A Method of Optimal Design for the Base Network in Structural Deformation Monitoring at Song Hinh Hydroelectricity, Vietnam

Quoc Khanh PHAM[1)]

[1)] Hanoi University of Mining and Geology, Viet Nam; Corresponding author: phamquockhanh@humg.edu.vn

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Abstract

The article mentions a method of optimal design for the base network in horizontal displacement monitoring at hydroelectric works, based on the average residual level of the measured values. When the target function is the weakest positional error, the obtained result after optimizing is the unique plan that no depends on the designers and their experience. Thus, this is helpful for the production units because they no need to have experts in designing the network. Experiment for the base network of deformation monitoring at Song Hinh hydroelectricity shows that 44%, 50% and 60% of the initial measurement can be reduced when the average residual level is chosen 0.5, 0.4 and 0.3, respectively. The weakest position error of the network after optimizing is 2.4 mm, 2.5 mm and 2.6 mm, respectively, all are smaller than requirement ±3.6mm. This method is mainly applied for the side-angle network that was measured by total station, without considering the optimal design network in the priority direction.

Keywords: *plane control network, optimal design, residual level, engineering surveying, positional error*

1. Introduce

The plane control network for serving construction, the base network in deformation monitoring for irrigation-hydroelectricity, underground works are always established at the area with difficult measuring condition. With the high accuracy requirement, this kind of network is designed as the dense triangle network so it is necessary to measure a lot of values. It takes much time and effort to measure so that the built network gains the requirement accuracy. Therefore, when the target function is chosen to be the weakest position error, optimal design for this kind of network is the efficiency solution because cutting down the measured values no affects the accuracy, additionally, brings economic efficiency to enterprises.

So far, problem of optimal design in geodesy has continuously been studied and further applied for satellite measurement networks (Alizadeh-Khameneh et al, 2016; Alizadeh-Khameneh, 2017). In the field of engineering surveying in Vietnam, the base network in horizontal displacement monitoring of hydropower works is measured periodic iteration, it is mainly an angle – side measuring triangle network that is established by high-precision electronic total station. The optimal design of the plane control based on the reliability of the network is called the type 1 design (Grafarend, E.W., 1974). The residual measuring level is an indicator of the reliability of the control network, the more the residual measurement values in the network are, the higher the efficiency of optimal design is and vice versa. This type of optimal design has been widely applied in China (Chen Yongqi et al, 1996; Li Deren, 2012; Zhang Zhenglu et al, 2008; Zhang Zhenglu, 2001). The optimal design according to the residual level of the measured values was researched in (Nguyen Quang Phuc, Hoang Thi Minh Huong, 2016, Zhang Zhenglu et al, 2008). Some recent studies on optimal design can be mentioned such as: optimizing deformation monitoring network according to basic edge correlations (Alizadeh-Khameneh, M.A., Sjöberg, L.E. & Jensen A.B.O., 2016), optimal design for the deformation monitoring network (Kutoglu, H.S. & Berber, M., 2015; Yetkin, M. & Inal, C., 2015); the basic concept on optimal design of the geodetic network (Amiri-Simkooei, A., Asgari, J., Zangeneh-Nejad, F. & Zaminpardaz, S., 2012), Optimal design according to cost, reliability and accuracy (M. Eshagh and R. Kiamehr, 2007). Optimization of deformation monitoring networks using finite element strain analysis (M. Amin Alizadeh-Khameneh, Mehdi Eshagh and Anna B.O. Jensen, 2018). The optimal design of the network according to two epoch (A Amiri Simkooei và nnk, 2012), Optimal design by the simulation method (Wojciech Pachelski, Paweł Postek, 2016), Optimisation of Lilla Edet Landslide GPS Monitoring Network (M.A. Alizadeh-Khameneh, M. Eshagh and L.E. Sjöberg, 2015). Almost studies optimized the network according to the basic problem and own proposal direction, no researches have mentioned the average residual level in the optimal design for the base network of structural horizontal displacement monitoring. Using the average residual measuring level as the indicator of reliability and the target function chosen to be position error not only determines the number of the measured values that can be omitted, but also ensures to gain requirement accuracy. Moreover, the design plan for each average residual measuring level is the unique for one network and the network is designed without depending on the experience of the designer. Therefore, this is the new approach that is different from the previous method.

2. The theoretical basis on optimal design

The problem about optimal design of a geodetic network that Grafarend, E.W. (Grafarend, E.W., 1974) proposed is shown in the general form as follows.:

$$\begin{cases} \min\limits_{X \in E^n} f(X) \\ g_i(X) \geq 0, i = 1,2,...m \\ h_j(X) = 0, j = 1,2,..., l \end{cases} \tag{1}$$

where, the first expression in formula (1) is called the target function, the second and third expressions are called the binding conditions. The nature of the optimal problem is to find the maximum or minimum value of the target function based on the binding conditionals to determine the optimal solution.

2.1. The redundant observations in the geodetic control network

Geodetic networks (such as survey network, construction network, deformation monitoring network) are only adjusted by the method of least squares when the network has redundant measured values. The redundant values in the geodetic network (indirect network or free network) are calculated as following (Tao Benzao, 2001):

- With the dependent network or the free network that has enough original data, then:

$$r=n-t \tag{2}$$

- With the free network

$$r=n-k+d \tag{3}$$

Where, n is total of the measured values in the network; t and k are the necessary values and the number of missing positioning components, d is missing number.

The average redundant measuring level is calculated according to the formula:

$$\bar{r} = \frac{r}{n} \tag{4}$$

2.2. The redundant measuring level of each observation

Assuming that the vector of measured values is L, vector of corrections is V, vector of parameters is X, approximation value is X_0, the adjusted value is $\hat{X}$, the weight matrix is P, then the error equation is determined as (Zhang Zhenglu, 2001):

$$V=A\hat{X}-L \tag{5}$$

In the generality adjustment problem, the adjusted values are calculated

$$\hat{X}=N^{+}A^{T}PL=Q_{XX}A^{T}PL \tag{6}$$

Where, N^{+} is the generality inverse matrix of the system of error equation; Q_{XX} is the covariance matrix of parameters.

With $N=A^{T}PA$. Replace in formula (5) the correction matrix is obtained:

$$V=(AQ_{XX}A^{T}P-E)L \tag{7}$$

Where E is the unit matrix.

According to the error propagation law, the covariance matrix of correction values is calculated as:

$$Q_{W}=P^{-1}-AQ_{XX}A^{T} \tag{8}$$

From that, gaining:

$$V=-Q_{VV}PL=-RL \tag{9}$$

with

$$R=Q_{VV}P \tag{10}$$

Matrix R is called the reliability matrix of the control network

Set:

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nn} \end{bmatrix} \tag{11}$$

In this matrix, the i^th^ element on the diagonal of the matrix R is called the redundant level of the i^th^ measured value, set:

$$r_i = r_{ii} \text{ và } r = \sum_{i=1}^{n} r_i \tag{12}$$

Where, r is the number of redundant observation in the network. When the weight matrix is the diagonal matrix (no correlation among the observations), then $0 \leq r_i \leq 1$. The observations that have $r_i=0$ are the mandatory ones, The observations with $r_i=1$ are the redundant ones which no affect accuracy of the network even though these are no measured.

2.3. The feature of the redundant level of the observations

The internal reliability r_i of the observation l_i has the following features (Li Deren, 2012; Zhang Zhenglu et al, 2008):

(1) $0 \leq r_i \leq 1$: the smaller r_i is the higher the importance of the observations. If $r_i=0$ the observation is unable to be omitted. The bigger r_i is, the lower the importance of the observations, if $r_i=1$ this observation has to be measured.

(2) In a network design plan, it is necessary to pay attention: In a certain grid design scheme include: graph, the number of observations, accuracy, sensitivity, the higher the precision of the observation is, the smaller the redundant measuring level r_i is; on the contrary, the lower the precision of the observation is, the bigger the redundant measuring level r_i is. Thus, the redundant level of the observations (the internal reliability) is contrary to its precision.

(3) In case of the measuring accuracy has been determined, in the network the more the measured values are, the bigger the redundant level of the observations.

(4) With the independent network, the redundant level of the observation no relates to the position of the benchmarks.

2.4. Relationship between the number of observations in the plane control network and the average redundant level of the observations

The number of observations are able to be determined through the average redundant level, from formula (4), shorten as follows

$$n = \frac{t}{1-\bar{r}} \tag{13}$$

In optimal design, depending on type of network, so that the observations have good effect, the average redundant level

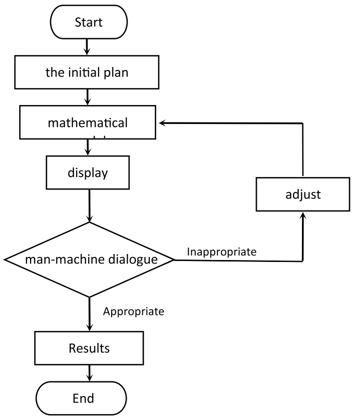

Fig. 1a. The optimal design with help of computers

Rys. 1a. Optymalizacja projektu ze wspomaganiem komputerowym

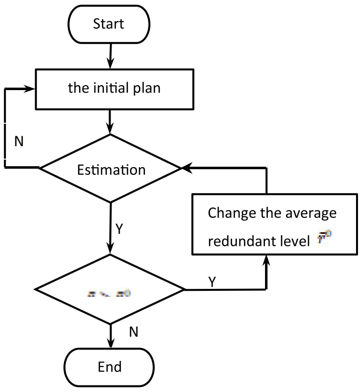

Fig. 1b. The optimal design according to the average redundant level of the measured values with the target function chosen to be the weakest position error in the network

Rys. 1b. Optymalizacja projektów odniesieniu do średniego poziomu redundancji mierzonych wartości z funkcją celu opartą o najmniejszy błąd pozycji w sieci pomiarowej

$\bar{r}$ is in the range of [0.3, 0.5] (Zhang Zhenglu, 2008). Symbolizing the average redundant level that belongs to the reliability range of [0.3, 0.5] as $\bar{r}^0$, the number of observations n^0 that is respective to the average redundant level is calculated as:

$$n^0 = \frac{t}{1-\bar{r}^0} \tag{14}$$

3. Solving the problem of optimal design of the geodetic control network

3.1. Solving the optimum problems with the help of computers

At present, the optimal design of the ground control network or the deformation monitoring network is mainly done with the help of computers, in fact, this is taking advantage of the calculation and judgment capabilities of computer in combination with the designer's practical experience. Computer helps to display design results at any time. Through man-machine dialogue, instantly adjusting the design plan (a. Add or remove some measurement values; b. Change the weight of the measurement values; c. Add or remove some control points in the network; d. Change the position of some points in the network; e. Change the original model of the network) until the designer satisfies with the proposed plan. Obviously, the end result of this design method is usually not a strictly optimal solution, but close to optimum. Moreover, the method has a simple mathematical model, convenient and flexible operation, the plan shows the reasonableness and feasibility of the design results. This design plan is implemented according to the process in Figure 1a.

3.2. Solving the optimum problems according to the average redundant level of the observations

Based on the theoretical research, the article proposes a process of the optimal design of the plane control network according to the average redundant level of the measured values, with the target function chosen to be the error of the weakest position in the network. The process is shown in Figure 1b and includes steps as follows:

1: The initial plan is that position of points and the network diagram must be designed on topographic maps and checked in the field. This plan should include all measurable values of the network.

2: Estimate the network according to the original design plan, with the limit error of the weakest position, and the accuracy of machines as required by the designer.

3: Comparison of the results (error of the weakest position with the input limit error), if the plan no gains requirement, it is necessary to redesign.

4: When the network has enough conditions for optimization, the average redundant level is chosen smaller, calculation for reducing the number of observations and the network is re-estimated whether it achieves the initial requirements.

Fig. 2. Hinh river hydroelectricity plants (https://triphunter.vn/places/phu-yen/items/ho-thuy-dien-song-hinh)

Rys. 2. Elektrownia wodna na rzece Hinh

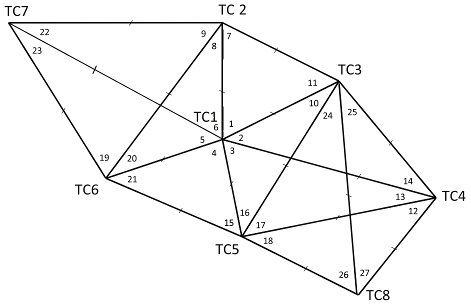

Fig. 3. The base network in horizontal displacement monitoring at Hinh river hydroelectricity

Rys. 3. Bazowa sieć kontrolno-pomiarowa dla badania przemieszczeń poziomych dla elektrowni

5: If the obtained accuracy of the network is better than the input requirement, then the average redundant level is adjusted much smaller and the network is re-estimated until gaining the requirements before stopping.

Comparing the optimal design method with the help of computers and the proposed method in the article, some comments are given as follows:

- The optimal design plan with the help of computers has generality characteristic, which can change many components of design plan. However, if the most optimal plan is chosen, this may be inappropriate to reality. Another disadvantage is without experience expert no gaining good results after optimum.
- The optimal design method according to the average redundant level of the observations with the target function chosen to be the error of the weakest position has narrower applicability. This method is done based on the network determined before on maps and fields. The average redundant level of the observations is chosen in the allowance range as [0.3, 0.5] to calculate the number of unnecessary observations that need to be omitted but still gaining the requirement accuracy. Moreover, this method no needs calculation experts but the final results are similar to the ones achieved from optimal design by computers

4. Experiment and discussion

4.1. Experimental area

The experiment of optimal design for the base network of the horizontal displacement monitoring was done at the Hinh river hydroelectric dam in Phu Yen province of Vietnam. This is a hydroelectric project with the earth-rock dam lied on the Hinh river in Ea Trol commune, Hinh river district. The hydroelectric dam is about 35 kilometres from Tuy Hoa city in the southwest. Hinh river hydroelectricity has a capacity of 70 MW including 2 units, annual electricity output of 370 million KWh, started in 1993 and completed in 2001. The normal rise water level in the reservoir is 209 m, dead water level is 196 m, total reservoir capacity is 357 million m^3. The elevation of the dam crest is 215 m, the highest flood discharge capacity is 6,952 m^3/s.

The plane base network is considered as the origin to monitor the horizontal displacement of the Hinh river hydroelectric dam. Figure 2 is the image of hydroelectric plant and dam, figure 3 is the diagram of the base control network for horizontal displacement monitoring at Hinh river hydroelectricity.

4.2. Data for research

The base network in horizontal displacement monitoring at Hinh river hydroelectricity includes 8 points, that are symboled from TC1 to TC8 (two points TC1 and TC7 were defined coordinates). According to Vietnam's regulations on the network of horizontal displacement monitoring of hydroelectric projects, the Hinh river hydroelectric dam is an earth-rock dam, so the accuracy of the monitoring point is ±5 mm (TCVN 9399-2012). The network of horizontal displacement monitoring usually consists of 2 levels, namely the base network and the monitoring network. Assuming the accuracy of the 2 network levels are respectively m_I and m_{II} the influence of the monitoring network system on the accuracy of the point P is determined as follows:

$$m_P^2 = m_I^2 + m_{II}^2 \tag{15}$$

K is called the accuracy declining coefficient between two network level, then

Tab. 1. The designed angles in the base network of the horizontal displacement monitoring at Hinh river hydroelectricity

Tab. 1. Projektowane do pomiaru kąty w sieci kontrolno-pomiarowej badania przemieszczeń poziomych dla hydroelektrowni na rzece Hinh

No	Angles			No	Angles			No	Angles		
	left	**middle**	**right**		**left**	**middle**	**right**		**left**	**middle**	**right**
1	TC2	TC1	TC3	10	TC5	TC3	TC1	19	TC7	TC6	TC2
2	TC3	TC1	TC4	11	TC1	TC3	TC2	20	TC2	TC6	TC1
3	TC4	TC1	TC5	12	TC8	TC4	TC5	21	TC1	TC6	TC5
4	TC5	TC1	TC6	13	TC5	TC4	TC1	22	TC2	TC7	TC1
5	TC6	TC1	TC7	14	TC1	TC4	TC3	23	TC1	TC7	TC6
6	TC7	TC1	TC2	15	TC6	TC5	TC1	24	TC4	TC3	TC8
7	TC3	TC2	TC1	16	TC1	TC5	TC3	25	TC8	TC3	TC5
8	TC1	TC2	TC6	17	TC3	TC5	TC4	26	TC5	TC8	TC3
9	TC6	TC2	TC7	18	TC4	TC5	TC8	27	TC3	TC8	TC4

Tab. 2. The designed sides in the base network of the horizontal displacement monitoring at Hinh river hydroelectricity

Tab. 2. Projektowane do pomiaru odległości w sieci kontrolno-pomiarowej badania przemieszczeń poziomych dla hydroelektrowni na rzece Hinh

No	Side		No	Side		No	Side	
	the first point	**the end point**		**the first point**	**the end point**		**the first point**	**the end point**
1	TC1	TC2	7	TC2	TC7	13	TC2	TC6
2	TC1	TC3	8	TC5	TC4	14	TC3	TC4
3	TC1	TC4	9	TC5	TC6	15	TC3	TC5
4	TC1	TC5	10	TC8	TC4	16	TC3	TC8
5	TC1	TC6	11	TC8	TC5			
6	TC2	TC3	12	TC6	TC7			

Tab. 3. The approximate coordinates of points

Tab. 3. Aproksymowane współrzędne punktów sieci kontrolno-pomiarowej

No	Name	Coordinate X (m)	Coordinate Y (m)	No	Name	Coordinate X (m)	Coordinate Y (m)
1	TC1	1429644.5460	277440.1230	5	TC5	1428937.2038	277222.4129
2	TC2	1430267.8209	277344.1670	6	TC6	1429502.2342	276873.8156
3	TC3	1430047.6716	277817.5782	7	TC7	1430561.2500	276420.7270
4	TC4	1429299.9189	277995.9955	8	TC8	1428889.8779	277877.6087

$$m_I = \frac{m_2}{K} \tag{16}$$

Formula (15) can be shown as

$$m_P^2 = \frac{m_{II}^2}{K} + m_{II}^2 \tag{17}$$

Calculated

$$m_{II} = \frac{m_P K}{\sqrt{1+K^2}} \text{ and } m_I = \frac{m_P}{\sqrt{1+K^2}} \tag{18}$$

Accuracy declining coefficient is usually chosen K=1-2, choosing K needs to comply the characteristic of network and accuracy of the observed equipment. In this example, formulas from (15) to (18) are used and K is chosen to be 2, calculating m_I= ±2.3 mm, m_{II}= ±4.5 mm. According to (TCVN 9399-2012), with the earth-rock dams, K should be chosen to be K=1, then m_I=m_{II}= ±3.6 mm. Because the network has high accuracy requirement, the initial intention of using equipment is electronic total station TC1700. According to specifications of machine, mean square error of angle measurement is 1.0", mean square error of side measurement is 1+1*ppm*. The initial plan includes total 43 observations, with 27 angle measured values, 16 side measured values, which are shown in Table 1 and Table 2.

4.3. Optimal design for networks

The base network in horizontal displacement monitoring for hydroelectric dam is the free network. With this characteristic, the network uses the average center point to be the coordinate origin, so it is hardly affected by error of the original data. Based on coordinates of TC1 and TC7, the approximate coordinates of other points in the network are calculated as Table 3.

Optimum for network according to the average redundant level of the measured values with the target function chosen to be the weakest position error is done the following steps:

a) Estimating the accuracy of the network by the algorithm of free adjustment with all measured values, the estimated results are shown in Table 4.

According to the estimated results, the point that has the weakest position error TC7, m_P=2.0(mm). From formula (3), the average redundant level of the measured value is calculated as 0.7, so the network is entirely optimal because the average redundant level is bigger than the range [0.3,0.5]

b) To determine the number of the omitted measuring values at each the redundant level in the range [0.3,0.5], as well as investigate the error of the weakest position, the network is designed in three plans that have the average redundant level, respectively $\bar{r}$=0.5; $\bar{r}$=0.4 và $\bar{r}$=0.3. The redundant levels of the measured values are shown in Table 5 and performed in figure 5.

The Figure 5 shows that the redundant level of almost the angle measuring values (from number 1 to number 27) is bigger than the redundant level of the side measuring values (from number 28 to number 43). So after optimum, the omitted measuring values are mainly angle values.

Tab. 4. Result of estimation for the initial design network

Tab. 4. Wyniki estymacji wstępnej dla projektowanej sieci kontrolno-pomiarowej

No	Name	X(m)	Y(m)	m_X(mm)	m_Y(mm)	m_P(mm)
1	TC1	1429644.546	277440.123	0.7	0.8	1.1
2	TC2	1430267.820	277344.168	1.0	0.8	1.3
3	TC3	1430047.671	277817.577	0.8	1.0	1.3
4	TC4	1429299.920	277995.994	0.8	0.9	1.2
5	TC5	1428937.206	277222.414	1.0	0.8	1.3
6	TC6	1429502.235	276873.817	0.9	1.1	1.4
7	TC7	1430561.250	276420.727	1.4	1.4	2.0
8	TC8	1428889.881	277877.607	1.0	1.1	1.4

Tab. 5. The redundant level of each measured value in the network

Tab. 5. Poziom redundancji dla kazdej mierzonej wartości w sieci kontrolno-pomiarowej

No	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
r	0.80	0.83	0.94	0.67	0.81	0.82	0.76	0.85	0.78	0.61	0.71	0.67
No	13	14	15	16	17	18	19	20	21	22	23	24
r	0.74	0.91	0.98	0.96	0.92	0.86	0.85	0.88	0.81	0.94	0.96	0.91
No	25	26	27	28	29	30	31	32	33	34	35	36
r	0.94	0.77	0.70	0.59	0.56	0.50	0.62	0.44	0.40	0.62	0.56	0.47
No	37	38	39	40	41	42	43					
r	0.36	0.40	0.65	0.54	0.59	0.71	0.63					

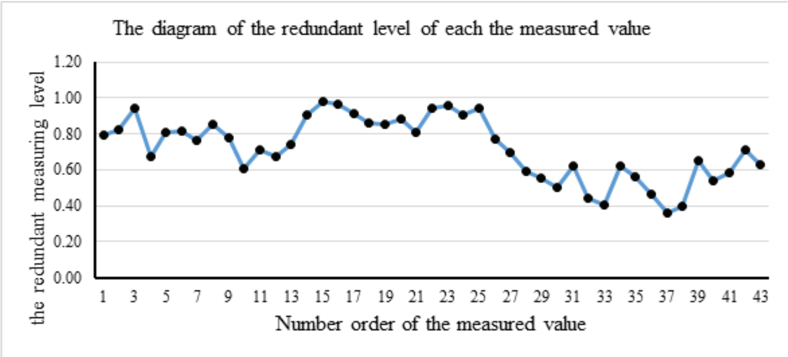

Fig. 5. The diagram of the redundant level of each the measured value

Rys. 5.Wykres poziomu redundancji dla każdej mierzonej wartości

c) The network optimum results with the binding condition as the weakest position error in three mentioned design plans are shown in the table 6.

The Table 6 shows that:

- The omitted measured values are usually the angle measuring values because these have large redundant level.
- Results of estimation in three plans with $\bar{r}$=0.5, 0.4 and 0.3 are good, error of the weakest position is smaller than the initial target ±3.6 mm.
- All three plans can be used to measure in the field, but in our opinion, the second plan with $\bar{r}$=0.4 should be chosen so that the network has good connection and no deviation in azimuth. In addition, the measured values in the field is also affected by many different sources of error, so the structure of network has to be tight.
- With this design plan, the initial network is omitted 23 the angle measuring values, the reality network only needs to observe 20 the measured values including 4 the angle measuring values (table 7), 16 the side measuring values as the initial design, the efficiency of the measuring volume reaches 53%. The shape of network after optimum is shown as Figure 6.

5. Discussion

Results of the experiment of the optimal design according to the average redundant measuring level with the target function chosen to be the weakest position error show that:

- The measuring values that are cut have the redundant level from high to low;
- When using this optimal design method, it is possible to calculate quickly the number of the omitted measuring values, the necessary values that are respective to the average redundant measuring level as formula (14);
- The number of the measured values before and after optimum that are respective to each the average redundant measuring level are different, the number of the omitted values at average is approximate 50% but the accuracy requirement of the weakest position is still ensured the same as the initial requirement.

6. Conclusion

- The base network in structural horizontal displacement monitoring should be optimized because this

Tab. 6. Table of comparing the number of the measured values and design efficiency before and after optimum

Tab. 6. Zestawienie porównywanej liczby wartości pomiarowych i projektowych współczynników efektywności przed i po optymalizacji

Plan	The average redundant measuring level	The number of angles	The number of sides	Total value	Mean square error of the weakest position TC7(mm)	The omitted measured values	Efficiency
initials $\bar{r}$	0.70	27	16	43	2.0		
optimum $\bar{r}^0$	0.5	8	16	24	2.4	19	44%
	0.4	4	16	20	2.5	23	53%
	0.3	2	15	17	2.6	26	60%

Tab. 7. The angular values after optimum with redundant measuring level

Tab. 7. Wartości kątów po optymalizacji z poziomem redundacji

No	Angle			redundant measuring level	No	Angle			redundant measuring level
	left point	middle point	right point			left point	middle point	right point	
4	TC5	TC1	TC6	0.673	12	TC8	TC4	TC5	0.674
10	TC5	TC3	TC1	0.610	27	TC3	TC8	TC4	0.697

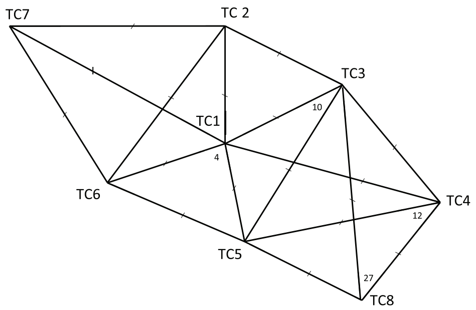

Fig. 6. The base network in horizontal displacement monitoring at Hinh river hydroelectricity after optimum with

Rys. 6 . Bazowa sieć kontrolno-pomiarowa do badania przemieszczeń poziomychdla elektrowni na rzece Hinh po optymalizacji na poziomie

kind of network is measured iteratively, has high accuracy requirement but usually uses the angle-side network.

- The average redundant measuring level is the important indicators in optimal design for network, the number of the measured values after optimizing are determined based on this indicator.
- Optimal design according to the average redundant level with the target function chosen to be the weakest position error achieves high efficiency, it is suitable for the network with a lot of the measured value and the angle-side network.
- This method only need to determine the average value from redundant measuring level of the measured values. The optimal result no depends on knowledge, experience of designer but still ensure tightness and consistence.
- This optimum method has no consider the priority direction in the design yet.

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Metoda optymalnego projektowania sieci bazowej w monitoringu deformacji konstrukcji w elektrowni wodnej Song Hinh, Wietnam

W artykule przedstawiono metodę optymalnego projektowania sieci bazowej w monitoringu przemieszczeń poziomych elektrowni wodnych na podstawie średniego poziomu rezydualnego zmierzonych wartości. Gdy funkcją docelową jest najsłabszy błąd pozycjonowania, uzyskany wynik po optymalizacji jest unikalnym planem, który nie zależy od projektantów i ich doświadczenia. Jest to więc pomocne dla jednostek produkcyjnych, ponieważ nie potrzebują one ekspertów do projektowania sieci. Eksperyment dla podstawowej sieci monitorowania deformacji w elektrowni wodnej Song Hinh pokazuje, że 44%, 50% i 60% początkowego pomiaru można zmniejszyć, gdy średni poziom pozostałości zostanie wybrany odpowiednio 0,5, 0,4 i 0,3. Najsłabszy błąd pozycji sieci po optymalizacji wynosi odpowiednio 2,4 mm, 2,5 mm i 2,6 mm, wszystkie są mniejsze niż wymagane ±3,6 mm. Metodę tę stosuje się głównie dla sieci kątów bocznych, które zostały zmierzone przez tachimetr, bez uwzględnienia optymalnej sieci projektowej w kierunku pierwszeństwa.

Słowa kluczowe: *pozioma sieć kontrolna, optymalizacja projektu, poziom residuum, pomiary inżynierskie, błąd pozycji*