Research article

Effects of Surveying Methods between GNSS and Direct Leveling on Elevation Values over Long Distance in Mountainous Area

TAKAHIKO KUBODERA*
Faculty of Science and Engineering, Toyo University, Saitama, Japan
Email: kubodera@toyo.jp

HIROMU OKAZAWA
Faculty of Regional Environment Science, Tokyo University of Agriculture, Tokyo, Japan

YOSHIHARU HOSOKAWA
Emeritus Professor, University of Miyazaki, Miyazaki, Japan

FUTOSHI KAWANA
Faculty of Regional Environment Science, Tokyo University of Agriculture, Tokyo, Japan

EIJI MATSUO
Faculty of Engineering, Kyushu Sangyo University, Fukuoka, Japan

MACHITO MIHARA
Faculty of Regional Environment Science, Tokyo University of Agriculture, Tokyo, Japan

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Abstract Water use facilities such as irrigation and drainage channels, water gate, hydraulic drop etc. are constructed to make water supply to paddy field and upland field. In a planning of irrigation project, it is necessary to obtain elevation value with accuracy and efficiency around project site. In generally, elevation values are obtained by the direct leveling survey with specific instruments, e.g. digital or auto level, a couple of staffs and turning plates. The direct leveling survey also needs several benchmarks, which are points of reference with high accuracy location information including latitude, longitude and elevation. There is, however, a serious problem that survey work of the direct leveling survey must begin at several benchmarks. In the case of survey work in mountainous area, surveyors must carry out the direct leveling survey over several very-long routes, because there are few benchmarks. On the other hand, in the Global Navigation Satellite System (GNSS) surveying, elevation values can be obtained indirectly by observing carrier phase from multi positioning satellites such as GPS, GLONASS since 2011. This study started to install the new benchmark on a 920 m high mountain, about 5 km away from some known benchmarks in Karuizawa Town, Nagano Prefecture. After surveying the new benchmark by the GNSS and the direct leveling, we compared its elevation values. Furthermore, a streamlined survey process, the influence on most probable value and standard deviation by the difference of using satellite, "GPS-only" and "GPS and GLONASS" were investigated in the GNSS surveying. As the results, our tests found that dramatically streamlined survey process, "GPS-only" can obtain an elevation value that is consistent with the value from the direct leveling survey. Therefore, the GNSS surveying is useful to obtain accurate elevation values over long distance like very long channels.

Keywords GPS, GLONASS, rigorous network adjustment, observation duration

INTRODUCTION

In agricultural irrigation projects, channels are planned to distribute water to the upland and paddy fields within the project area. The channels in such project areas tend to be long. For distributing water in long channels, it is important to use surveying technologies that clarify the elevations of planned channel locations. Conventional survey techniques are time- and labor-intensive. Therefore, the development of survey techniques that are accurate and efficient has been promoted.

It is difficult for developing countries to prepare expensive surveying equipment and use highly advance surveying systems. Such countries request that advanced nations provide them assistance on surveying techniques. Japan once conducted a questionnaire survey on the GNSS continuous observation system in countries receiving overseas development assistance from Japan (Nakagawa el al., 2014). The GNSS continuous observation system uses GNSS-based control stations (i.e., observation stations with GNSS antennas and receivers) for data acquisition, and the system includes analysis and provision of the obtained data. The survey showed that 16 of the 23 countries surveyed had already introduced the GNSS continuous observation system (Nakagawa et al., 2014). Nine of those 16 countries reported using the system for agricultural purposes (Nakagawa et al., 2014). Judging from the questionnaire results, the use of surveying techniques using GNSS in agriculture is being promoted internationally. It is predicted that surveying using the GNSS continuous observation system will become the mainstream technique. The introduction of the GNSS continuous observation system can be expected to drastically eliminate the technical gap between developing countries and developed countries.

In conventional direct leveling, whereby the elevations of planned locations for channels are determined, the relative height are directly surveyed by using level, vertical leveling staffs and turning plates (Okazawa et al., 2014). Observations are made by repeatedly placing the level and the leveling staff at certain intervals along the route from the benchmark to the new point (Okazawa et al., 2014). The problem with this method is that considerable work is required to conduct leveling of a route for planned water channels if the route is in a mountainous area without any benchmarks nearby. The data used in this method are a series obtained in the observations from the benchmark to the new point; therefore, observation errors occurring between the benchmark and the new point greatly affect the final results. Even one error in the routes is not permissible, and the responsibility of the surveyor is always great. There are other problems, such as difficulties in determining what routes to use to access the survey points and the problem of traffic density and traffic safety at the survey points.

In GNSS surveying, which started to be used in 2011, the phases of carrier waves from GPS and GLONASS positioning satellites are observed. All that's required is for the GNSS equipment to be set at the new point. Three-dimensional coordinates of the new point are determined by obtaining the baseline vector from the GNSS-based control station to the new point. A geoid model is necessary for determining the elevation, because the datum of GNSS surveying is a reference ellipsoid and the datum for the elevation is the geoid. In Japan, Japan geoid model “GSIGEO2011”, which is a high-accuracy geoid model, was created (Kodama et al., 2014). The new geoid model has made GNSS leveling possible. GPS and GLONASS are separate systems and the observed data are different. Use of GPS-only or GPS and GLONASS is stipulated for public surveying in Japan. Use of GLONASS-only is not authorized. Studies have compared the use of GPS to the use of GLONASS (Ikeda and Sada, 2012; Mylnikova et al., 2015; Yasyukevich et al., 2015).

Based on such circumstances in Japan, GPS-only and combination of GPS and GLONASS were used in this study. The areas where GNSS leveling is done for agricultural channel planning tend to be far from the existing benchmark. Therefore, the authors selected a location for a new point at the elevation of about 920 m in a mountainous area. The new point was surrounded by large areas of paddy fields and of upland fields for cabbage and blueberry cultivation. Even though the target area already had irrigation channels, the local farmers requested that the accurate elevation of the area be determined.

To examine the conformity of the elevation values surveyed by GNSS leveling and those surveyed by direct leveling, both techniques were used in observing the new point. The most probable value and the standard deviation of the elevation obtained by each technique were determined by rigorous network adjustment and were compared. In GNSS leveling, the influence of the difference between GPS-only observation and GPS and GLONASS observation on the most probable value and the standard deviation was clarified. To investigate the improvements in observation efficiency achieved by GNSS leveling, the work volume of observation by GNSS leveling and by direct leveling were determined and compared.

METHODOLOGY

Methodology of GNSS Leveling

The new point location was set near a paddy field area in a mountainous area at an elevation of about 920 m and about 5 km from the first-order benchmark in Karuizawa Town, Nagano Prefecture. Table 1 shows the outline of the GNSS leveling and direct leveling done for this study.

Table 1 Outline of the GNSS leveling and direct leveling done for this study

Method	Number of new point	Used known point	Used satellite	Date
GNSS leveling	1	3 GNSS-based control stations	GPS, GLONASS	23.Sep.2014
Direct leveling	1	3 first-order benchmarks	None	19-20.Sep.2013

The observation technique used in GNSS leveling was static relative positioning with carrier phase observable. Because the static is most accurate method in GNSS surveying such as the fast static, RTK and so on. The GNSS leveling equipment used was Trimble R8 GNSS of Nikon Trimble Co., Ltd. (Fig. 1). The geoid model used was Japan geoid model "GSIGEO2011". The map of network plan for GNSS leveling was the Y-shaped connected traverse (Fig. 2). The GNSS-based control stations used in the GNSS leveling were the three points No.960610, No.950269 and No.960613. The new point is denoted as No.4101. No.4101 is denominated by the author to distinguish it from other points. Fig. 3 shows the GNSS-based control station No.950269. The provision of GLONASS data, in addition to GPS data, was started in 2013. This study used GPS-only, GPS and GLONASS data from GNSS-based control stations.

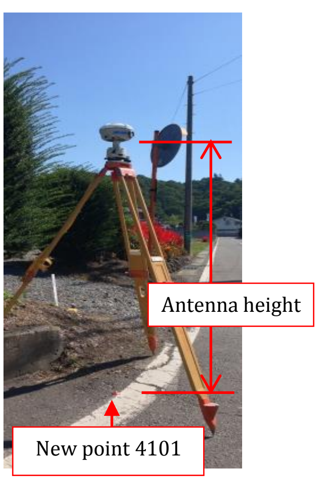

Fig. 1 GNSS leveling survey

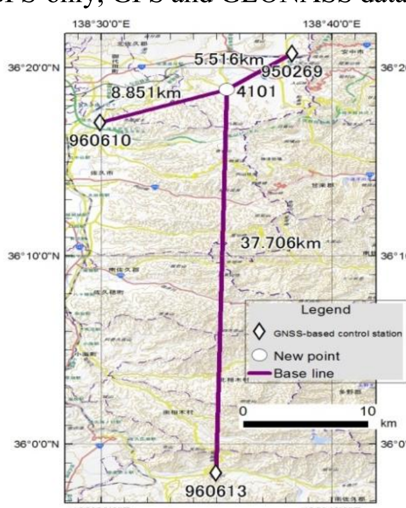

Fig. 2 Map of network plan for GNSS leveling

Fig. 3 GNSS-based control station No.950269

Methodology of Direct Leveling

The direct leveling was done to compare with GNSS leveling. Because the direct leveling is most accurate method in leveling survey. The equipment used for direct leveling was digital levels and bar-code leveling staffs of Leica Geosystems Co., Ltd. or Topcon Corp (Fig. 4). The digital level is accurate than auto level when reading the staff. Even though different levels used because surveyed at same time on different routes, there are no different results comparing Leica and Topcon level. Fig. 5 shows the map of network plan for direct leveling. The first-order benchmarks used in direct leveling were the three points No.18050 (Elevation 948.8876 m), No.18049 (Elevation 938.1914 m) and No.546 (Elevation 940.1693 m). Three intersection points No.1, No.2 and No.3 were set for examining each section. The new point is denoted as No.4101. Fig. 6 shows the first-order benchmark No.546. The first-order benchmark is the benchmark with the highest accuracy. The elevation is marked in units of 0.1 mm.

Fig.4 Direct leveling survey

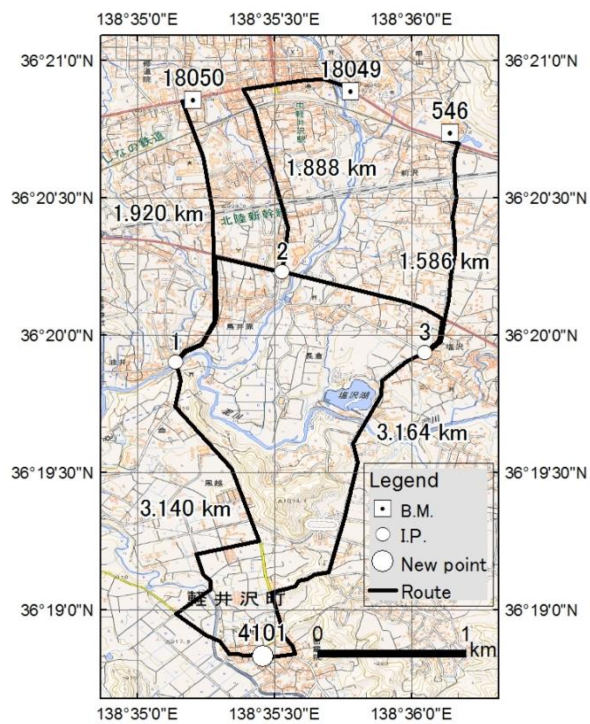

Fig. 5 Map of network plan for direct leveling

Fig. 6 First-order benchmark No.546

Results of Work Volume of GNSS Leveling and Direct Leveling

Table 2 shows the work volume for GNSS leveling and that for direct leveling. GNSS leveling was done by one person (the author). The observation hours in GNSS leveling were 5 continuous hours. The survey manual for elevation surveying by GNSS leveling specifies that the observation hours for GNSS leveling shall be at least 5 continuous hours (Geospatial Information Authority of Japan. 2015). Direct leveling was done by 24 people, including the author. The 23 people, excluding the author, were divided into 6 groups of 3 or 4 persons to survey within 2 days. The observation hours for direct leveling was 11 hours in 2 days. The total observation duration is the observation hours multiplied by the number of observation persons. The total observation duration for GNSS leveling were 5 hours, and those for direct leveling were 264 hours. The total observation duration in GNSS leveling were about one-fiftieth (1/50) that of direct leveling. Even though the result varies depending on the length of the route for direct leveling, the examination clarified that GNSS leveling is able to dramatically improve observation efficiency. Based on the experience of conducting both leveling methods, the author is able to conclude that the use of GNSS leveling helped overcome many problems regarding direct leveling, including planning for routes to the survey points, problems of traffic conditions and traffic safety at the survey points, and the mental stress on the surveyor in work that does not allow even one error.

Table 2 Work volume for GNSS leveling and that for direct leveling

Method	Number of observation persons	Observation hours [h]	Total observation duration [h]
GNSS leveling survey	1	5	5
Direct leveling survey	24	11	264

Rigorous Network Adjustment

To determine the most probable value and standard deviation of the elevation of the new point based on the observed data (i.e., the relative height or baseline vectors), rigorous network adjustment was done for the data obtained by GNSS leveling and direct leveling. In rigorous network adjustment, an observation equation and a residual equation are formulated for the unknowns of the new point, a normal equation is formulated by using the least-squares method and that equation is solved (e.g. Tajima and Komaki, 2001).

Eq. (1) is the formulated observation equation.

$$\mathbf{AX} = \mathbf{L} \tag{1}$$

Where $\mathbf{A}$: Coefficient matrix

$\mathbf{X}$: Unknown vector

$\mathbf{L}$: Constant vector

The unknown vector is the unknown to be determined, and the constant vector includes the observed values and the values for the known points. Practically, each observed values contains error. Therefore, a residual equation shown as Eq. (2) is formulated.

$$\mathbf{V} = \mathbf{AX} - \mathbf{L} \tag{2}$$

Where $\mathbf{V}$: Residual vector

Then, a normal equation is formulated based on the least-squares method such that the sum of squares of the residual vector $\mathbf{V}^{\mathrm{T}}\mathbf{PV}$ for which the weight is considered is the smallest. Eq. (3) is the formulated normal equation. The weight is a function of distance.

$$\mathbf{A}^{\mathrm{T}}\mathbf{PAX} = \mathbf{A}^{\mathrm{T}}\mathbf{PL} \tag{3}$$

Where $\mathbf{P}$: Weight matrix

Eq. (4) shows the solution for the normal equation, and Eq. (5) shows the residual. To fulfill the requirement for high accuracy, the unknown is determined by using the observed value, which is greater than the unknown, and the least-squares method. The most probable value of the unknown, which is the most probable value for the elevation of the new point, is determined as a solution Eq. (4) to the normal equation obtained by using the least-squares method.

$$\hat{\mathbf{X}} = \left(\mathbf{A}^{\mathrm{T}}\mathbf{PA}\right)^{-1}\mathbf{A}^{\mathrm{T}}\mathbf{PL} \tag{4}$$

Where $\hat{\mathbf{X}}$: Solution of the normal equation obtained by using the least-squares method.

$$\hat{\mathbf{V}} = \mathbf{A}\hat{\mathbf{X}} - \mathbf{L} = \mathbf{A}\left(\mathbf{A}^{\mathrm{T}}\mathbf{P}\mathbf{A}\right)^{-1}\mathbf{A}^{\mathrm{T}}\mathbf{P}\mathbf{L} - \mathbf{L} \tag{5}$$

Where $\hat{\mathbf{V}}$: Residual of the normal equation obtained by using the least-squares method.

Eq. (6) shows the standard deviation of unit weight. The standard deviation of unit weight is the standard deviation of the observed weight.

$$m_0 = \sqrt{\frac{\hat{\mathbf{V}}^{\mathrm{T}}\mathbf{P}\hat{\mathbf{V}}}{n-m}} \tag{6}$$

Where m_0 : Standard deviation of unit weight

n : Number of the observation equations

m : Number of the unknowns

The inverse matrix of the coefficient matrix of the normal equation is shown as Eq. (7), which is called the weight coefficient matrix.

$$\mathbf{Q} = \left(\mathbf{A}^{\mathrm{T}}\mathbf{P}\mathbf{A}\right)^{-1} \tag{7}$$

Where $\mathbf{Q}$: Inverse matrix of the coefficient matrix of the normal equation

Eq. (8) shows the standard deviation of the most probable value of the unknown. This standard deviation is the standard deviation of the most probable value of the elevation of the new point.

$$m_i = m_0\sqrt{q_{ii}} \tag{8}$$

Where m_i : Standard deviation of the most probable value of the unknown

q_{ii} : Diagonal line element of $\mathbf{Q}$

However, rigorous network adjustment uses matrices to determine the many unknowns; therefore, computer applications are used in actual situations. Rigorous network adjustment for GNSS leveling was done by using TOWISE 4.1.1 (Japanese version) of Nikon Trimble Co., Ltd. and that for direct leveling was done by using BLUETREND XA (Japanese version) of FukuiComputer, Inc.

RESULTS AND DISCUSSION

Generally, the accuracy of the most probable value is evaluated by the standard deviation. The probability, the observed value vary within the standard deviation around the most probable value, is known as 68.3 %. The most probable value and standard deviation of the elevation of the new point No.4101 determined through rigorous network adjustment using the values obtained by GNSS leveling and those obtained by direct leveling are shown in Table 3. The most probable value determined by GNSS leveling using GPS-only was 919.928 m. That determined by GNSS leveling using GPS and GLONASS was 919.946 m. That determined by direct leveling was 919.921 m. The standard deviation of GNSS leveling using GPS-only was 0.018 m. That of GNSS leveling using GPS and GLONASS was 0.021 m. That of direct leveling was 0.010 m. The standard deviation of direct leveling was the smallest. That for GNSS leveling using GPS-only was the second smallest. That for GNSS leveling using GPS and GLONASS was the third smallest.

The most probable value and standard deviation of the altitude of the new point No.4101 determined through rigorous network adjustment of the values observed by GNSS leveling, those obtained by direct leveling, and the discrepancy between the two values are shown in Table 4. The discrepancy was obtained by subtracting the value observed by direct leveling from the value observed by GNSS leveling. The discrepancy between GNSS leveling using GPS-only and direct leveling was 7 mm. The discrepancy between GNSS leveling using GPS and GLONASS and direct leveling was 25 mm. The results can be regarded as mutually consistent, even though the leveling techniques are different. We can conclude that elevation with high accuracy, i.e., sufficiently consistent with the results of direct leveling, was obtained by GNSS leveling using GPS-only. The reason for the discrepancy between the results of GNSS leveling using GPS-only and the results of GNSS leveling using GPS and GLONASS is thought to be that GPS and GLONASS are different systems. It is thought that GPS-only observation and analysis is better than GPS and GLONASS when and where enough satellites are available for GPS-only operation.

Table 3 Most probable value and standard deviation of the elevation of the new point

Method	Used satellite	Name of new point	Most probable value [m]	Standard deviation [m]
GNSS leveling survey	GPS-only	4101	919.928	0.018
	GPS+GLONASS	4101	919.946	0.021
Direct leveling survey	None	4101	919.921	0.010

Table 4 Discrepancy of elevations between GNSS leveling and direct leveling

	Used satellite	Name of new point	Most probable value [m]	Standard deviation [m]
Discrepancy	GPS-only	4101	+ 0.007	+0.008
	GPS+GLONASS	4101	+ 0.025	+0.011

CONCLUSION

As the conclusions, the points are summarized in the following.
(1) The total observation duration in GNSS leveling were about one-fiftieth (1/50) that of direct leveling. GNSS leveling is able to dramatically improve observation efficiency.
(2) The discrepancy between GNSS leveling using GPS-only and direct leveling was 7 mm. The discrepancy between GNSS leveling using GPS and GLONASS and direct leveling was 25 mm. The sufficiently consistent with the results of direct leveling was obtained by GNSS leveling using GPS-only.
(3) It is thought that GPS-only observation and analysis is better than GPS and GLONASS when and where enough satellites are available for GPS-only operation.

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