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ESTABLISHMENT OF A SUITABLE REFERENCE SYSTEM FOR THE GEODETIC HORIZONTAL CONTROL NETWORK IN HYDROELECTRIC CONSTRUCTION IN VIET NAM

Purpose. To propose an approach that can be applied efficiently when selecting the coordinate system used in hydroelectric construction in Viet Nam.

Methodology. The efficiency of the proposed approach is first demonstrated by comparing the relative reduction of distances between the Gauss-Krüger and 3-degree and 6-degree UTM projections. It is then proved with an experiment at a hydroelectric power in Viet Nam by comparing the reductions of distances estimated by the proposed approach and those computed from using the VN-2000 coordinate system that is frequently applied.

Findings. The experimental results indicated that the proposed approach is more efficient in establishing the geodetic horizontal network in hydroelectric construction in Viet Nam with much smaller distortion in the geometrical size and shape of the network.

Originality. This work is the first study on selection of the geodetic horizontal network in hydroelectric construction in Viet Nam based on the average height and the longitude of the center of the construction area.

Practical value. The approach proposed in this work can be applied easily and efficiently in practical applications of hydroelectric power construction in Viet Nam, particularly in the areas with high altitude with reference to the ellipsoid as well as the areas located far away from the central meridians of the Viet Nam's VN-2000 reference system.

Keywords: *geodetic horizontal control network, reference system, Gauss-Krüger, UTM, HN-72, VN-2000, Viet Nam, hydroelectric power*

Introduction. Horizontal control networks used in hydroelectric works in Viet Nam are usually established in mountainous areas with high altitudes above mean sea level [1]. These are special networks with a high accuracy requirement and are built based on a rigorous process and strict mathematical equations so that the distortions of the size and the shape of the networks are kept minimal [2, 3]. With this in mind, there have been several studies to increase the accuracy of these networks at different stages, especially in concrete or roller compacted hydroelectric dam construction. For example, at the network design stage, various considerations should be taken such as choosing surveying instruments [4] with high accuracy as possible [5, 6], using forced centering pillars, designing a network with a strong geometry condition [7], or selecting a suitable reference system to guarantee small distortion in the network's size [8, 9]. In terms of network optimization [10, 11], at the data processing stage, gross errors or blunders need to be detected and eliminated from the measurements [12, 13] before a suitable adjustment method is applied.

Hydroelectric power factories are usually constructed in small, narrow, and hilly areas in which rivers and streams have steep slopes [14]. As a result, hydropower plants, which are usually situated far away from the dams, often have large altitudes, some of which are up to 1000 m. In Viet Nam, the engineering geodetic networks are established based on a national coordinate system such as Hanoi 1972 (HN-72) or Viet Nam 2000 (VN-2000) [15, 16]. However, Viet Nam has not had a unified regulation of using coordinate systems for constructing hydroelectric works so far. With a network made directly on a national reference system, a large distortion in the size, i.e., distances between points, occurs frequently in hydroelectric power construction. Distance measurements of a network are usually projected to a suitable plane according to the elevation of the construction site by the Gauss-Krüger or Universal

Transverse Mercator (UTM) projection, by which the distortion of the network in its size is small. This results in flexible selections of the reference system for each specific network so that the reductions used to project the network's measurements to the local reference plane are the smallest. This article studies a method to establish a reference system using the UTM projection for the horizontal network in hydroelectricity construction in Viet Nam which is termed a "mean central meridian coordinate system". The proposed approach is tested with the control network at Thuong Kon Tum hydroelectric power of Viet Nam.

The remainder of the study is organized as follows. The theoretical basis of the coordinate system and reference plane for the engineering geodetic control network is described in Section 2. Section 3 shows the experiment and Section 4 concludes the study.

Theoretical basis of the coordinate system and reference plane for the engineering geodetic control network. A general principle in processing data of a geodetic horizontal network in engineering surveying is that all measurements in the network are projected to a selected horizontal reference plane. There are two steps in this projection that are projecting the measurements from the Earth's surface to the ellipsoid and from the ellipsoid to the reference plane. To this end, the reductions must be determined based on which the direction and distance measurements are corrected.

Measurement reduction. *Reduction of direction measurements.* When direction observations are projected to the reference plane, a reduction is added to the direction between measured points 1 and 2 that is calculated by

$$\delta''_{1,2} = \frac{\rho''}{6R_m^2}(x_1 - x_2)(2y_1 + y_2),\qquad(1)$$

where (x_1, y_1) and (x_2, y_2) are the coordinates of the two points, R_m is the mean radius of the ellipsoid ($R_m \approx 6372$ km); ρ'' is the radian-to-degree constant ($\rho'' \approx 206{,}264.8062$). In engineer-

ing geodetic networks with short sides not exceeding 5 kilometers, the direction reductions are small and are usually ignored.

Reduction of distance measurements. Fig. 1 shows the reduction of the distance measurement measured on the Earth's surface to the ellipsoid and the reference surface. A reduction (ΔS_H) to project the distance measurement between two points A and B on the Earth's surface to the ellipsoid is calculated by [17, 18]

$$\Delta S_H = -S \frac{H_m - H_0}{R_m}, \qquad (2)$$

where $S = AB'$ (Fig. 1) is the length of the horizontal distance; H_m is the mean height of the two points w.r.t the ellipsoid surface; H_0 is the elevation of the selected reference surface w.r.t the ellipsoid.

A reduction added to the distance on the ellipsoid to project to the reference surface is calculated approximately by [17, 18]

$$\Delta S_H = S\left(k - 1 + \frac{Y_m^2}{2R_m^2}\right)\Delta S_{mp} = S\left(k - 1 + \frac{Y_m^2}{2R_m^2}\right), \qquad (3)$$

where Y_m is the mean coordinate in the Y direction of the two points A and B; k is the scale factor of the projection, i.e., the distortion coefficient in length at the central meridian of the projection (the central meridian coincides with the vertical axis of the coordinate system); $k = 1$ with the Gauss-Krüger projection and $k = 0.0006$ or $k = 0.9999$ with the UTM projection with the 6° zone or the 3° zone, respectively. In Viet Nam, from 2000 up to now, the UTM projection has been used with the VN-2000 coordinate system, while the Gauss-Krüger projection had been used before in the HN-72 system [15].

The two projections of Gauss−Krüger and UTM are different in their scale factors. As a result, the reduction of distances in the Gauss-Krüger projection is positive and increases from the central meridian to the edges of the projection zone. In contrast, in the UTM projection, the reduction is either positive or negative depending on the relative position of the middle point of the side w.r.t the central meridian. To ensure the size of the horizontal control network to be similar to that measured on the Earth's surface, the reduction of distances must be small as possible. For this reason, the elevation of the reference surface (H_0) and the coordinate system (represented by the longitude of the central meridian L_0) need to be chosen reasonably. They have usually been selected as [17, 18]:

- the size of the ellipsoid is chosen so that its surface is coincident with the average height of the construction area to minimize the reduction of distances to the ellipsoid;
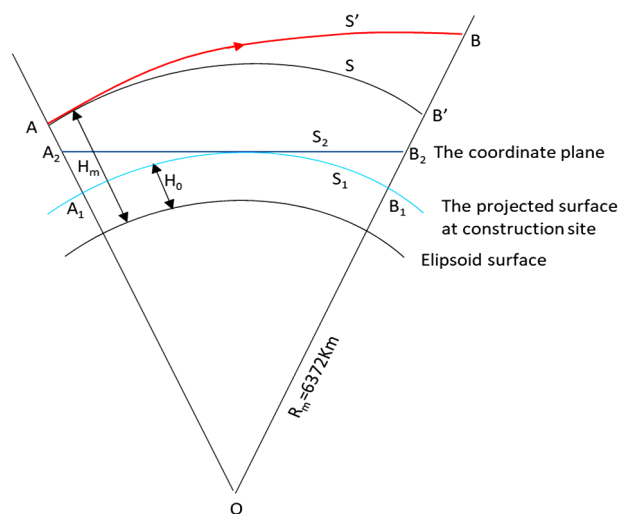
- the central meridian is chosen suitably according to the projection and zone width that are used;

- for the Gauss-Krüger projection with the scale factor $k = 1$, the central meridian is selected so that $Y_m = 0$, i.e., the central meridian is with the longitude being the same as the mean longitude of the construction site;

- for the UTM projection, the central meridian is chosen in a way so that its distance to the center of the construction site is ± 180 or ± 90 km corresponding to a 6-degree or a 3-degree zone. As a result, the mean longitude of the construction site is $Y_m = \pm 180$ km with a 6-degree zone or $Y_m = \pm 90$ km with a 3-degree zone.

With the selection of the coordinate system as mentioned above, when a distance is projected from the ellipsoid to the reference plane, the reduction ΔS_{mp} estimated using (3) is small if the middle point of the side is located near the center of the construction site where the scale factor is $k \approx 1$. On the contrary, if the middle point of the side is located further from the center of construction site, the reduction is larger. The influence of choosing the central meridian on the reduction ΔS_{mp} in the Gauss-Krüger and UTM projections can be measured by the relative reduction of the distances as

$$\frac{\Delta S_{mp}}{S} = k - 1 + \frac{Y_m^2}{2R_m^2}. \qquad (4)$$

In (4), the relative reduction of the distance $\frac{\Delta S_{mp}}{S}$ changes according to different values of Y. Table 1 shows the values estimated from points at different distances to the center of the construction site according to the Gauss-Krüger and UTM projections.

From Table 1, some comments are given as:

- the reduction used to project a distance from the ellipsoid to the reference plane in the Gauss-Krüger projection is small and varies slowly when the average coordinate increases far from the central meridian;

- the reduction in the UTM projection is larger and increases more quickly when the average y coordinate increases further from the central meridian. Moreover, the reduction has opposite signs if the side is on the right and on the left of the central meridian, thereby causing significant distortion to the network.

Nowadays, in Viet Nam, the VN-2000 reference system with the UTM projection is used to minimize the reduction ΔS_{mp} in projection to the reference plane, a new method is proposed to choose the coordinate system and the projection surface for the construction of the horizontal geodetic network in hydroelectric works.

Proposal of the method for choosing the coordinate system and height of the projection surface in the UTM coordinate system. When using the UTM projection, the central meridian of the projection zone is chosen to be the average meridian of the construction site, so the coefficient of length distortion at the central meridian is $k = 0.9999$ (with the 3° zone) and $k = 0.9996$ (with the 6° zone). To let the distortion coefficient in length be equal to 1 (i.e., the reduction is equal to 0), a reduction $\frac{T}{R_m}S$ needs to be brought into (3) to eliminate the first part at the right side of the equation. Then, the height of the projection surface (ellipsoid) is chosen to be coincident with the average height of the construction site. The coordinate system selected as mentioned above is called "the average meridian coordinate system". The method of choosing the central meridian of the average coordinate system is depicted in Fig. 2.

The reduction in projecting the side to the plane is calculated as

$$\Delta S_{mp} = S\left(k - 1 + \frac{Y_m^2}{2R_m^2} + \frac{T}{R_m}\right), \qquad (5)$$

Fig. 1. Reduction of distance measurements on the ellipsoid surface and the reference plane

Table 1

Relative reduction of distances estimated from points at different distances to the center of the construction site with Gauss-Krüger and UTM projections. Y_m is 90 or 180 km with the Gauss-Krüger projection, the 3-degree UTM projection or 6-degree UTMprojection

Projection	$\Delta S_{mp}/S$					
	$Y_m - 20$ km	$Y_m - 10$ km	$Y_m - 5$ km	$Y_m + 5$ km	$Y_m + 10$ km	$Y_m + 20$ km
Gauss-Krüger projection	1/20300	1/812000	1/3246000	1/3246000	1/812000	1/203000
UTM projection with the 3° zone	−1/25200	−1/47300	−1/91100	1/89200	1/43100	1/20400
UTM projection with the 6° zone	−1/11800	−1/22800	−1/44200	1/46000	1/22300	1/10800

with the condition $\Delta S_{mp} = 0$ when $Y_{mp} = 0$; is determined

$$T = R_m(k - 1). \qquad (6)$$

In the UTM projection with the 3° zone or the 6° zone, T is 637 or 2548 m, respectively. This proves that the coefficient T affects similarly as the average height of the measured side to the reduction in the side after projecting to ellipsoid. Therefore, in fact, in the average meridian coordinate system, the central meridian is chosen to coincide with the average meridian at the construction site and the height of the projection surface is $H_m - H_m + T$. Thus, with the proposed average meridian coordinate system, the reduction in length is calculated as:

- the reduction after projecting to ellipsoid

$$\Delta S_H = -S\frac{T + H_m - H_0}{R_m}; \qquad (7)$$

- the reduction after projecting to the reference plane

$$\Delta S_{mp} = S\left(k - 1 + \frac{Y_m^2}{2R_m^2}\right). \qquad (8)$$

In (7) and (8), the values of the coefficients T and k depend on the projection zone in the UTM projection. In the 3° zone, the distortion coefficient at the central meridian is $k = 0.9999$, then $T = 637$ m, and in the 6° zone, $k = 0.9996$, $T = 2548$ m.

Experiment of establishing the reference system for the horizontal control network at Thuong Kon Tum hydroelectricity. *Introduction of the works.* Thuong Kon Tum hydroelectricity is the work with hydroelectric plant far from the dam and linked to the dam by pipeline. The capacity of the work is 220 MW. The dam and water receiving gate are located in the Dak Nghe River, Dak Tang commune. The hydroelectric plant is located upstream of the river Dak Lu, Ngoc Tem c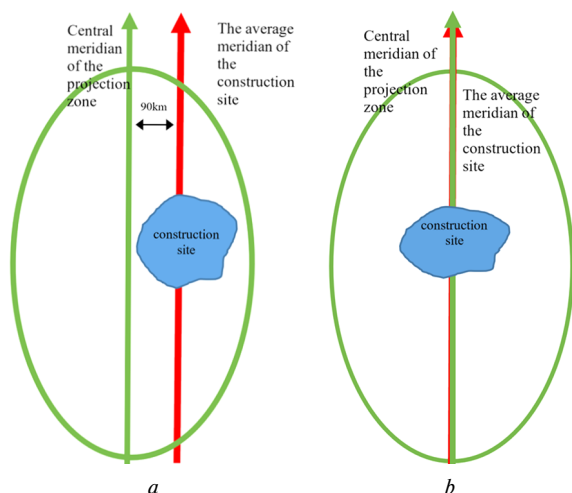ommune. The entire work belongs to the Konplong district, Kon Tum, Viet Nam. The energy line (water tunnel) is nearly 20 km long and the water column is 937 m high. Fig. 3 is the image of the dam and water reservoir.

The horizontal control network was built at the area of the water receiving gate, the energy line, and the plant to serve the construction in 2015. The network was measured by GPS in the VN-2000 reference system with the 3° projection zone. The central meridian was chosen at 107°30′00″. The network has nine points (from TC-01 to TC-09), which are distributed into three clusters. The average height of the points is $H_0 = 700$ m. A diagram of the construction plane network at Thuong Kon Tum hydroelectricity is shown in Fig. 4. The measurements of the horizontal geodetic network at Thuong Kon Tum are adjusted by the TBC 3.0 software. The adjusted coordinates and heights of points are given in Table 2.

Choosing the coordinate system for the network. To keep the geometric size of the network close to the real shape (i.e., small distortion), the coordinate system is chosen according to two plans as following.

Plan 1. The central meridian is chosen to be 90 kilometers away from the average meridian of the construction site. With this plan, the GPS coordinates need to be transformed to the projection zone where the central meridian is ± 90 km away from the average meridian of the construction site, and then projected to the chosen projection surface ($L_0 = 107°28′30″$, $H_0 = 700$ m). The results are shown in Table 3.

Fig. 3. Dam and water reservoir of the study area

Fig. 2. The principle of central meridian selection:

a − rules for choosing the central meridian of the UTM projection with the 30 zone; b − the central meridian of the UTM projection with the 30 zone in the average meridian coordinate system

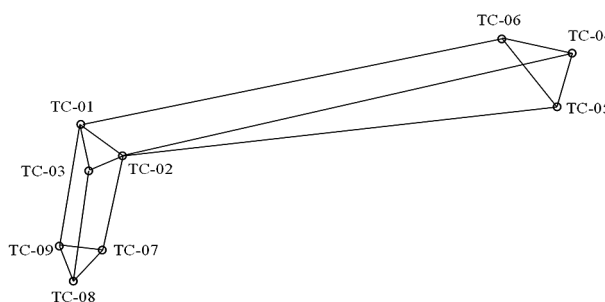*Fig. 4. Diagram of the construction horizontal geodetic network at Thuong Kon Tum hydroelectric work*

Coordinates and heights of points of the construction network

No	Name of point	Coordinate		GPS height, m
		X, m	Y, m	
1	TC-01	1,630,242.4840	578,998.9040	1230
2	TC-02	1,629,937.4520	579,554.6530	1214
3	TC-03	1,629,327.4820	579,202.1710	1204
4	TC-04	1,639,120.1980	597,084.1710	278
5	TC-05	1,636,681.6750	597,194.5470	443
6	TC-06	1,639,587.0130	594,986.0770	607
7	TC-07	1,625,237.0830	578,638.8360	1199
8	TC-08	1,624,808.1070	578,193.0830	1205
9	TC-09	1,625,515.7990	578,268.6040	1163

Plan 2. The construction coordinate system is chosen to be the average meridian coordinate system. This is the new method proposed in the article. The central meridian is chosen to coincide with the average meridian of the construction site. Procedure for establishing the coordinate system is conducted according to the following steps: Firstly, the coordinates are transformed to the projection zone where the central meridian coincides with the average meridian of the construction site ($L_0 = 108°19'00''$). Then, the coordinates of points are corrected by the adding the reduction ΔS_H (7) to the sides with the results shown in Table 4. The next step is the transformation of coordinate to the average plane that has the height of $H_0 = 700$ m, with the results shown in Table 5.

Comparison of the distance between the two plans. Table 6 shows the comparison results of the distances between the two plans of choosing coordinate system and the reductions from the two plans after projecting to the plane.

The calculated results of the construction horizontal control network at Thuong Kon Tum hydroelectricity shows that the reduction in length after projecting to the plane in the UTM projection has relatively large values and increase quickly when the average y coordinate of the side is far from the chosen central meridian. In Table 6, side number 15 has the reduction of 102 mm with the traditional UTM coordinate system. On the contrary, the reduction in the average meridian system has a smaller value, also increases when the average y coordinate of the side is far from the central meridian, but the biggest reduction that belongs to side number 15 is only 11.8 mm.

Moreover, to check rationality and accuracy of calculation, the network was measured for testing three sides by a TCR 407 total station. The measured sides were transformed to the average plane of this work with $H_0 = 700$ meters. These results were compared to the lengths of the same sides in two plans of choosing the coordinate system as mentioned. Results of calculating the differences of lenth between the two plans and testing measurement are shown in Table 7.

The results of comparison in Table 7 show that the reductions in length in the case of using "the average meridian coor-

Results of coordinate transformation according to the first plan

No	Point name	The first zone $L_0 = 107°30'$, $H_0 = 0$ m		The second zone $L_0 = 108°28'30''$, $H_0 = 700$ m	
		X, m	Y, m	X, m	Y, m
1	TC-01	1,630,242.4840	578,998.9040	1,630,430.3248	581,699.7778
2	TC-02	1,629,937.4520	579,554.6530	1,630,125.3194	582,255.6247
3	TC-03	1,629,327.4820	579,202.1710	1,629,515.2400	581,903.1698
4	TC-04	1,639,120.1980	597,084.1710	1,639,311.0797	599,786.1487
5	TC-05	1,636,681.6750	597,194.5470	1,636,872.2854	599,896.8095
6	TC-06	1,639,587.0130	594,986.0770	1,639,777.7146	597,687.7587
7	TC-07	1,625,237.0830	578,638.8360	1,625,424.3078	581,340.2234
8	TC-08	1,624,808.1070	578,193.0830	1,624,995.2331	580,894.4666
9	TC-09	1,625,515.7990	578,268.6040	1,625,703.0149	580,969.9180

Results of the coordinate transformation to the average meridian coordinate system

No	Point name	The first zone $L_0 = 107°30'$, $H_0 = 0$ m		The second zone $L_0 = 108°28'30''$, $H_0 = 700$ m	
		X, m	Y, m	X, m	Y, m
1	TC-01	1,630,242.4840	578,998.9040	1,630,278.2786	491,066.9830
2	TC-02	1,629,937.4520	579,554.6530	1,629,971.2261	491,621.6350
3	TC-03	1,629,327.4820	579,202.1710	1,629,362.5241	491,266.9357
4	TC-04	1,639,120.1980	597,084.1710	1,639,090.2025	509,184.4877
5	TC-05	1,636,681.6750	597,194.5470	1,636,651.3319	509,285.9767
6	TC-06	1,639,587.0130	594,986.0770	1,639,564.6591	507,088.1379
7	TC-07	1,625,237.0830	578,638.8360	1,625,274.0937	490,688.7817
8	TC-08	1,624,808.1070	578,193.0830	1,624,846.7215	490,241.4695
9	TC-09	1,625,515.7990	578,268.6040	1,625,554.1537	490,319.5508

Results of the coordinate transformation to the average plane

No	Point name	The first zone $L_0 = 107°30'$, $H_0 = 0$ m		The second zone $L_0 = 108°28'30''$, $H_0 = 700$ m	
		X, m	Y, m	X, m	Y, m
1	TC-01	1,630,278.2786	491,066.9830	1,630,457.2014	491,066.0026
2	TC-02	1,629,971.2261	491,621.6350	1,630,150.1152	491,620.7155
3	TC-03	1,629,362.5241	491,266.9357	1,629,541.3464	491,265.9772
4	TC-04	1,639,090.2025	509,184.4877	1,639,270.0924	509,185.4957
5	TC-05	1,636,651.3319	509,285.9767	1,636,830.9541	509,286.9958
6	TC-06	1,639,564.6591	507,088.1379	1,639,744.6011	507,088.9158
7	TC-07	1,625,274.0937	490,688.7817	1,625,452.4673	490,687.7598
8	TC-08	1,624,846.7215	490,241.4695	1,625,025.0482	490,240.3985
9	TC-09	1,625,554.1537	490,319.5508	1,625,732.5580	490,318.4884

Comparison of the distances of the sides between two plans of choosing coordinate system

No	Side		Length of side, m		Difference, mm	Reductions after projecting to the plane, mm	
	Beginning point	End point	In the average meridian system	In the VN-2000 system		In the VN-2000 system	In the average meridian system
1	TC-01	TC-02	634.0413	634.0300	−11.3	−10.9	1.2
2	TC-01	TC-03	937.4328	937.4159	−16.9	−16.5	1.8
3	TC-02	TC-03	704.5841	704.5717	−12.4	−12.0	1.3
4	TC-04	TC-05	2441.2493	2441.3036	54.3	55.5	5.1
5	TC-04	TC-06	2149.6060	2149.6485	42.5	43.1	3.5
6	TC-05	TC-06	3649.7801	3649.8526	72.5	73.6	6.0
7	TC-07	TC-08	618.7239	618.7117	−12.2	−11.7	1.4
8	TC-07	TC-09	463.4783	463.4692	−9.1	−8.8	1.0
9	TC-08	TC-09	711.8063	711.7921	−14.2	−13.8	1.7
13	TC-01	TC-07	5019.0070	5018.9128	−94.2	−91.2	10.3
14	TC-02	TC-08	5307.6913	5307.5924	−98.9	−95.9	10.8
15	TC-01	TC-08	5494.5346	5494.4288	−105.8	−102.3	11.8

Comparison of the lengths after transforming with the one from the direct measurement

No	Name of the side		The length of the side, m			Difference, mm	
	The beginning	The end	Plan 1	Plan 2	Testing mesurement	Plan 1	Plan 2
1	TC-02	TC-01	634.0300	634.0413	634.0386	−8.6	2.7
2	TC-02	TC-03	704.5717	704.5841	704.5809	−9.2	3.2
3	TC-06	TC-04	2149.6485	2149.6060	2149.6113	37.2	−5.3

dinate system" has much smaller values than using the normal coordinate system. This proves the network that is established in this coordinate system has smaller distortion than the one established in the UTM coordinate system with the central meridian which is far from the average meridian of the construction site.

Conclusions. The article has proposed a workflow in choosing the coordinate system used in hydroelectric power construction in Viet Nam. In the first step, the ellipsoid is chosen so that its surface is coincident with the average height of the construction area to minimize the reduction of distances from the Earth's surface to the ellipsoid. In the second step, the central meridian is selected in a way that distances mea-

sured at the center of the construction site are preserved after being projected into the reference plane. The associated system of equations used in computing the reductions of distance and direction measurements has also been presented to be applied with both the Gauss-Krüger and the UTM projections.

The approach proposed in the article has been tested by the experiment for the geodetic horizontal network at Thuong Kon Tum hydroelectricity in Viet Nam. This is the typical type of network which is difficult to process in actual applications. Results from the experiment demonstrated that the average coordinate system has small reductions when the sides of the network are projected from the ellipsoid to the reference plane. The largest reduction is 11.8 millimeters, which is much small-

er than that obtained from the VN-2000 coordinate system at 102.3 millimeters. As a result, the network distortion is smaller. The system of equations presented can be applied efficiently in reality.

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Створення придатної системи орієнтування для геодезичної горизонтальної опорної мережі при гідроелектробудівництві у В'єтнамі

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Мета. Запропонувати підхід, який можна ефективно застосувати при виборі системи координат, що використовується при гідроелектробудівництві у В'єтнамі.

Методика. Ефективність запропонованого підходу спочатку продемонстрована шляхом порівняння відносного зменшення відстаней між проекціями Гаусса-Крюгера та 3- й 6-градусною універсальною поперечною проекцією Меркатора (UTM). Ефективність підходу доведена за допомогою експерименту на гідроелектростанції у В'єтнамі шляхом порівняння скорочень відстаней, оцінених за допомогою запропонованого підходу й розрахованих значень із використанням системи координат VN-2000, що часто використовується.

Результати. Результати проведеного експерименту показали, що запропонований підхід є більш ефективним при створенні геодезичної горизонтальної мережі при гідроелектробудівництві у В'єтнамі зі значно меншими спотвореннями геометричних розмірів і форми мережі.

Наукова новизна. Ця робота є першим дослідженням із вибору геодезичної горизонтальної мережі при гідроелектробудівництві у В'єтнамі на основі середньої висоти й довготи центру району будівництва.

Практична значимість. Запропонований у цій роботі підхід можна легко та ефективно застосувати на практиці при будівництва гідроелектростанцій у В'єтнамі, зокрема в районах із великою висотою по відношенню до еліпсоїда, а також районах, що розташовані далеко від центральних меридіан В'єтнамської системи координат VN-2000.

Ключові слова: *опорна мережа, система орієнтування, Гаусс-Крюгер, UTM, HN-72, VN-2000, В'єтнам, гідроелектробудівництво*