JGD2000 (vertical) -The New Height System of Japan-

Tetsuro IMAKIIRE and Eiichi HAKOIWA

Abstract

JGD2000 (vertical), the official height system and data set of Japan,is constructed using the newest leveling survey results and orthometric height system. This paper introduces the background and procedure of the construction of the new height system and data set, as well as the characteristics of the change of height around the Japanese Islands.

The old height data set published in FY1969 was based on the normal orthometric height system, because not enough detailed gravity data was available. The detailed gravity data was used for the calculation of the new height data set. The newest results of leveling surveys are archived into "LAGSAS", the database of leveling surveys with analysis function, which supported the calculation of the height data of bench marks.

Network adjustment is carried out with a single fixed point, the datum of leveling in Tokyo. As the Hokkaido network was directly connected to the main part of Japan for the first time by the leveling survey along the Seikan Tunnel, the Hokkaido network was also simultaneously adjusted in the nationwide adjustment.

The height values of more than 20,000 bench marks have been determined and opened to the public. Evaluation of the calculation, such as inspection of loop closures, shows that the consistency of new height data set is satisfactory enough.

1. Introduction

In Japan, a leveling survey to control the height of land was started by the Army Land Survey in 1883. The result of the first nationwide leveling survey (1892-1914) was used for the production of maps as well as for public construction works. However, the results themselves were not opened to the public.

When the Survey Act was established in June 1949, basic survey results gained the role of controlling public surveys. Network adjustments were carried out successively area by area by manual calculation from 1953 to 1963. The results were opened to the public for the areas where the calculation had been completed, in order. This was the first publication of the leveling survey results to control the public surveys.

The second publication of leveling survey results was done in 1969 as the "Adjusted height data in FY1969", which covered the national territory except Hokkaido, the northern main island of Japan, by the simultaneous adjustment computation of the survey data obtained from 1962 to 1968. The results on Hokkaido were published in 1972 as "Adjusted leveling results in FY1972", using the computation results by the adjustment with the single fixed point BM6996, which is located near Oshoro tidal station on the western coast of Hokkaido, independent from other area's results. Both these two results are called the "old leveling data set".

About thirty years have passed since the second leveling data set was published. Although renewal of height data has been done partially during the repeated nationwide leveling surveys, they gradually became inconsistent due to crustal deformation by earthquakes, volcanic eruption or ground subsidence caused by pumping up of underground water, for example. Therefore, Geographical Survey Institute (GSI) decided to establish a third official height system, "JGD2000 (vertical)" to resolve this inconsistency and to meet the development of social needs.

As we can provide detailed gravity data covering all Japan, the gravity value can be estimated accurately at any point. Therefore we decided to adopt "orthometric height" instead of "normal orthometric height", which was adopted for the former two data sets. The height data for about 21,000 bench marks are renewed in this computation.

The procedure of this renewal was carried out according to the long-term plan for the establishment of new results determined in 1993.

"JGD2000 (vertical)" was published in April, 2002 with the new coordinates of horizontal control points, which were provided following the revision of Survey Act.

These new results are based on the nationwide leveling survey directly connecting Honshu, Hokkaido and Kyushu. A simultaneous adjustment was carried out for the computation on the main routes of these surveys. This is another main characteristic besides the adoption of orthometric height.

1.1 Policy for building up the official height data set

"The official height data" means height data for a bench mark or a control point officially provided by GSI for practical survey purposes. The data set of official height for benchmarks is provided, adopting orthometric height based on the gravity model determined from the newest observation as described before.

The benchmarks can be divided into two categories. One is the first order bench marks which are located along the leveling routes surveyed repeatedly. The others are bench marks of the first, second and third order which are not surveyed repeatedly. GSI has been carrying out leveling surveys with accurate levels and cross sea leveling by the transit method and tilting screw method.

As vertical ground movement caused by crustal deformation and ground subsidence by human activities is widely seen on the Japanese islands, time dependent vertical movement has been grasped by repeating the first order leveling survey. However, the height of bench marks has not been determined with a vertical movement velocity field model in the same epoch. Therefore we decided to build up the new official height system for bench marks using the following procedure.

1) Height data should be determined by the nationwide leveling survey conducted from 1986 to 1999, as well as four cross sea leveling surveys, calculating the orthometric height by a nationwide network adjustment.
2) Weight for the network adjustment should be determined based on the accuracy of direct leveling and cross sea leveling.
3) Adjustment calculation should be conducted with a single point fixed at the vertical datum point, as is defined in the Survey Act. A local datum should be defined by a mean sea level derived from tidal observation for isolated islands, where the leveling routes are not connected from the datum.
4) The orthometric height should be determined by the newest survey results for the first, second and third order benchmarks which have not been repeatedly surveyed. The adjustment should be done based on the nationwide adjustment results, treating the benchmarks connecting to such routes as fixed points.
5) Epoch reduction based on vertical movement velocity field is not used.
6) If newer observation data surveyed after year 2000 exists, the newer data should be used for the height deteminating calculation, by fixing the heights of adjacent benchmarks which have been determined by the nationwide network adjustment.

An orthometric height is defined by the length of a plumb line from the geoid. The observations necessary to determine the orthometric height are a leveling survey and a gravity survey. The data obtained by this combined observation is the difference of gravity potential between the benchmarks. It is necessary to know the mean value of gravity from the geoid to the observation point to convert the gravity potential to orthometric height. However, since such a mean value of the gravity cannot be observed, the gradient of gravity value under the ground should be estimated theoretically.

Helmert height, which is derived from the simplest assumption for the gradient, is adopted as an orthometric height for the newest calculation. The assumption is that as free air gradient is a constant value, –0.3086mgal/m, and the density of the crust is 267,103kg/m^3, the underground gradient of gravity is +0.0848mgal/m, after Prey's correction.

It is necessary to obtain gravity values at every point where a level is set up for exact difference of gravity potential. However, such gravity data was not provided. Therefore imaginary leveling data is provided by using the adjusted heights of neighboring bench marks for one observation, to estimate the gravity value between these two bench marks from the gravity data on them (Kuroishi, 1998).

The gravity data on each benchmark is processed by the following procedure. GSI has a gravity database containing gravity data obtained by institutes such as GSI, AIST (National Institute of Advanced Industrial Technology), and Nagoya University. This database provides a detailed gravity value not only at the benchmarks along each leveling route, but everywhere within the land part of the Japanese islands. DEM of about 250m grid based on the digital map data set KS110-1 of GSI was used, too. A detailed Bouguer Anomaly grid model with every 1 minute of latitude and every 1.5 minutes of longitude is constructed. The procedure for estimation of gravity value was established considering the topographic correction based on this grid model (Kuroishi, 1998). The height of each benchmark is calculated using the gravity value derived from this method.

1.2 Calculation

GSI has been developing “LAGSAS”, the total analysis system for leveling and gravity survey for determination of height of benchmarks from survey results, since 1980. This system was completed with the revision of the program and checking of a great number of observation data for construction of “JGD2000 (vertical)”. As it was planned that the results would be published in April 2000, the same date as the publication of JGD2000 (horizontal), the newest results of this point were calculated. However, the publication was delayed as the revision of the Survey Act had been delayed. Therefore, new data acquired after 2000 are also used with the interpolation method for the calculation.

1.3 Evaluation and analysis

A new height system is introduced that uses Helmert’s orthometric height instead of normal orthometric height. Therefore the systematic difference between orthometric height and normal orthometric height caused by the effect of using the real gravity field was analyzed. Evaluation of precision was carried out by comparing the values of closure or standard deviation. The geographical distribution of the difference of the old and new height is investigated to analyze the vertical crustal deformation.

2. Calculation

2.1 The policy for the establishment of the new height data set

2.1.1 The strategy and procedure of calculation

The first nationwide first order leveling survey started in 1883 from a suburb of Tokyo. The ninth nationwide leveling survey is being conducted at present. Mainly the results of the eighth and ninth surveys are used for the calculation. Network adjustment of observed height difference data is carried out to obtain the most probable orthometric height by the least squares method.

(1) Strategy for the calculation

The final strategy for calculation was decided after the following considerations.

1) Fixed points for the adjustment of nationwide network

The basic strategy for adjustment adopted one fixed point, the datum of leveling. However, the propriety of this strategy should be proved by comparison with other strategies which adopted heights from the mean sea level at a number of tidal stations as fixed values. Because the mean sea levels at the stations differ site by site, the residuals of adjustment become larger as more stations are adopted. The combination of tidal stations which gave the smallest residual was the case that four stations, Oshoro (Hokkaido), Aburatsubo (Honshu), Kure (Shikoku) and Hosojima (Kyushu) were fixed. The result adopting this strategy gave the nearest height values compared to the results by the calculation with the datum of leveling as unique fixed point. As the difference between these two calculations was small, the basic strategy was considered appropriate.

2) Inspection on the height value of the datum of leveling

An inspection on the height value of the datum of leveling was carried out to prove that it is reasonable to adopt the datum of leveling as the fixed point. The height value of the datum was calculated from the sea level of the tidal stations and from the surrounding bench marks, which are considered to be very stable. It was proved that the height value of the datum has been very stable recently from the comparison of the results of various calculation methods. As the Survey Act regulates that the height should be determined referred to the datum of leveling, the adjustment is carried out by fixing the height of the datum point, which is 24.4140m.

3) Determination of the weight of cross sea leveling

The weight of leveling observation for the network adjustment in LAGSAS is determined to be inversely proportional to the length of the observation routes. The weight of cross sea leveling should be determined consistently with this definition.

4) Determination of the height of isolated islands

As it is impossible to connect the leveling routes of isolated islands with the datum of leveling, the local datum was determined from tidal observation data for each island. The height of the island was determined referring to the local datum.

(2) Observation data

The data used for the adjustment are as follows:

1) Leveling observation data (including cross sea leveling and restoration survey)

- observed height difference (difference of elevation between neighboring bench marks after temperature correction for staff)
- length of the segment of observation (distance between the neighboring benchmarks)
- other information (observation date, session number, route number, bench mark ID, record of restoration)

2) Gravity data

- gravity value for each bench mark (bench mark ID, latitude, longitude, estimated height, gravity value)

(3) Procedure of the calculation

The policy for the calculation is determined according to the discussion as written above. The calculation was carried out based on the observation data which is described in the former section. All leveling routes in Japan are classified in order. The adjustment is first carried out for the highest order routes. Following this adjustment, the lower order adjustments are carried out using the interpolation method order by order. The procedure is as follows:

1) The first order leveling routes are selected for the highest order routes as a backbone. The second order leveling route in the Omaezaki region is added to the backbone. Nationwide adjustment is carried out fixing the leveling datum. Provisional height value used for the calculation of orthometric height is estimated from normal orthometric height. After adjusting the entire routes, the calculated height value is used as the new provisional height. Thus the second adjustment is carried out for the routes all over Japan. This procedure is repeated until the height values converge into the final values to get the “orthometric height”. The flow chart of this calculation is shown in Fig.1. The adjustment program in LAGSAS has a routine to calculate orthometric height from temporal height value. If observation on the leveling routes for monitoring ground subsidence was conducted several times, the data obtained at the nearest date to the survey period for the surrounding routes are used. However, the newest data is used to obtain the final height value by interpolation, after the nationwide adjustment has been done.

2) If there are no recent observations for the first order routes, interpolation is carried out by the old observation using the values of the backbone adjustment as a given condition.

3) The calculation for the second and third order leveling routes are carried out by the interpolation method using the results of first and second step as given conditions.

2.1.2 Height of leveling datum

(1) Selection of the fixed point for adjustment calculation

The sea levels at the tidal stations on the coast of the Sea of Japan are about 20-40cm higher than the mean sea level of Tokyo Bay. The sea level in Kyushu is about 10-15cm higher. It is about 10-20cm lower at the stations on the eastern coast of Hokkaido, besides being 5-20cm higher on the western coast of Hokkaido (Fig.2).

The adjustment with the four, seven, eleven, thirteen and twenty-five fixed points are carried out using the twenty-five tidal stations of GSI and JMA (Japan Meteorological Agency).

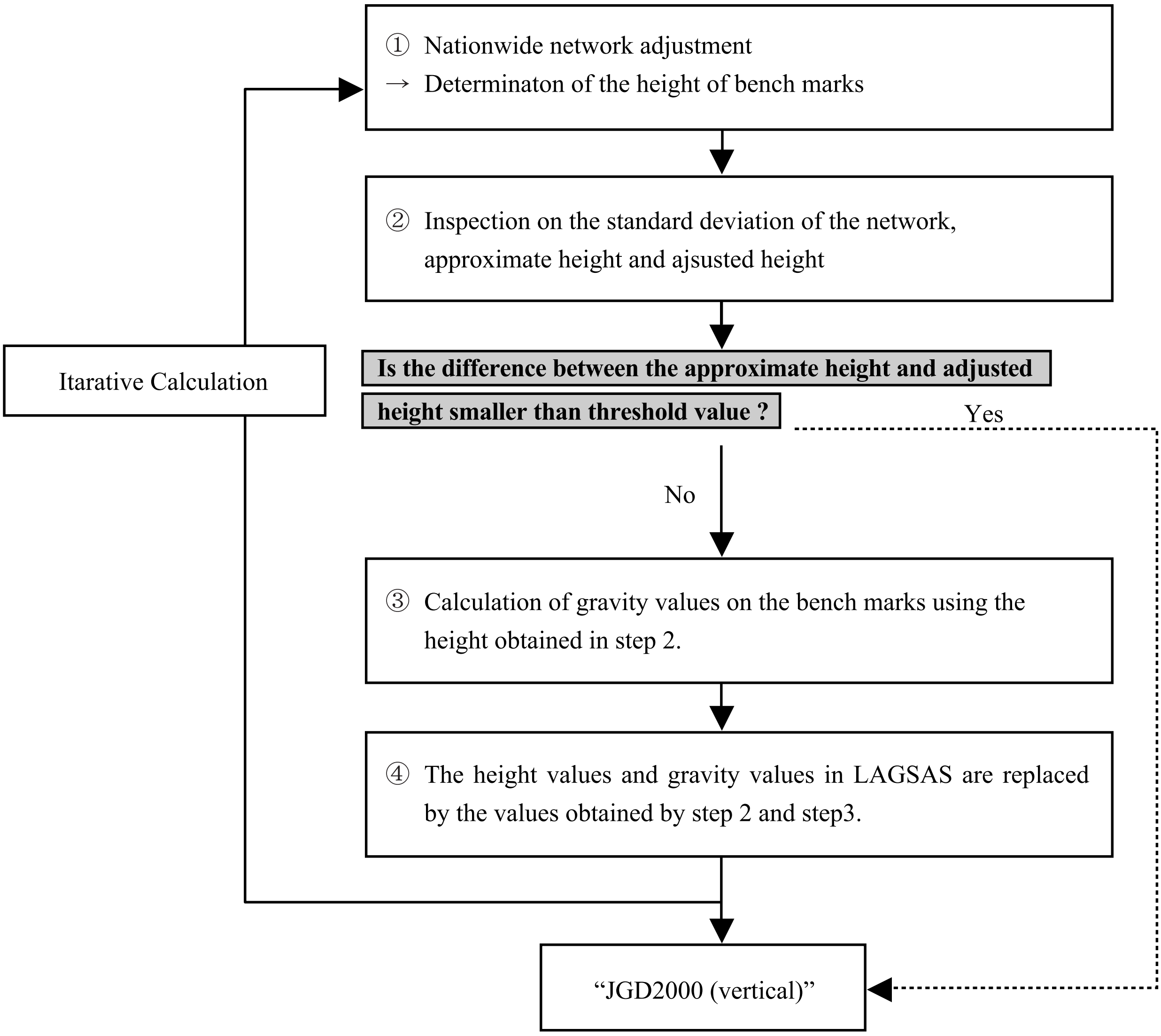

Fig. 1 Flow of the adjustment calculation

This calculation revealed the following facts.

1) Standard deviation for unit weight (m_0) and junction point tends to be larger when the tidal stations on the coast of the Sea of Japan are fixed.
2) Standard deviation for unit weight for the calculation with four fixed stations, Oshoro, Aburatsubo, Kure and Hosojima, are the same as that calculated with one fixed point, the leveling datum. The standard deviation of this condition is 1.5mm, and standard deviation of the junction point is improved by about 30%.
3) Standard deviation for unit weight and the junction points, derived from the other conditions for fixed points, are larger than those derived from the one fixed point calculation.

The height value from the calculation with four fixed points is lower than those derived from one fixed point, the leveling datum, generally. However, the results are the nearest to the values derived from one fixed point calculation and the difference is small.

(2) Evaluation of the leveling datum value

(a) The history of the leveling datum

Even the height of the datum of leveling might not be very stable, as crustal deformation is very conspicuous in Japan. Therefore the height of the leveling datum has been monitored by a leveling survey carried out every year. We evaluated the stability of the height of the datum of leveling by several methods. Fig.3 shows the changes

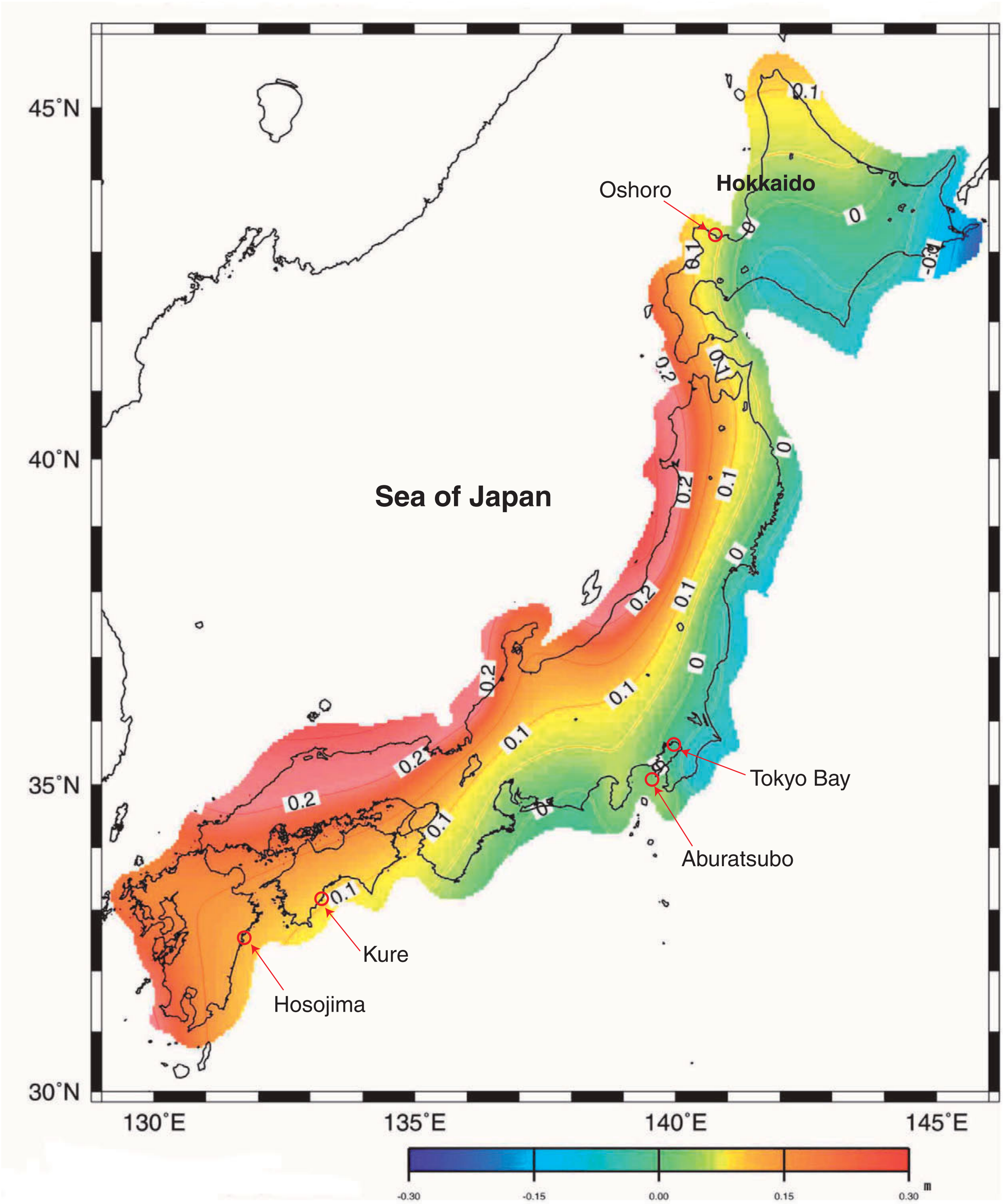

Fig. 2 The mean sea level in Japan referred to the mean sea level in Tokyo Bay

of the height value of the leveling datum obtained from three different analyses. The height of leveling datum fluctuated within ±5cm from the Kanto Earthquake (1923) to the 1970s. However, it seems very stable from the 1970s to today. From the result of these surveys, it was decided that its adopted value 24.4140m need not be changed. Because of this, the height value of the leveling datum is defined as 24.4140m for the calculation of JGD2000 (vertical). The vertical crustal movement at Aburatsubo tidal station deduced from the tidal variation is shown in Fig.4 as a reference.

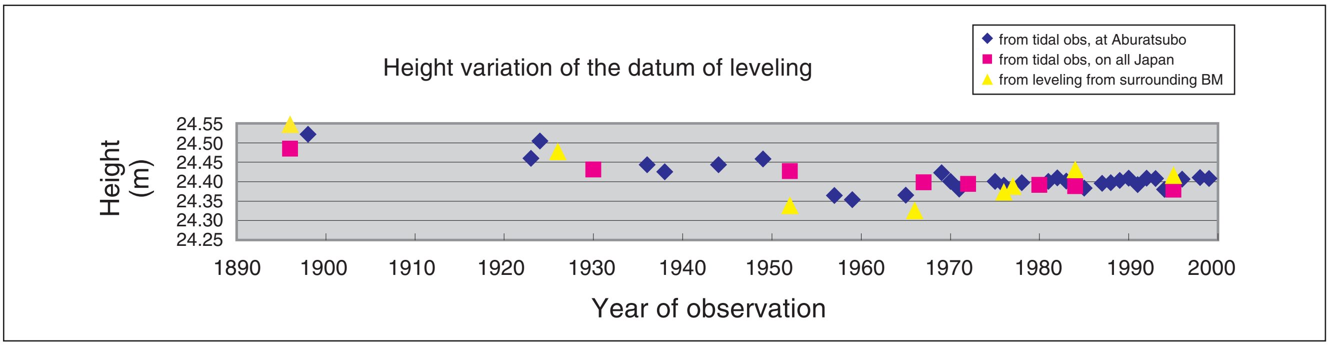

Fig. 3 Height variation of the datum of leveling

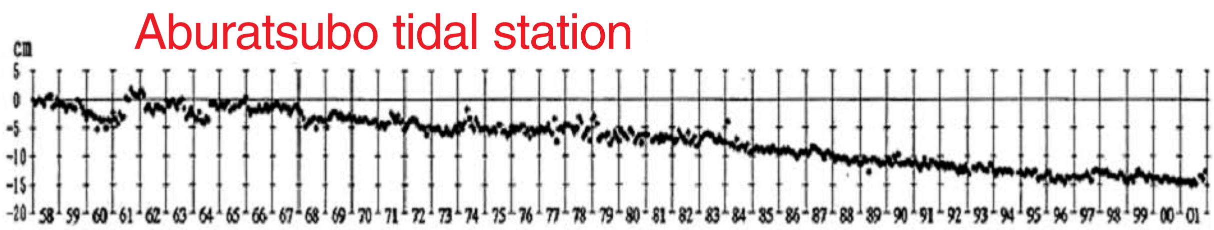

Fig. 4 Vertical crustal movement at Aburatsubo tidal station by Kato & Tsumura (1979) method

Table 1 Standard deviation of cross sea leveling

	SD (m_1)	Distance	S for adjustment	Obs. Method
Kitan	2.4 mm/km	10.833 km	16.000 km	Transit
Akashi	3.4 mm/km	15.443 km	32.111 km	Transit
Naruto	3.9 mm/km	1.399 km	42.250 km	Tilting screw
Hoyo	3.2 mm/km	14.568 km	28.444 km	Transit

2.1.3 Determination of the weight for cross sea leveling

The adjustment program in LAGSAS, with which the network adjustment calculation is carried out all over Japan, defines the weight as the inverse of observation distance. The weight for cross sea leveling should be determined consistently with this definition. The precision of leveling survey is represented by the standard deviation for 1km (m_0). On the other hand, the precision of cross sea leveling is generally represented by the standard deviation for one observation set (m_1).

If the unit weight observation is defined as the 1km leveling survey, the weight of the direct leveling survey is represented by the inverse of observation distance S_0 (km). On the other hand, the weight for cross sea leveling is given by m_0^2 / m_1^2.

Accordingly, the fictitious distance (S) of cross sea leveling for the weight calculation is computed as $S=(m_1)^2/(m_0)^2$.

The value for m_0 used for this determination is 0.6mm because of the following reasons.

1) The standard deviation determined from the difference between forth and back observation with the digital level is 0.58mm.
2) The regulation for the first order leveling survey defines m_0 as 0.6mm.
3) The standard deviation calculated from loop closure in Kyushu, where the newest survey was carried out from 1987 to 1988, is 0.57mm.

The standard deviation for the cross sea leveling (m_1) is based on the following table (Table1).

2.1.4 The datum value for isolated islands

As isolated islands cannot be connected to the leveling datum, the local datum should be established from the local mean sea level determined by tidal observation. The height of bench marks in such isolated islands is determined from this local datum. Adoption of local data is approved by Article 11, term 4 of the Survey Act.

2.2 Preparation for the calculation

2.2.1 Establishment of LAGSAS

The development of LAGSAS started about twenty years ago. The results of the leveling survey from the Meiji era are stored in the database of LAGSAS. The system composition LAGSAS database was reviewed for the improvement of the program at the opportunity of the establishment of JGD2000 (vertical).

LAGSAS has various calculation routines, such as network adjustment with orthometric or normal orthometric correction, as well as a database with a height difference file, route file, history file and gravity file.

The details of the data used for the calculation are described below.

(1) Observation data

(a) Direct leveling data

The data set obtained during FY1987 to 1999 is used for the nationwide adjustment.

(b) Cross sea leveling

The routes between Honshu block (including Kyushu) and Shikoku are connected by cross sea leveling. The transit method is used for the Akashi and Hoyo straits, and the tilting screw method is used for the Naruto strait. The cross sea leveling result in the Kitan strait is not included in this nationwide adjustment.

(c) Public survey data

First order public surveys carried out in the Seikan tunnel, Akashi strait, Boso peninsula, Tokyo metropolitan area, Nobi plain and Osaka-Kobe area are used for the adjustment.

(2) The data on ground subsidence or crustal deformation area

In order to keep consistency with the surrounding area, the observation data of which survey epoch is closest to the newest nationwide leveling survey are used for areas with ground subsidence and crustal deformation. After the nationwide network adjustment, the interpolation is carried out with the newest survey data (obtained during 1998-1999) for ground subsidence and crustal deformation areas, such as Aomori, Hachinohe, Sendai, the Tokyo metropolitan area, Izu, Omaezaki, Nagoya, Osaka and Saga.

(3) Observation data of the first order leveling route not used for the nationwide adjustment

Local network adjustment or interpolation method is used for those leveling routes.

(4) Observation data on isolated islands

The newest observation data in those islands are used.

(5) Second and third order leveling route

The newest observation data for the routes where surveys have been repeatedly carried out, such as Omaezaki and Izu, are used for the calculation. The old data, such as that obtained in FY1951, are used for routes not surveyed recently.

(6) History data

The history data in LAGSAS includes the data for restored bench marks before FY1999. For the bench marks restored in FY2000, the calculation is carried out separately.

(7) Gravity data

The gravity data necessary for the calculation of the orthometric height is the gravity value on each bench mark. The gravity value on a bench mark is estimated from the detailed gravity model (Kuroishi 2004), with interpolation.

It is necessary to use the orthometric height itself for the calculation of orthometric correction. Therefore the approximate height is estimated by the nationwide network adjustment by using the normal orthometric correction. Those height correction values derived from this calculation are used for the next estimation of orthometric correction. Iterative calculation is carried out until the correction becomes smaller than the threshold value for all bench marks to obtain final values. The gravity value on a bench mark, which is stored in the gravity file, is also the final value after the iteration.

2.2.2 Development of application program

Application programs, which are necessary for the calculation of JGD2000 (vertical), have been developed for the gravity correction to obtain the orthometric height in the network adjustment. Various application programs written in the C language were developed for workstations. The contents of those programs are:

1) Network adjustment programs and a loop closure calculation program

The network adjustment programs consist of programs for “adjustment without gravity related correction”, “adjustment with normal orthometric correction”, “adjustment with gravity correction (for orthometric, normal and dynamic height)” and “interpolation”. The “loop closure calculation program” can treat one hundred loops simultaneously, as the number of loops in nationwide network is about ninety.

2) Record making system for the restored bench marks

It is refined to be able to handle the global geodetic system, which is used for the JGD2000 (horizontal) for the coordinates of the bench marks.

2.3 Calculation

(1) Overview

The inspection on the accuracy is carried out based on the observation data of the eighth nationwide survey, which was completed in FY1996. The height difference between the datum of leveling and Aburatsubo tidal station, the change of sea level at tidal stations, and the weight for cross sea leveling are inspected. The route map for the second and third order leveling routes was compiled, too.

After installation of the database and programs on workstations was completed, adjustment calculation of the eighth nationwide survey data for orthometric height was carried out using the new database and application programs.

The additional calculation and development of database and programs were carried out in FY1999.

The calculation for the first order routes, which were not included in the nationwide adjustment, the second and the third order leveling route, as well as the road bench marks, is carried out at this stage.

An additional nationwide network adjustment was carried out to include the newest observation data, which were obtained for the Chugoku, Shikoku and Kyushu areas in FY1999. Carrying out local adjustments after the nationwide adjustment, the calculation for JGD2000 (vertical) was completed. The flow of this procedure is shown in Fig.5.

(2) Treatment on the route not to satisfy the allowance accuracy level

The allowance level adopted for the series of the calculation was $15\mathrm{mm}\sqrt{S}$, where S is the length of the leveling routes in km. 9.9 % (262/2639) of the routes could not satisfy this accuracy level. The ratio of the leveling routes of which the standard deviation is larger than 10cm was 16 % (42/262).

2.3.1 Formulae used for the calculation

The equations used for the calculation are as follows.

(1) Network adjustment calculation (by observation equation method)

$$H_{i+1} = H_i + \Delta h_{i,\,i+1}$$

$$\begin{aligned}
v_{12} &= -x_1 + x_2 - (H_1 - H_2 + \Delta h_{12})\,,\ P_{12}\\
v_{23} &= -x_2 + x_3 - (H_2 - H_3 + \Delta h_{23})\,,\ P_{23}\\
&\cdots\ \cdots\ \cdots\ \cdots\ \cdots\ \cdots\ \cdots\\
v_{i,\,i+1} &= -x_i + x_{i+1} - (H_i - H_{i+1} + \Delta h_{i,\,i+1})\,,\ P_{i,\,i+1}
\end{aligned}$$

1) H_i : approximate height for bench mark i.
2) x_i : correction for the approximate height of bench mark i.
3) $\Delta h_{i,\,i+1}$: observed height difference between bench mark i and i+1

(staff correction and orthometric correction are added).

(correction for the observed height difference)

$$\Delta h_{i,\,i+1} = h_{i,\,i+1} + \Delta C_{i,\,i+1} + \Delta G_{i,\,i+1}$$

$\Delta h_{i,\,i+1}$: height difference (unit m)
$h_{i,\,i+1}$: observed height difference (unit m)
$\Delta C_{i,\,i+1}$: staff correction (unit m)
$\Delta G_{i,\,i+1}$: orthometric correction (unit m)

(staff correction)

$$\Delta C_{i,\,i+1} = \left\{ C_0 + (T - T_0)\alpha \right\} h_{i,\,i+1}$$

$\Delta C_{i,\,i+1}$: Staff correction (unit m)

C_0 : Staff parameter at the standard temperature (the correction value for the unit length / unit m)

T_i : measured temperature at the time of the observation (unit ℃)

T_0 : standard temprature (unit ℃)

α : expantion rate of the staff (unit m/℃)

$h_{i,\,i+1}$: observed height difference (unit m)

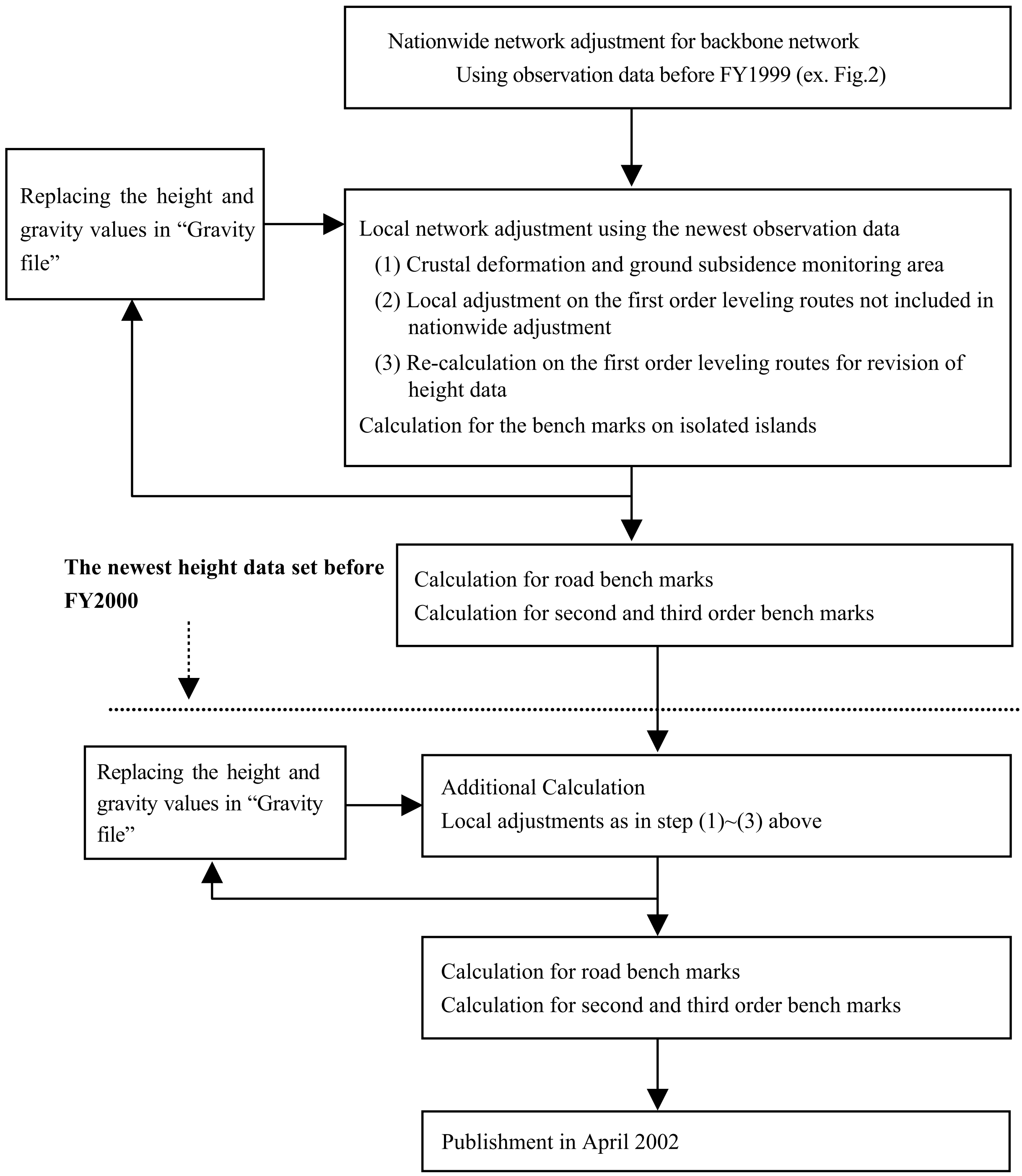

Fig. 5 Flow of the calculation

(orthometric correction)

$$\Delta C_{i,\,i+1} = \left[\left\{(g_i + g_{i+1})/2\right\} - \gamma^0\right]\Delta h_{i+1}/\gamma^0 + H_i(G_i - \gamma^0)/\gamma^0 - H_{i+1}(G_{i+1} - \gamma^0)/\gamma^0$$

$\Delta C_{i,\,i+1}$: orthometric correction (unit m)

g_i : gravity value at bench mark i (surface gravity : unit $mgal$)

Δh_{i+1} : observed height difference from BMi to BM_{i+1} (unit m)

γ^0 : 980619.92$mgal$ (normal gravity at Lat.45°: unit $mgal$)

H_i : height at BMi (orthometric height : unit m)

G_i : average gravity value at BMi (average from surface to geoid : unit $mgal$)

$$G_i = g_i + 0.0424H_i$$

4) $\upsilon_{i,\,i+1}$: residual for height difference between BMi and BM_{i+1}

5) $P_{i,\,i+1}$: weight for the observation between BMi and BM_{i+1}

$$V = AX - L, \quad P$$

V : residual vector

A : matrix for coefficient parameters

X : vector for unknowns (correction to approximate height)

L : constant vector

P : weight matrix

(2) Normal equations

$$(A^tPA)X = A^tPL$$

$$\therefore X = (A^tPA)^{-1}A^tPL$$

(3) Results of adjustment

Standard deviation of observation for unit weight

$$m_0 = \sqrt{V^tPV/(m-n)}$$

m : numbers of observation equations

n : numbers of unknown parameters

Standard deviation for adjusted height of bench marks

$$M_1 = m_0\sqrt{q_{11}},\ M_2 = m_0\sqrt{q_{22}},\ \cdots\cdots,\ M_n = m_0\sqrt{q_{nn}}$$

$$\underset{(nm)}{Q} = (A^tPA)^{-1} = \begin{bmatrix} q_{11} & q_{12} & \cdots & \cdots & q_{1n} \\ q_{21} & q_{22} & \cdots & \cdots & q_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ q_{n1} & q_{n2} & \cdots & \cdots & q_{nn} \end{bmatrix}$$

Iterative calculation is carried out until the values for each x_i become less than 0.05mm exchanging the approximate height with the corrected height (H_i+x_i)

2.3.2 Nationwide network adjustment

(1) Overview

The routes selected as the highest order, which include most of the first order leveling routes, a part of the ground subsidence monitoring routes and crustal deformation monitoring routes such as the Omaezaki region, are defined as the backbone network. Nationwide network adjustment with the datum of the leveling as unique fixed point is carried out (Fig.7). The periods of the observations which are used for the adjustment are shown in Table 2. The flow of the calculation is shown in Fig.1.

(2) Loop closure

The loop closures obtained by these calculations for orthometric height and normal orthometric height are shown in Fig.8 and Fig.9. The permissible value for the loop closure is 2.0mm$\sqrt{S}$ (S: The length of the loop: unit km). The number of the loops whose loop closure exceeds

Table 2 Period of observation used for nationwide adjustment

District	Hokkaido	Tohoku	Kanto	Hokuriku	Chubu	Kinki	Chugoku	Shikoku	Kyushu
Period of Data	1987 ~ 1999	1986 ~ 1999	1991 ~ 1997	1989 ~ 1995	1990 ~ 1998	1988 ~ 1995	1986 ~ 1999	1990 ~ 1999	1987 ~ 1999

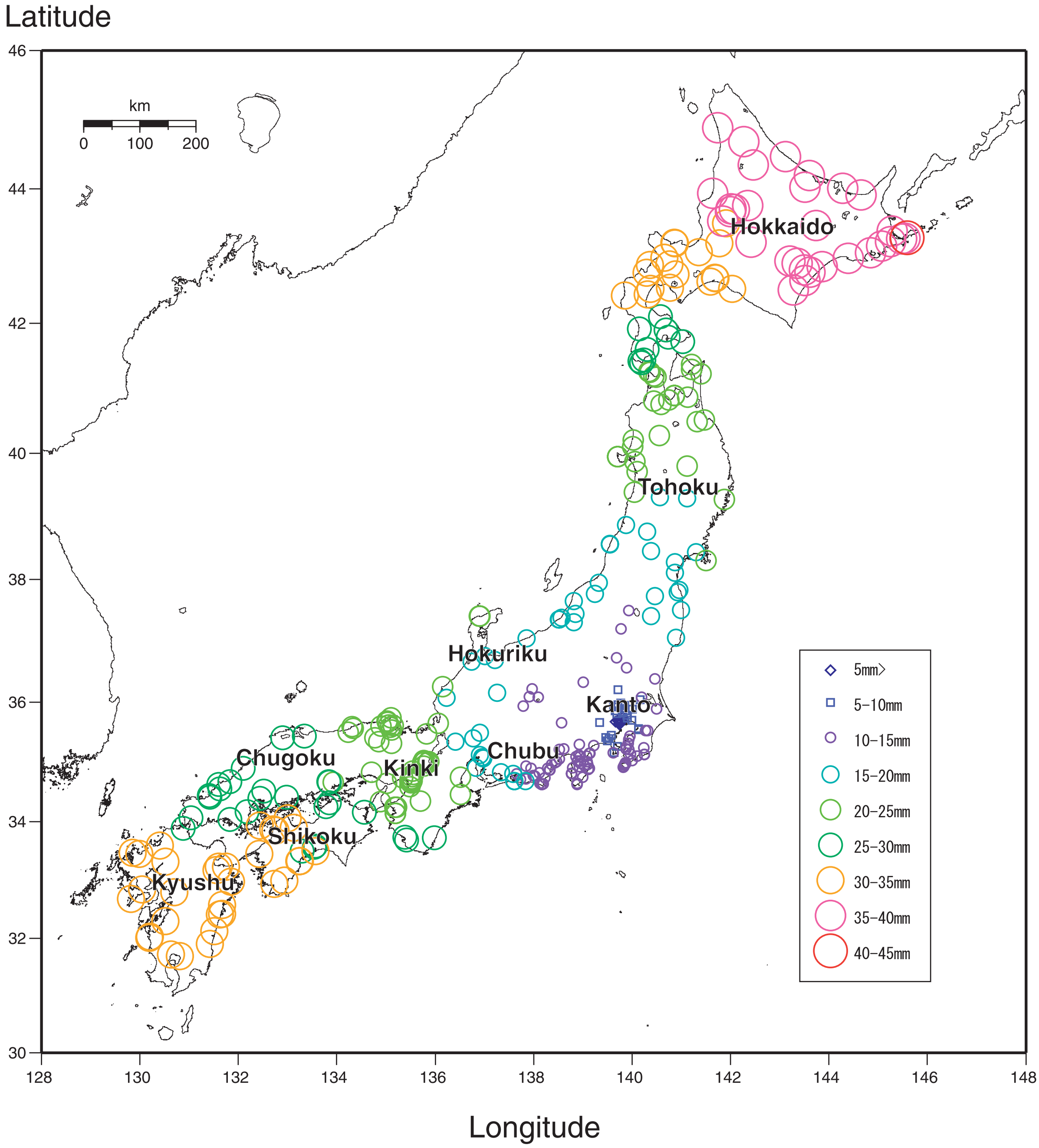

Fig. 6 Standard deviation of junction bench marks calculated from nationwide adjustment

this limit is 14 (with orthometric correction) and 13 (with normal orthometric correction) out of the 86 loops.

(3) Precision of the results

The precision of the results obtained from nationwide network adjustment is as follows.

1) Standard deviation for unit weight: 1.45mm
2) Standard deviation for connecting point: Minimum 0.16mm, Maximum 40.02mm

The distribution of the standard deviation for connecting points is shown in Fig.6. As the datum of leveling in Tokyo is selected to be a single fixed point for the adjustment, the standard deviation of the connecting points is larger as the points become farther from the datum. The standard deviations are 40-45mm in eastern and northern Hokkaido, and 35-40mm in southern Kyushu.

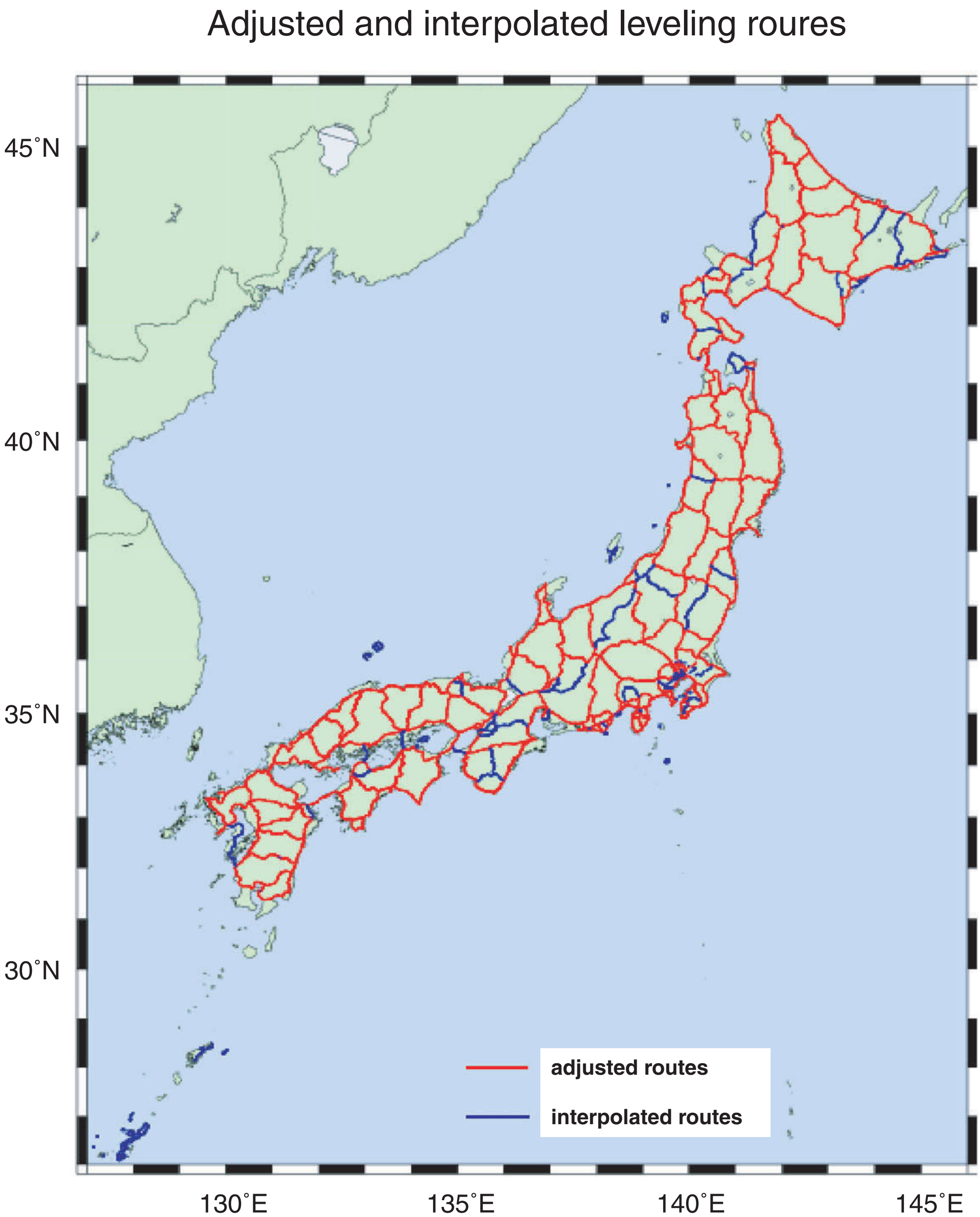

Fig. 7 Leveling routes including nationwide adjustment and interpolation calculation

2.3.3 Publication of the adjusted height

The closure is large on the first, second and third order leveling routes which are not included in the nationwide adjustment. For the height of bench marks in such routes, the newest possible observation data are used.

The height value for a bench mark is calculated to the order of 0.1mm regardless of the order of leveling routes. However, the published heights for the first order bench marks are given to the order of 0.1mm besides the data for the second and third order bench marks are given to the order of 1mm.

The numbers of bench marks published in JGD2000 (vertical) are shown in Table 3 and Table 4.

3. Evaluation and discussion

The new height system in JGD2000 (vertical)

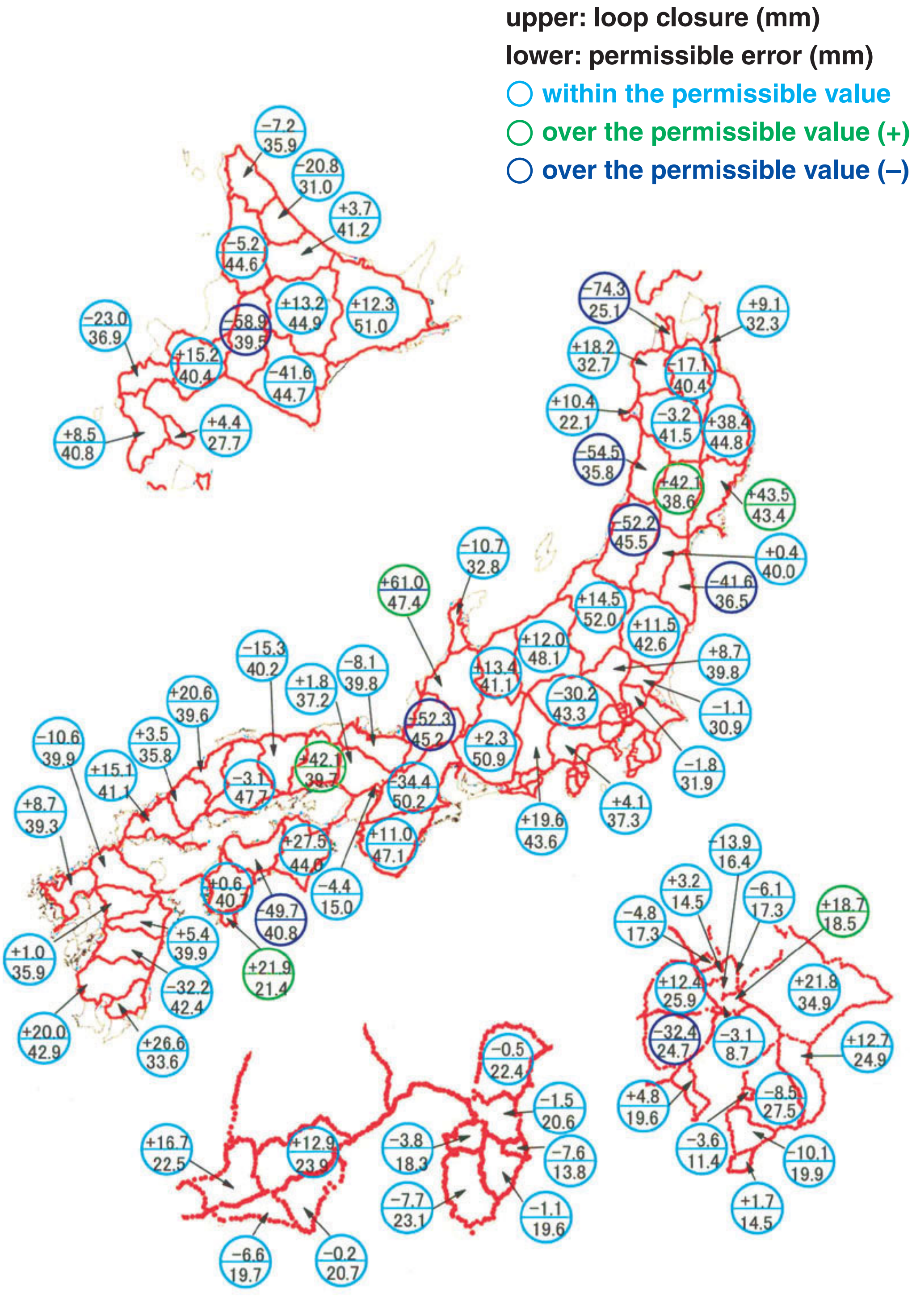

Fig. 8 Loop closure for orthometric height system : JGD2000 (vertical)

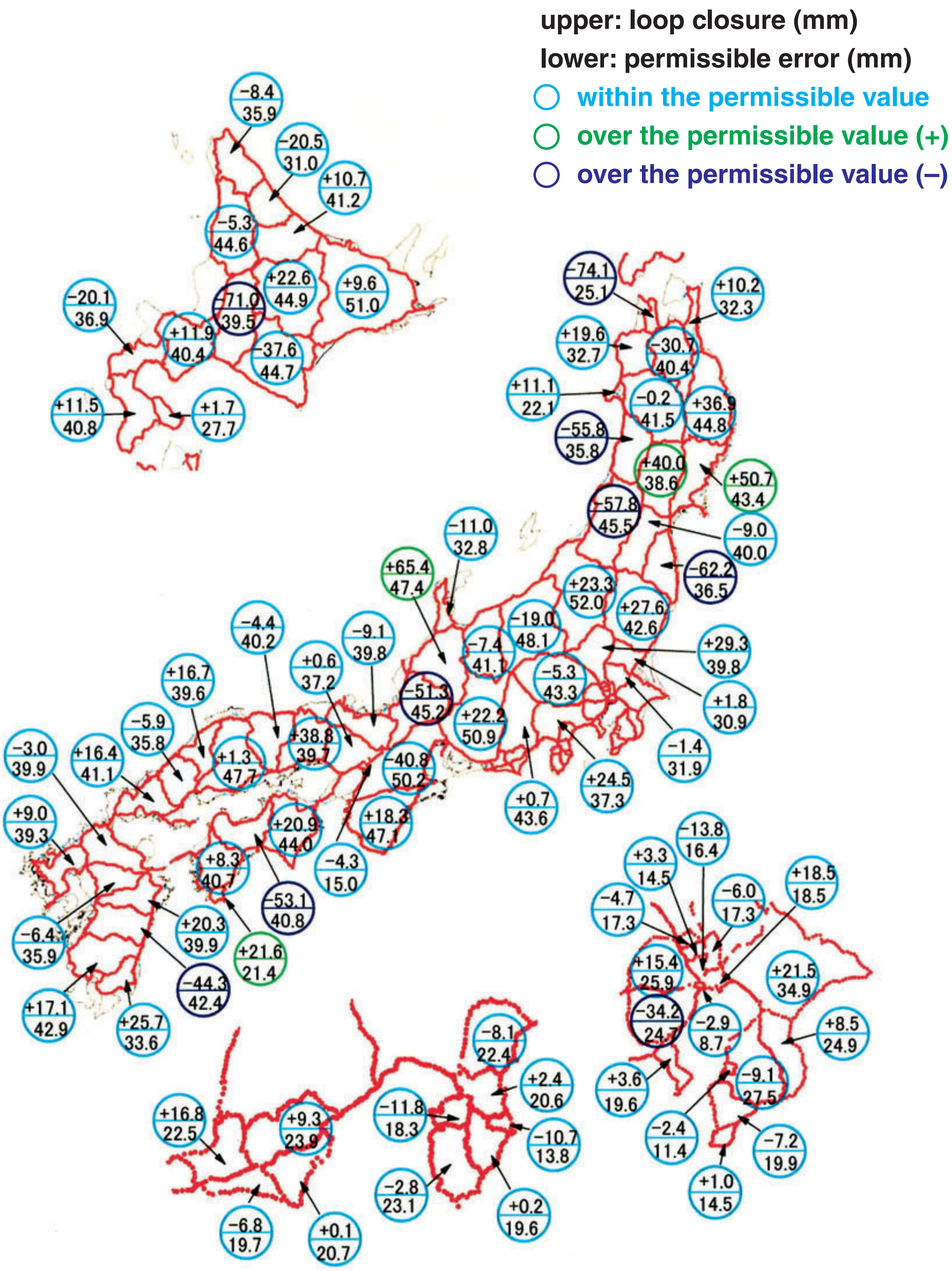

Fig. 9 Loop closure for normal orthometric height system

Table 3 Numbers of bench marks of which height data are published

Order of BM	Number
First order BM	16,172
Second order BM	4,019
Third order BM	458
Total	20,649

Table 4 The categories of the first order bench marks

Category	Number
Fundamental	96
First order	10,538
Road BM	4,675
Sub-fundamental	585
Junction BM	183
Cross sea BM	43
Tidal station BM	33
Others	19
Total	16,172

adopts Helmert orthometric height, changing from normal orthometric height. Therefore, in this section, the spatial distribution of the difference between orthometric height and normal orthometric height is inspected to evaluate the systematic error included in the normal orthometric height, which neglects the real gravity field.

Next, the precisions of both kinds of heights are evaluated from the loop closure or standard deviation of the height value derived from the nationwide adjustments using the same network.

Finally, the spatial distribution of height changes from old height values is discussed.

3.1 Systematic difference between orthometric height and normal orthometric height

The difference between orthometric height in JGD2000 (vertical) and height in the old normal orthometric height system has been calculated. The difference between orthometric height and normal orthometric height originates from the systematic error of normal orthometric height which neglects the difference between the real gravity value and the normal gravity value. The height values of both systems, obtained using the same data and the same network, are compared. The height differences are considered to be correlated to the elevation of bench marks. For example, the difference between the two height systems on leveling route 187, which goes through Nomugi Pass, in the central mountainous area of Japan, are shown in Fig.10. The height value in the orthometric system is about 19cm larger compared to the normal orthometric height at the highest first order BM on the Nomugi Pass, where the elevation is 1,670m.

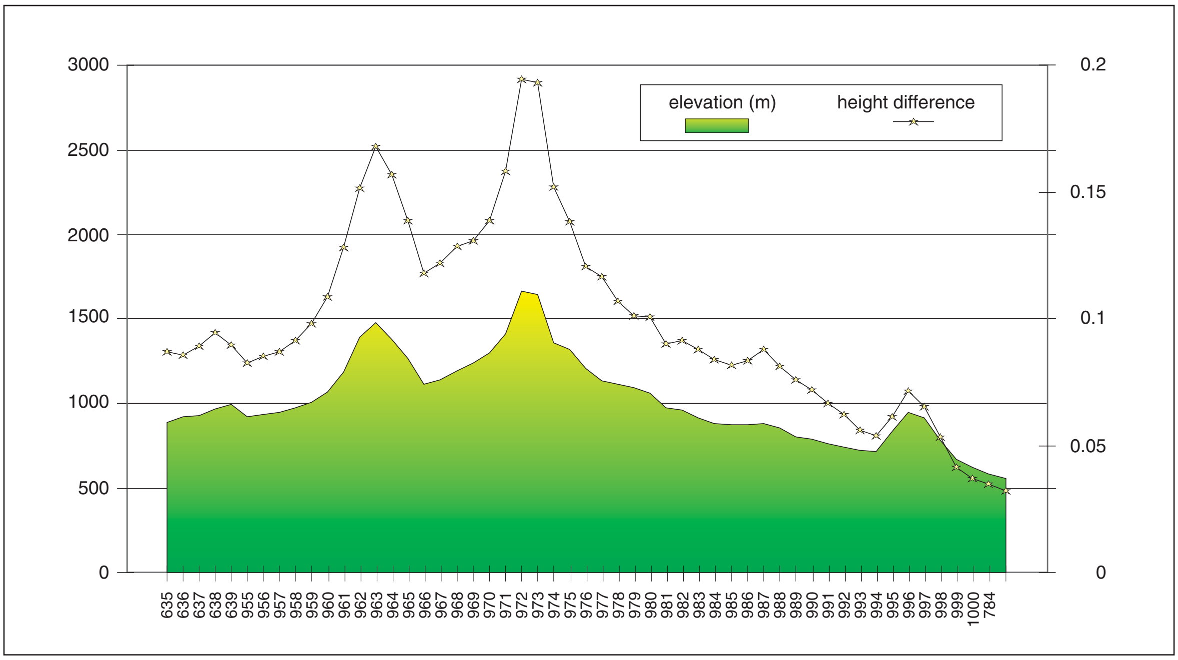

Fig. 10 Difference between orthometric height and normal orthometric height along the leveling route through Nomugi Pass

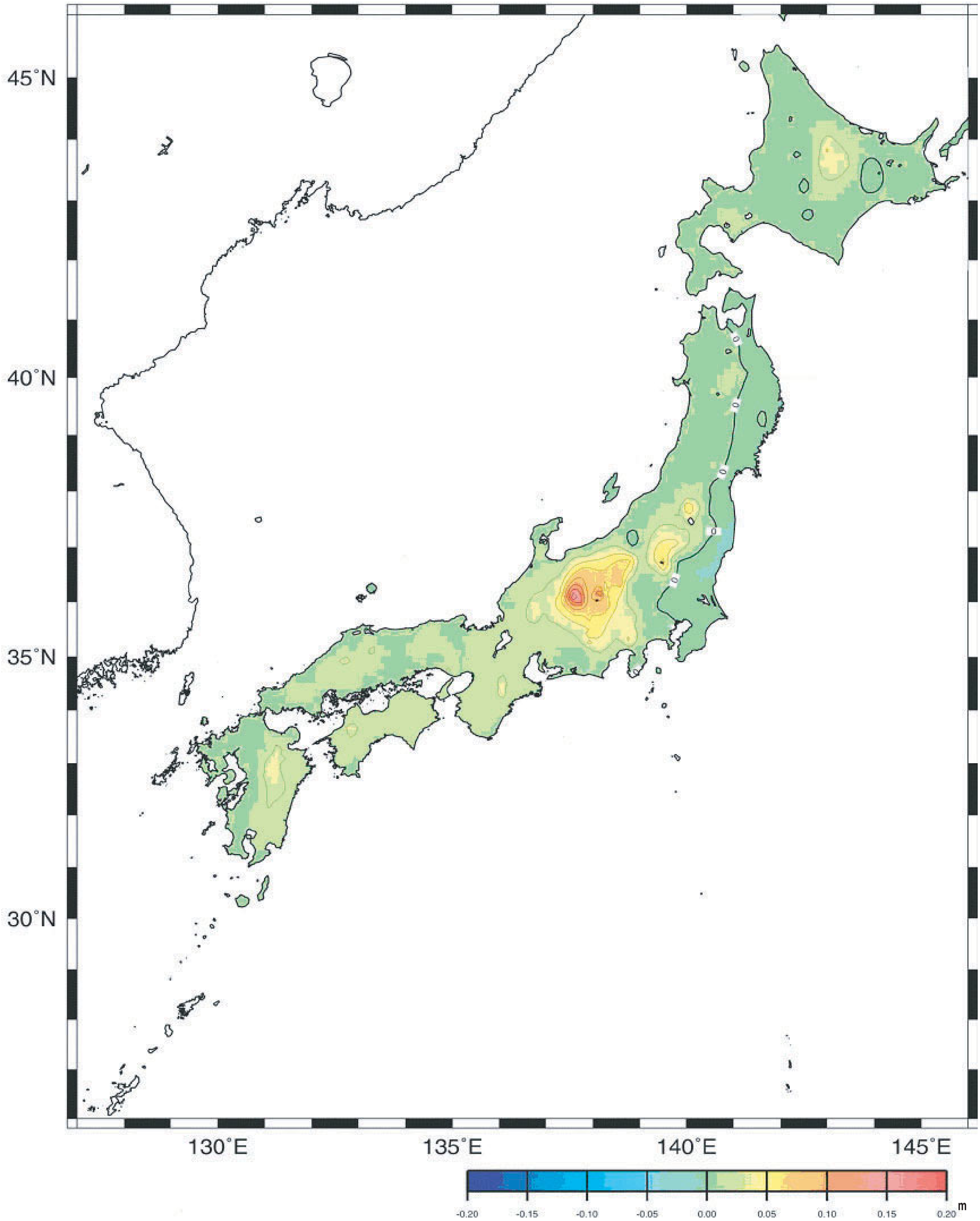

Fig. 11 Height difference between orthometric height and normal orthometric height systems

Figure 10 shows the profile of the height difference between two systems along the leveling route through Nomugi Pass. From Fig.11, which shows the height difference between two systems all over Japan, larger differences are seen in a mountainous area in Chubu district. There are eight bench marks where the difference is larger than 15cm. All of them are located in areas where the elevation is higher than 1,300m. However, for most of the bench marks (93%), the height difference is smaller than 2 cm.

3.2 Evaluation of the observation data and change of height system

Fig.8 shows the loop closures calculated in the orthometric height system for the evaluation of observation data. The "observation data" used in the adjustment is the sum of height differences between two benchmarks, staff corrections and orthometric corrections. The loop closures on the normal orthometric height system were also investigated. The comparison of these two systems is shown in Table 5. Though no improvement of the number of loops exceeding the regulation limit can be seen, the standard deviation for loop closure is slightly reduced.

Table 5 tatistics on the loop closures by orthometric system and normal orthometric system for nationwide adjustment

	Orthometric system	Normal orthometric system
Number of loops	86	86
Number of loops excessing the threshold value (minus)	8	9
Number of loops excessing the threshold value (plus)	6	4
Average of loop closures (mm)	–1.021	–0.988
Standard deviation of lop closures (S.D)mm	23.736	25.877

3.3 Overview of calculation results

The standard deviation for unit weight (m_0) deduced from the nationwide adjustment is 1.45mm. The standard deviation deduced from the loop closures is 1.35mm. This means that the calculation results are satisfactory concerning accuracy. The standard deviations of junction points are 0.16mm in Tokyo and 40.02mm in Nemuro, Hokkaido. The standard deviation (m_0) for the Hokuriku, Chubu and Kinki districts where additional adjustment was carried out is 2.05mm. The standard deviation for observation is 1.07mm. Therefore these observations are satisfactory, too.

3.4 Discussion on the comparison between old and new height data

The nationwide average of the change of height is 1.1mm. As a matter of course, change can be ignored around Tokyo, near the fixed point, datum of leveling. In Hokkaido the change is generally minus (–13cm on average) and in Kyushu plus (+16cm on average).

There is a zone of subsidence on the Pacific coast from eastern Hokkaido to Kanto. This subsidence is considered to be caused by the subduction of the Pacific plate. The effect of the East of Hokkaido earthquake (1994) might be included in this subsidence.

A trend of upheaval is seen from Shikoku to Kyushu. However, it cannot be specified whether this is crustal deformation or a systematic difference between the old and new height systems. The upheaval in the mountainous area in Chubu is caused by the change of height system from normal orthometric height to orthometric height.

The characteristics of each district are as follows.

(1) Hokkaido district

The old height data set in Hokkaido was calculated in 1972, independent of "adjusted height in FY1969" in Honshu. "Adjusted height in 1972" in Hokkaido was calculated by fixing BM6996 near Oshoro tidal station as a single fixed point. Therefore the difference of reference sea level (about 12 cm) might be included in this difference. The minus height change is widely seen in eastern Hokkaido. It is considered that this height change is affected by the subduction of the Pacific plate.

(2) Tohoku district

The average of height difference is about –8cm. Generally, the eastern coast of Tohoku district shows

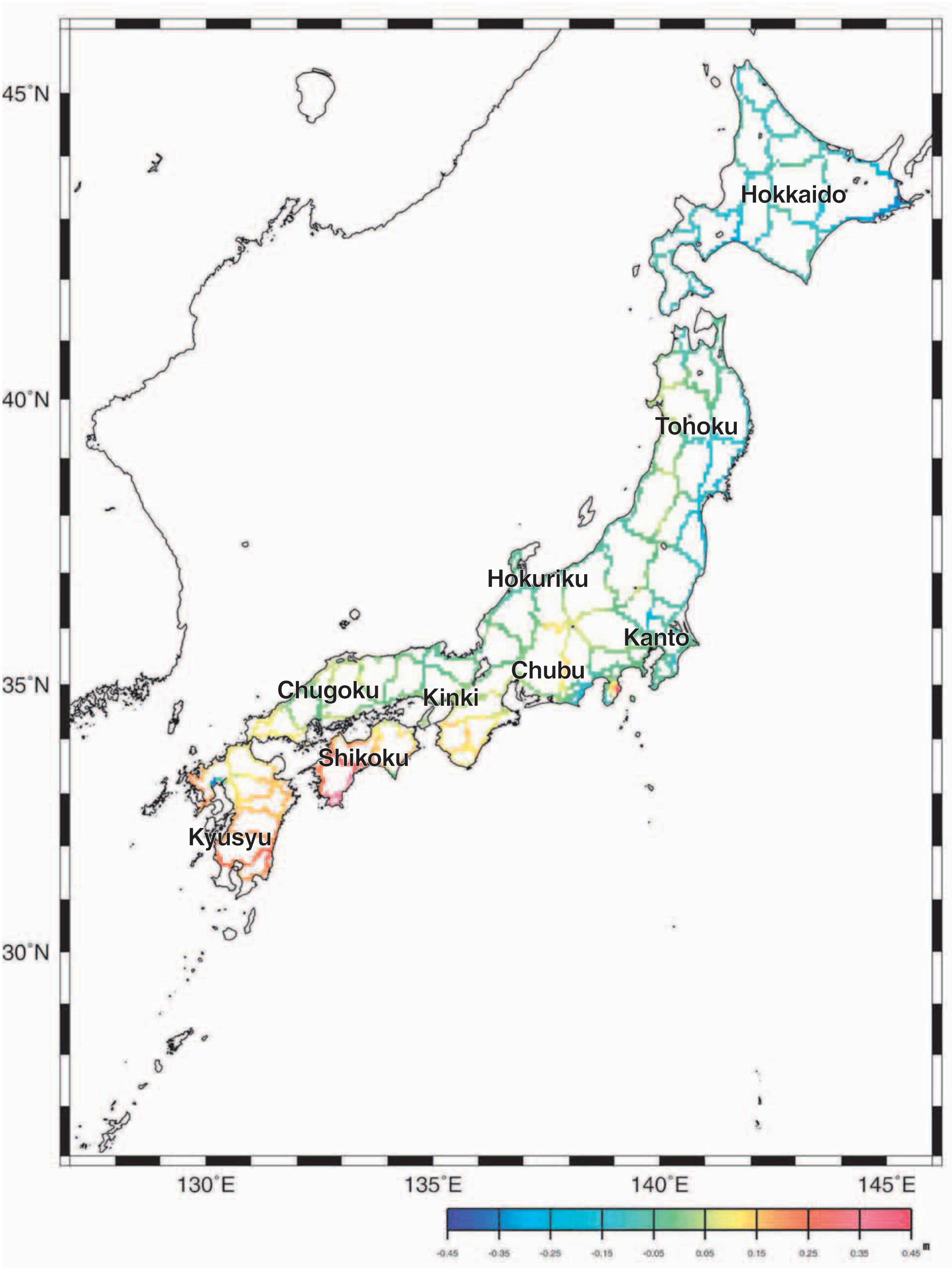

Fig. 12 Comparison of old height and new height

subsidence. This might be related to the subduction of the Pacific plate, too. The trend of upheaval around the Oga peninsula might have been caused by long term crustal deformation, even though co-seismic subsidence occurred accompanying the Central Sea of Japan earthquake in 1983.

(3) Kanto district

There is no significant change of height. The change of height is as small as –1cm around the Tokyo metropolitan area, because bench marks located near the datum point of leveling and revision of height data was carried out in 1988 within this area. Local subsidence areas are seen in the north-central Kanto district. The reason for the subsidence is considered to be pumping up of underground water.

(4) Hokuriku district

The average height change in Hokuriku is about –4cm. There are some ground subsidence zones along the coast of the Sea of Japan. However, no significant subsidence is seen, because of the revision of data in 1985.

(5) Chubu district

The average of the height change in the Chubu district is about +1cm. A zone of subsidence is seen along the western coast of Suruga Bay. It is considered that subduction of the Philippine Sea plate caused this subsidence. The prominent uplift is seen in the western part of Izu Peninsula. This uplift is considered to be caused by volcanic activity such as magma intrusion.

The new height data is generally higher than the old height data around central mountain areas as described before. This notable trend of uplift is caused by the change of height system.

(6) Kinki district

The average of height change in the Kinki district is about +5cm. As the revision of height data was carried out around Osaka in 1988 and Kobe in 1995 (after the Southern Hyogo Prefecture Earthquake in 1995), no significant height changes are seen in these areas.

(7) Chugoku district

The average of height change in the Chugoku district is about +4cm. No significant change of the height is seen in this area.

(8) Shikoku district

The average of height change in the Shikoku district is about +17cm. Subsidence is seen around Cape Muroto, the eastern peninsula poking into the Pacific Ocean. It is considered to be caused by the subduction of the Philippine Sea plate. Whether the trend of uplift seen around south-west Shikoku is derived from the change of height system or problem of the old observation data set has not been ascertained.

(9) Kyushu district

The average of height change in the Kyushu district is about +15cm. A notable subsidence is seen in Saga, the north-western prefecture of Kyushu. This area is a ground subsidence zone affected by underground water pumping. The southern part of Kyushu shows uplift widely. Whether this trend is caused by the change of height system or problem of the old observation data set has not been ascertained.

4. Conclusion

JGD2000 (vertical), the new height system adopting orthometric height, has been established based on the new nationwide leveling results. The height data set for bench marks is considered to be sufficiently reliable from the verification of survey accuracy.

Acknowledgement :

Dr. Makoto Murakami gave us a lot of important comments and suggestions, which helped us very much to improve our report. We would like to express sincere thanks to him.

We used GMT software (Wessel and Smith, 1991) to present several figures in this report.

References

Kato, T. and Tsumura, K. (1979) : Vertical crustal deformation estimated from tidal observation data

(1951~1978), Bulletin of Earthquake Research Institute, Vol.54, 559-628 (in Japanese)

Kuroishi, Y. (1998): Estimation of surface gravity at benchmarks and its errors on the determination of Helmert height in Japan, CJournal of the Geodetic Society of Japan, Vol.44, No.4, 223-236 (in Japanese)

Kuroishi, Y. (1999) : A study on the improvement of precision of height system - Estimation of surface gravity and effects of its errors on the determination of Helmert height in Japan, Research Report of Geographical Survey Institute, A1-No.214, 165-166 (in Japanese)

Kuroishi, Y., Kunimi, T. and Saito, T. (2000) : A study on the improvement of the precision of height system (second year) - An examination of the strategies for nationwide network adjustment and comparison of the difference between two height systems, Research Report of Geographical Survey Institute, A1-No.225, 135-136 (in Japanese)

Saito, T. and Narita, T. (2001) : Improvement of the database and application program in LAGSAS, the integrated analysis system for leveling survey, Technical report of Third Geodetic Division (in Japanese)

Wessel P, Smith WHF (1991) Free software helps map and display data. EOS Trans. Amer. Geophys. U. 72: pp. 441, 445-446