlement (m)	Prediction accuracy	Observed settlement (m)	Deviation (m)
94	11/2/ 2003	-0.0531	0.0027	-0.0528	**- 0.0003**
95	15/5/2003	-0.0721	0.0054	-0.0707	**- 0.0014**
96	1/8/2003	-0.0723	0.0114	-0.0757	**0.0034**
97	6/11/2003	-0.0644	0.0205	-0.0673	**0.0029**

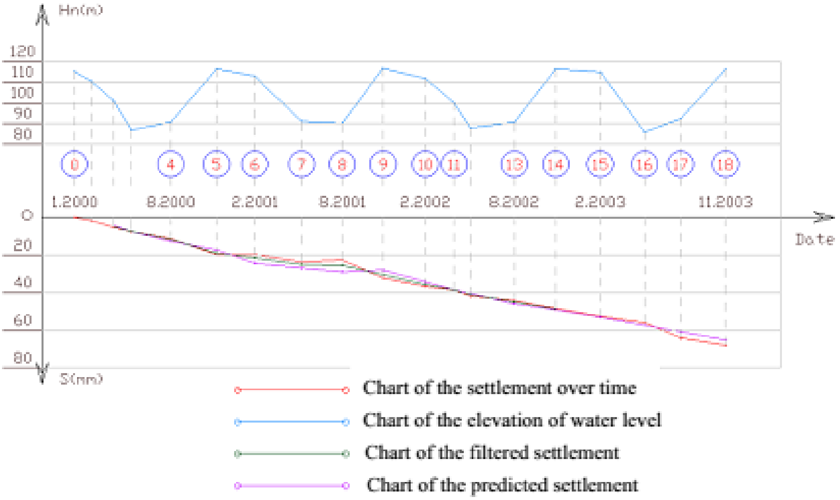

Figure 4.7: Chart of predicted settlement at PVM8

2. At the point SM8 (2000-2003)

$$S = -0.0148t$$

Table 4.11: Predicted settlement in 4 cycles in 2003

Cycles	Monitoring time	Predicted settlement (m)	Prediction accuracy	Observed settlement (m)	Deviation (m)
94	11/2/ 2003	-0.0415	0.0018	-0.0406	**- 0.0009**
95	15/5/2003	-0.0525	0.0038	-0.0506	**- 0.0019**
96	1/8/2003	-0.0541	0.0079	-0.0505	**- 0.0036**
97	6/11/2003	-0.0520	0.0141	-0.0509	**- 0.00011**

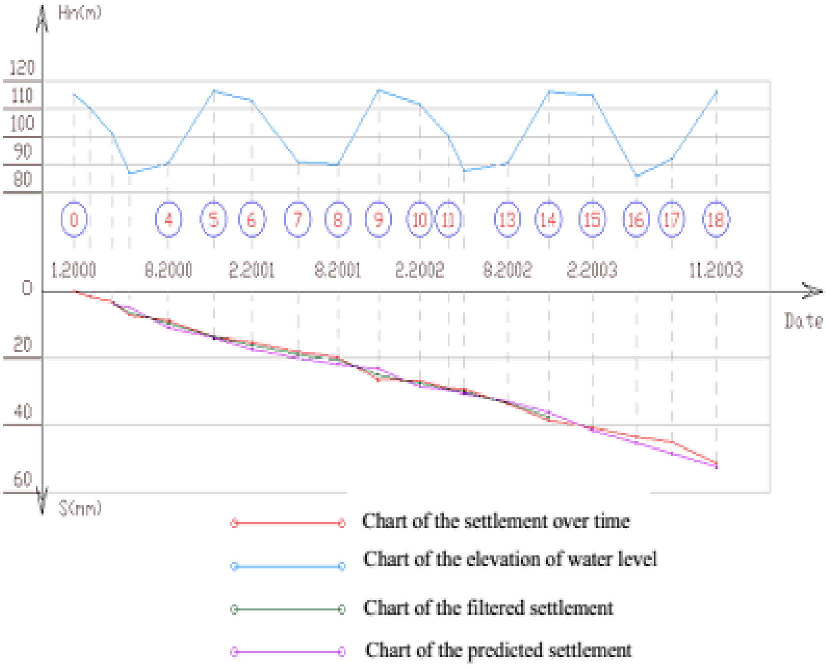

Figure 4.8: Chart of predicted settlement at SM8

3. At the point PVM8 (giai đoạn 2013-2015)

$$S = -0.0070t$$

Table 4.12: Predicted settlement in 8 cycles in 2015

Cycles	Monitoring time	Predicted settlement (m)	Prediction accuracy	Observed settlement (m)	Deviation (m)
174	2/2/2015	-0.0190	0.0017	-0.0207	**0.0017**
175	10/4/2015	-0.0214	0.0034	-0.0231	**0.0017**
176	11/5/2015	-0.0231	0.0055	-0.0241	**0.0010**
177	19/6/2015	-0.0336	0.0081	-0.0356	**0.0020**
178	5/8/ 2015	-0.0266	0.0126	-0.0320	**0.0054**
179	3/9/ 2015	-0.0245	0.0189	-0.0288	**0.0043**
180	6/10/2015	-0.0231	0.0265	-0.0266	**0.0035**
181	13/11/2015	-0.0236	0.0353	-0.0242	**0.0006**

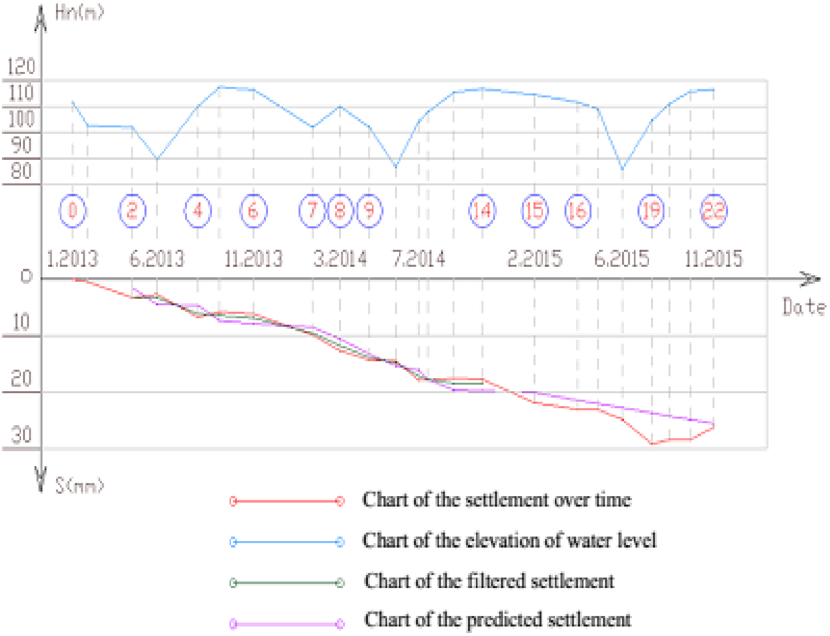

Figure 4.9: Chart of predicted settlement at PVM8 (2013 -2015)

4. At the point SM8 (2013-2015)

$$S = -0.0055t$$

Table 4.13: Results of prediting settlement in 2015

Cycles	Monitoring time	Predicted settlement (m)	Prediction accuracy	Observed settlement (m)	Deviation (m)
174	2/2/2015	-0.0123	0.0007	-0.0134	**0.0011**
175	10/4/2015	-0.0136	0.0014	-0.0159	**0.0023**
176	11/5/2015	-0.0142	0.0022	-0.0160	**0.0018**
177	19/6/2015	-0.0166	0.0033	-0.0197	**0.0031**
178	5/8/ 2015	-0.0159	0.0051	-0.0186	**0.0027**
179	3/9/ 2015	-0.0158	0.0076	-0.0183	**0.0025**
180	6/10/2015	-0.0159	0.0107	-0.0182	**0.0023**
181	13/11/2015	-0.0165	0.0143	-0.0163	**-0.0002**

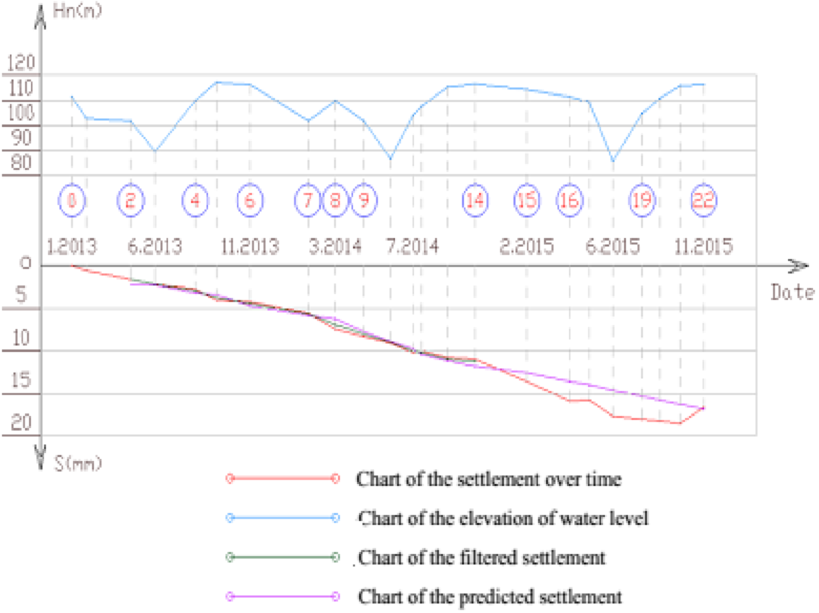

Figure 4.10: Chart of predicted settlement at SM8

Comment: Kalman filter is capable to responding in prediction of settlement of hydroelectric dams. The obtained results have high reliability, the method can predict best in 6 months.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. The thesis proposes the standard for assessing stability of benchmarks in two cases: positioning according to the cluster of benchmarks or the most stable benchmark. On that basis, the procedure of data processing is built suitably, which contribute to solve flexibly the positioning for the base network.
2. The elevation of water level in the reservoir has the biggest impact on the settlement of hydroelectric dams. The thesis builds mathematical base and calculation procedure for determining the influence value of this factor. Result from experiment proved the rightness and reliability of the built procedure. This procedure is suitable to apply for assessing the subsidence influence of all external factors that have periodic change rules.
3. Based on researching about dynamic model of Kalman filter, the thesis establishes the suitable calculation procedure to apply for predicting settlement of hydroelectric dams. The experimental results prove good applicability of this method in predicting the settlement.

RECOMMENDATIONS

1. In deformation monitoring at hydroelectric works, technical specification must be determined clearly; the stability standard of benchmarks needs to be unified.
2. At present, in production reality, the number of cycles conducted at hydroelectric dams are different. Therefore, it is neccesary to monitor according to the change of elevation of water level, at least 4 cycles each year in order to have enough data for analyzing settlement and assessing safety of dams.

SCIENTIFIC WORKS OF PhD STUDENT PUBLISHED RELATE TO THE CONTENT OF THE THESIS

1. Le Duc Tinh, Ta Thi Thu Huong, Nguyen Thi Kim Thanh (2018), *“*Application of data difference adjustment mehod for processing the settlement monitoring network*”*, *National Conference on Earth Science and Resources with Sustainable Development, Hanoi*, p43-48.
2. Pham Quoc Khanh, Nguyen Thi Kim Thanh (2018), “Application of artificial neural networks for lanslide forecasting models in the mountainous areas of Xin Man district, Ha Giang province”, *Proceedings of the 4th international conference Vietgeo 2018 on geological and geotechnical engineering in response to climate change and sustainable development of infrastructure, Quang Binh, Vietnam, 21-22 September*, p477-483.
3. Le Duc Tinh, Tran Khanh, Nguyen Thi Kim Thanh (2019), “Forecasting structural displacement based on geodetic monitoring data*”*, *Journal of Mining and Earth Sciences*, Vol.60, Issue 3, p40-44.
4. Nguyen Thi Kim Thanh, Diem Cong Trang, Tran Thuy Linh (2019), “Research about completing procedure of analyzing stability of benchmarks in dams settlement monitoring”, *The 15th Young Scientific Conference, 11/2019, Institute of Construction Science and Technology*.
5. Tran Khanh, Le Duc Tinh, Nguyen Thi Kim Thanh (2020), “Assessment of the influence of water-level elevation in the reservoir on settlement of the hydroelectric dam”, *Journal of Mining and Earth Sciences*, vol 62 (6).
6. Tran Khanh, Le Duc Tinh, Nguyen Thi Kim Thanh (2020), “Application of Kalman filter method for predicting settlement of hydroelectric dams”, *National Conference on Earth Science and Resources with Sustainable Development.*