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Vertical Crustal Movement in the Tohoku District, Japan, Deduced from Dynamic Adjustment of Levelling and Tidal Data

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Abstract

The levelling data of the network covering the Tohoku district, Japan, were analyzed in order to study the vertical crustal movement in this seismically active area. Analysis was performed for the levelling data obtained during 1966 to 1995, together with the sea level data at tidal stations along the Pacific coast and Japan Sea coast within the network. We applied a dynamic adjustment (velocity model), in which not only corrections to the assumed height but also rate of vertical movement linear with time at the benchmarks were assumed to be unknowns in order to take into account the effect of rapid vertical crustal movement to the results of survey.

A comparison between the adjusted levelling data and tidal data shows that the mode of vertical crustal movements at tidal stations deduced from sea level data coincides well with that from levelling data. Based on both of them, the contour maps of the rate of vertical movement in the Tohoku district were charted for three intervals: (I) 1966-1977, (II) 1973-1981, and (III) 1978-1995. These maps give us a whole view of the vertical crustal movements in the Tohoku district. The results are summarized as follows:

1- The most fundamental trend is extensive subsidence along the Pacific coast. But the rate of this subsidence is reduced during the third interval.

2- Significant uplift is found around the northwestern part of the Tohoku district, north of Fukaura area, with a rate of 18 mm/a during the first interval. This land uplift is extended southward making a large uplift area and the rate is changed to 4 mm/a during the second interval and 8 mm/a in the third one.

3- A rapid local subsidence is seen around Hanamaki area during interval I and similar is seen in Yokote basin in interval II. As to whether there is any relation between both of these subsidences with the subducting plate or should be considered as just local subsidence, more detailed study is required.

4- The crustal movement in the north of Taira area during the discussed periods is prominent. It was a rapid subsidence during the first interval. Then, the subsidence changed to uplift gradually and extended westward forming a large uplift area, rate of uplift during interval II and III became 4 mm/a, and 10 mm/a, respectively.

1- Introduction:

Since the advent of the plate tectonic theory in the late 1960's, many of geophysical phenomena, such as earthquakes and recent crustal movements, have been successfully interpreted based on the theory. For instance, in the study of the Japanese island arc, a lot of geophysical phenomena have been investigated in relation to the interactions among the continental plate, on which the island arc exists, and the subducting oceanic plates, i.e. the Pacific and the Philippine Sea plates.

The Japanese island arc is usually divided into five sub-arcs, called the Kurile, northeastern Japan, southwestern Japan, Ryukyu, and Izu-Bonin island arcs (Uyeda and

Sugimura, 1970). Among these sub-arcs, tectonics in the northeastern and the southwestern Japan have been investigated extensively based on frequently repeated geodetic data. In the present study, we used levelling and sea level data in the northeastern Japan (Tohoku district, Fig. 1) to reveal spacio-temporal change of vertical deformation of the island arc.

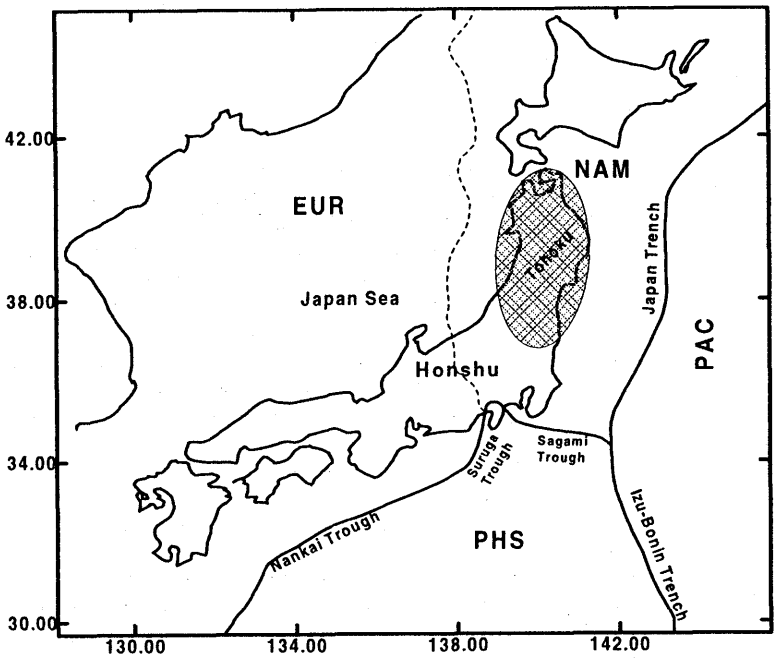


Fig. 1. Location of tohoku district (shaded area) and major plate boundaries in and near Japan. EUR, NAM, PHS, and PAC are Eurasian, North American, Plilippine Sea, and Pacific plates respectively. The broken line is the developing plate between EUR and NAM in the Japan Sea.

Recent intensive geophysical research has revealed various important aspects of the Tohoku district. Explosion seismic experiments, for example, have provided the detailed structure of the crust and the upper mantle (Yoshii and Asano, 1972).

As for the crustal movement in the Tohoku district, many investigations have been performed during the two recent decades (e.g. Mizoue, 1967; Dambara, 1971; Kato, 1979; Ishii et al., 1981; and Miura et al., 1989). In this study, we are trying to make more detailed study on the contemporary vertical crustal movement in Tohoku district using both frequently repeated levelling data and the sea level records in the area. For this purpose, we employ a new adjustment technique of geodetic data which allows to incorporate a velocity model to reveal characteristics of the contemporary crustal movement in the Tohoku district.

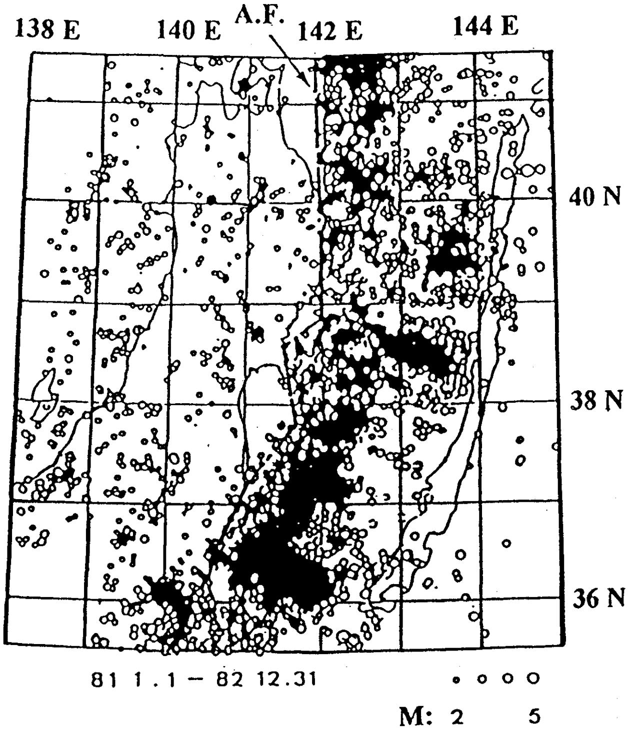


Fig. 2. Epicenter distribution of microearthqakes shallower than 60 km with a magnitude greater than 2 occurring in the period from January. 1982 to December. 1983. Solid line indicated by "AF" (Hasegawa et al., 1985).

Fig. 2 shows an epicenter distribution of shallow micro-earthquakes (Hasegawa et al., 1985), most of which occur beneath the Pacific ocean between the Japan trench and coastal line of northeastern Japan island arc. The western boundary of active micro-earthquakes zone is called the as eismic front "**AF**" (Yoshii, 1975). In addition, a relatively high seismicity is notable along the so-called volcanic front "**VF**" which is located landward of the "**AF**" (see Fig. 3). The shallow micro-earthquakes in the land are confined to the upper crust as shown in Fig. 3, (Takagi et al., 1977). Also, a shallow seismic activity is distinguished in the Japan Sea side of the northeastern Japan. Deep seismic activity beneath the northeastern Japan that represents the subducting Pacific plate is well exhibited by double-planed distribution pattern as shown in Fig. 3, (Wadati, 1935; Hasegawa et al., 1978; Takagi, 1985). Our ultimate goal of research is to integrate these geophysical information with geodetic data to clarify tectonics undergoing in this area.

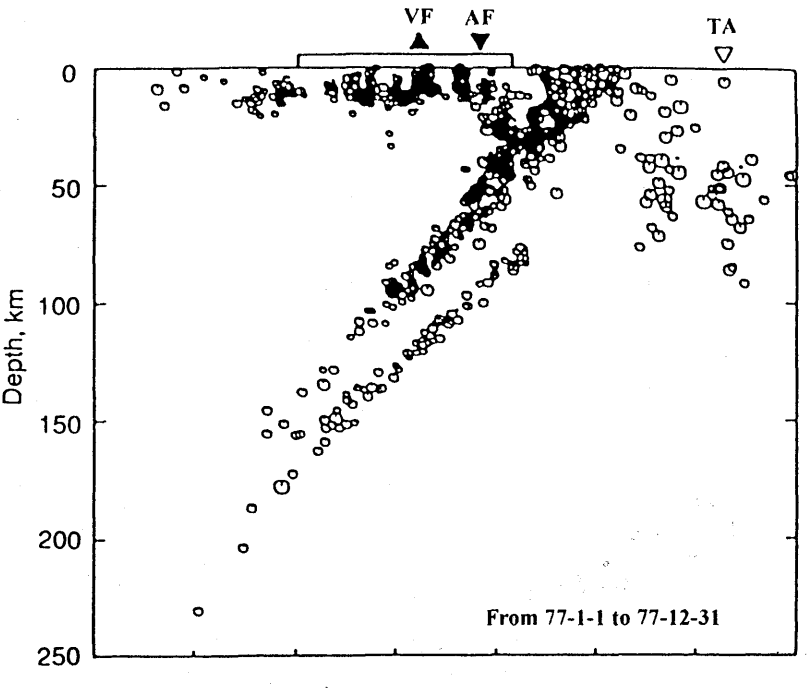


Fig. 3. Focal depth distribution of microearthquakes in the region from 39° N to 40° N projected onto a vertical cross-section in the E-W direction. Double-planed distribution pattern of deep quakes is obvious. TA, AF, and VF denote the Japan trench axis, the aseismic and volcanic fronts, respectively (Takagi, 1985).

2- Vertical Crustal Movement of Tohoku District:

2-1 Vertical Crustal Movements Deduced from Sea Level Data:

A method of tidal data analysis proposed by Kato and Tsumura (1979) was used to deduce crustal movements from monthly mean sea level data. This method can be briefly expressed by following equation:

$$\mathbf{h}_r = \mathbf{h} + \Delta\mathbf{h}_a + \Delta\mathbf{h}_f, \qquad (1)$$

where **h** is the monthly mean sea level after correction for the equi-pressure surface of 1000 mb. $\Delta\mathbf{h}_a$ is the mean annual variation, and $\Delta\mathbf{h}_f$ is the average mean value of a group of stations in an oceanic region. That is to say, the method is to consider the monthly mean sea level data after removing the mean annual variation and regional mean fluctuation as the crustal movement, $\mathbf{h}_r$, at the tidal station. For more details about this technique, the readers are recommended to refer to Kato (1983) and Kato and Tsumura (1979).

There are eleven tidal stations within the discussed area shown in Fig. 4, Hachinohe, Miyako, Kamaishi, Ofunato, Ayukawa, Soma, Nezugaseki, Oga, Fukaura, Asamushi, and Ominato.

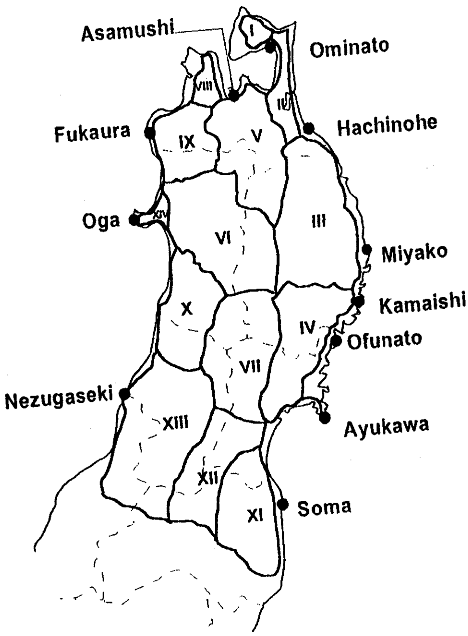


Fig. 4. First order levelling loops (I to XIV) and tidal stations (solid circles) in Tohoku district.

According to the definition of regions of tidal stations in Japan proposed by Kato (1983), the above eleven tidal stations belong to two regions. Hachinohe, Miyako, Kamaishi, Ofunato, Ayukawa, and Soma belong to the region along the Pacific coast, and Nezugaseki, Oga, Fukaura, Asamushi, and Ominato belong to the region along the Japan Sea coast. In order to analyze these data with the method proposed by Kato and Tsumura (1979), some more data from other tidal stations in both of these two regions were added. Finally nine tidal stations in the former region (Hachinohe, Miyako, Kamaishi, Ofunato, Ayukawa, Soma, Onahama, Choshi, Katsu-ura), and thirteen tidal stations in the latter region (Toyama, Kashiwazaki, Nezugaseki, Awashima, Ogi, Oga, Fukaura, Asamushi, Ominato, Matsumae, Makodate, Oshoro, Wakkanai) were processed, separately. All the tidal data were taken from the "Annual Report of Sea-Level Data" published by the Coastal Movement Data Center of Japan (1991). Even though there are tidal data observed before 1965 at most of the above mentioned tidal stations (see Fig. 5), only the data after 1965 were used, since we limited the period of the present study for the recent 30 years.

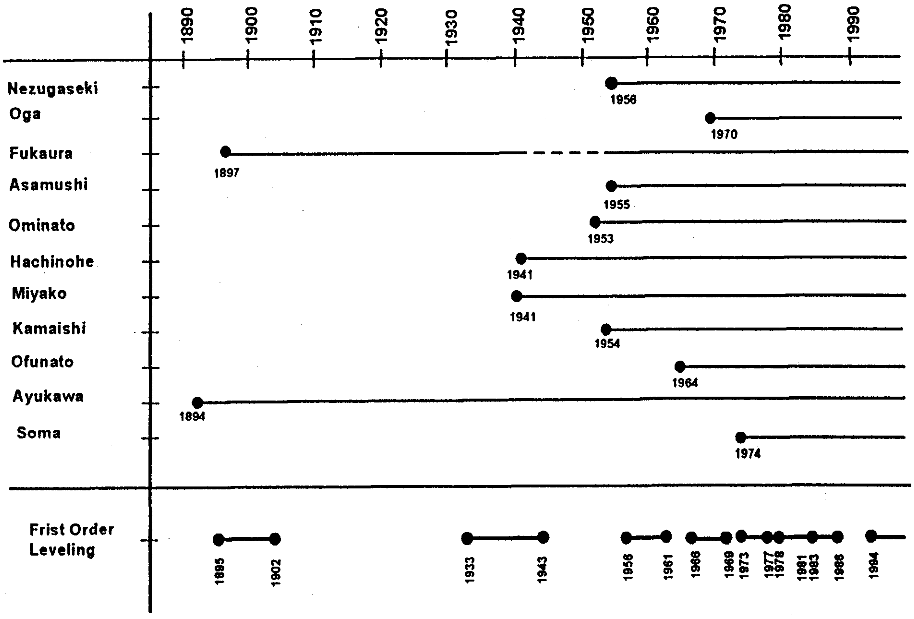
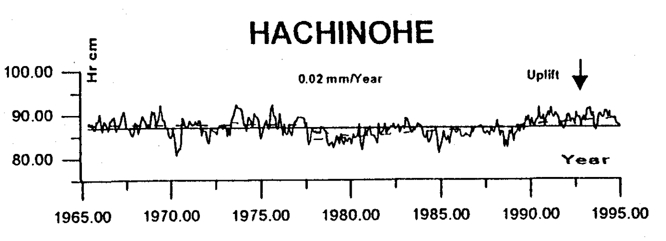
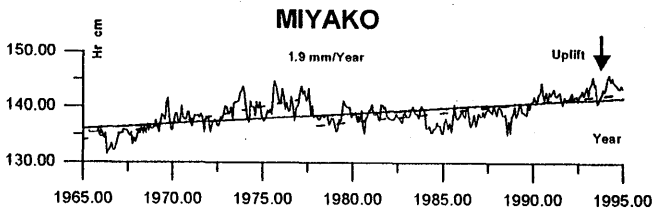
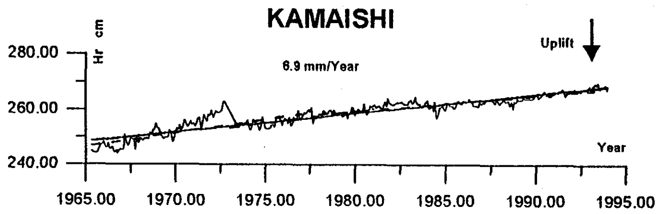


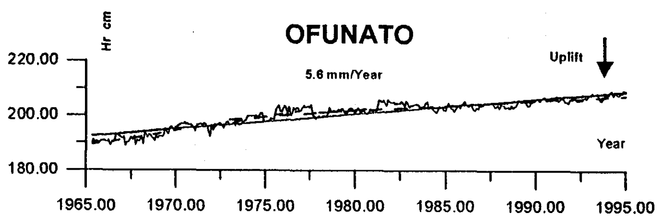
Fig. 5. Observation periods of see level data and first order levelling in Tohoku district.

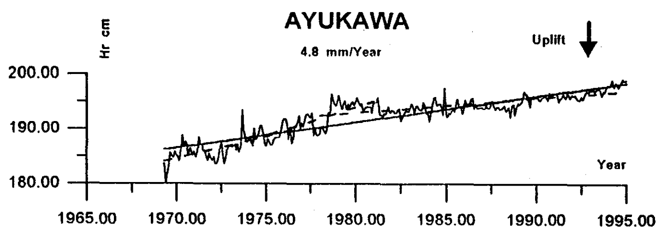
Fig. 6 shows the obtained vertical movements at eleven stations: Hachinohe, Miyako, Kamaishi, Ofunato, Ayukawa, Soma, Nezugaseki, Oga, Fukaura, Asamushi, and Ominato. The linear trend of vertical crustal movement fitted at each station is also shown in the same figure.

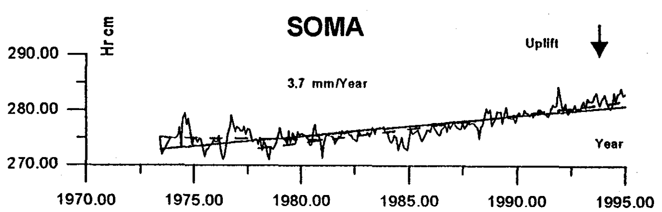



MIYAKO
Hr cm
1.9 mm/Year
Uplift
Year
150.00
140.00
130.00
1965.00
1970.00
1975.00
1980.00
1985.00
1990.00
1995.00


KAMAISHI
Hr cm
6.9 mm/Year
Uplift
Year
280.00
260.00
240.00
1965.00
1970.00
1975.00
1980.00
1985.00
1990.00
1995.00


OFUNATO
Hr cm
5.6 mm/Year
Uplift
Year
220.00
200.00
180.00
1965.00
1970.00
1975.00
1980.00
1985.00
1990.00
1995.00


AYUKAWA
Hr cm
4.8 mm/Year
Uplift
Year
200.00
190.00
180.00
1965.00
1970.00
1975.00
1980.00
1985.00
1990.00
1995.00


SOMA
Hr cm
3.7 mm/Year
Uplift
Year
290.00
280.00
270.00
1970.00
1975.00
1980.00
1985.00
1990.00
1995.00

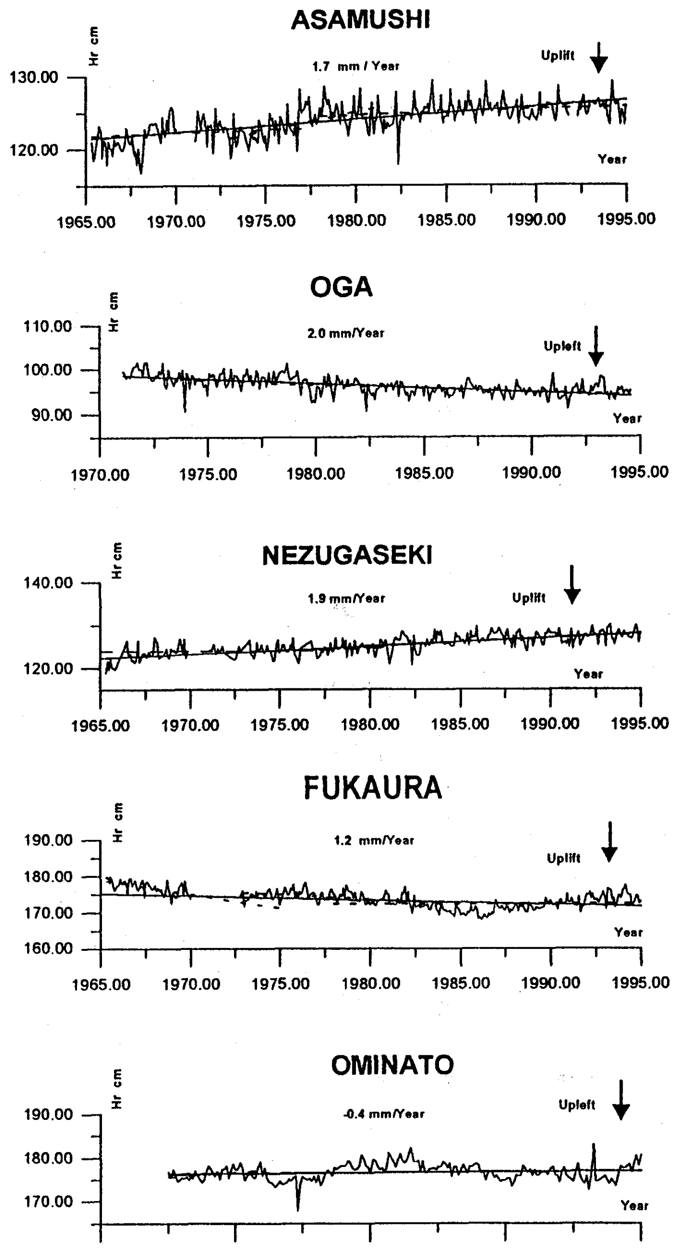


Fig. 6. The rate of vertical crustal movements of the tidal stations from see level data. Straight line shows the linear trend for the whole period. Dashed lines show the linear trend for each interval with interval I from 1965 to 1977, Interval II from 1973 to 1981, and interval III from 1978 to 1994. Arrow indicates Upheaval of crust.

2-2- Vertical Crustal Movement Deduced from Levelling Network Adjustment:

Since the Tohoku district is an active region in crustal movements, the error epoch of levelling (which is due to the vertical crustal movements during the observation epoch) should be taken into account in the adjustment of levelling network. For this purpose, we will estimate not only corrections to the approximate heights in the reference epoch but also corrections to their rates of vertical movements, which are linear functions of time "**t**" within a certain period at each benchmark. This kind of model is called the velocity model (Yu and Yu, 1983; Papo and Perelmuter, 1984; Fujii, 1991; Xia, 1993).

The motion of the **i**-th benchmark at time **t**, $H_{i,t}$, can be described by the following equation:

$$H_{i,t} = H_{i,0} + \Delta_i + R_i \Delta t + h_i \quad , \qquad (2)$$

where $H_{i,0}$ is the approximate height of **i**-th benchmark at the reference time t_0, Δ_i is the correction to approximate height $H_{i,0}$, R_i is the rate of vertical movement linear with time at **i**-th benchmark, Δt is the time difference between epoch **t** and reference epoch t_0, and h_i is a new parameter that we have introduced which represent the sudden change of **i**-th benchmark at a certain time between t_0 and **t**. Note that for a point where h_i exists, there should be at least three epochs of repeated levelling data to estimate the three parameters Δ_i, R_i, and h_i.

In levelling, approximate height $H_{i,0}$ is generally obtained from observed height differences and height of a starting benchmark. Precise levelling gives height differences, l_{ij}, between benchmarks **i** and **j**. Thus we obtain the error equation as follows:

$$V_{ij} = H_{j,t} - H_{i,t} - l_{ij,t} \quad , \qquad (3)$$

where V_{ij} is the residual of $l_{ij,t}$, which is the observed height difference between benchmark **i** and **j** at time **t**. From equations (2) and (3) we obtain the following equation:

$$V_{ij,t} = \Delta_j - \Delta_i + R_j \Delta t - R_i \Delta t + h_j - h_i + d_{ij} \quad , \qquad (4)$$

where

$$d_{ij} = H_{j,0} - H_{i,0} - l_{ij,t} \quad . \qquad (5)$$

Equation (4) leads to the following observation equation in matrix form :

$$V_n = A_{n,m} X_m + d_n \quad , \qquad (6)$$

where V_n is a residual vector when **n** is the total number of observation, $A_{n,m}$ is the coefficient matrix when **m** is the number of parameters, X_m is the unknown parameter vector. Vector X_m includes Δ_i and R_i, the unknown parameters to be solved. The elements of the coefficient matrix **A** are 0, 1, -1, or time interval such as $t_i - t_j$, and the row sum is generally equal to zero. d_n is a given constant vector.

When we assume that both the corrections to the approximate heights and the rates of vertical movements at all bench marks are unknown, we have a rank deficit system of the normal equation. Therefore, in order to get a solution in such a particular case, the inverse of a singular matrix has to be reached through some special mathematical treatment called the algebra of generalized inverses of matrices (Mousa, 1992; El-Fiky, 1992a and b; El-Gazouly, 1988). Alternatively, another approach can be used by imposing constraints called inner constraints such that the singularity of the normal equation is recovered. Generally, these cases are called as the pseudo-inverse.

The inner constraint technique will be applied in this study by using two constraint equations, i.e., two reference datums such as one for height and one for the rate of vertical movement. To apply this technique we will follow the way called quasi-stable points network adjustment method (Zhou, 1980). It assumes that the center of gravity of a certain number of selected quasi-stable points, which are relatively stabler than other moving points, is unmoved. As a guide to the reader, a brief description of this technique will be given bellow.

Let us introduce a constraint equation

$$\mathbf{E}\overline{\mathrm{X}} = \mathbf{0} \quad , \tag{7}$$

where $\mathbf{E}$ is a constraint matrix and $\overline{\mathrm{X}}$ is estimated parameters. When $\mathbf{E}$ satisfies the following relation.

$$\mathbf{A}\mathbf{E}^{\mathrm{T}} = \mathbf{0} \quad , \tag{8}$$

we have the following modified normal equation system:

$$\begin{pmatrix} \mathrm{N} & \mathrm{E}^{\mathrm{T}} \\ \mathrm{E} & 0 \end{pmatrix} = \begin{pmatrix} \mathrm{N}^{+} & \mathrm{E}^{\mathrm{T}}(\mathrm{E}\ \mathrm{E}^{\mathrm{T}})^{-1} \\ (\mathrm{E}\ \mathrm{E}^{\mathrm{T}})^{-1} & 0 \end{pmatrix} , \tag{9}$$

where the superscripts "T" and "+" represent the transpose and pseudo-inverse of a matrix. Usually, the element of $\mathbf{E}$ matrix is 1 or 0 in the case of a levelling network. Then divide $\overline{\mathrm{X}}$ into two submatrices, $\overline{\mathrm{X}}_1$ containing only corrections to the approximated height, and $\overline{\mathrm{X}}_2$, containing only vertical velocity, as

$$\overline{\mathrm{X}} = [\overline{\mathrm{X}}_1 \quad \overline{\mathrm{X}}_2]^{\mathrm{T}} \quad , \tag{10}$$

where $\overline{\mathrm{X}}_1 = [\mathbf{\Delta}_1 \quad \mathbf{\Delta}_2 \ ....\mathbf{\Delta}_n]^{\mathrm{T}}$, $\quad \overline{\mathrm{X}}_2 = [\mathbf{R}_1 \ \mathbf{R}_2 \ ....\mathbf{R}_n]^{\mathrm{T}}$

Consequently, $\mathbf{E}$ is divided into $\mathbf{E}_1$ and $\mathbf{E}_2$, and takes the following form:

$$E = \begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix} \quad , \qquad (11)$$

where $\mathbf{E_1}$ and $\mathbf{E_2}$ are the constraint matrices of order $\mathbf{k{\times}1}$ ($\mathbf{k= m/2}$, when $\mathbf{m}$ is number of observations) of the height and the rate of vertical movement respectively. For the case of levelling, $\mathbf{E_1}$ and $\mathbf{E_2}$ are

$$\mathbf{E_1 = [1\ 1\ \ldots\ldots\ldots 1]} \quad , \qquad \mathbf{E_2 = [1\ 1\ \ldots\ldots\ldots\ldots 1]}.$$

Thus the constraint equations are

$$\mathbf{E_1 \overline{X}_1 = 0} \quad , \qquad \mathbf{E_2 \overline{X}_2 = 0} \ .$$

The solution is given by

$$\mathbf{\overline{X} = N^{+}A^{T} Pd} \quad , \qquad (12)$$

where $\overline{X}$ is the estimated parameters, $\mathbf{P}$ is the weight matrix, and the other parameters are as mentioned before. The covariance matrix $\mathbf{\Sigma_{(X)}}$ of the estimated parameters is

$$\mathbf{\Sigma_{(X)}} = \hat{\sigma}_o \mathbf{N^{+}} \ . \qquad (13)$$

$\hat{\sigma}_o$ is the a posterior variance given by

$$\hat{\sigma}_o = \mathbf{V^{T}PV/(n - m)} \quad , \qquad (14)$$

where $\mathbf{(n\text{-}m)}$ is the degree of freedom when $\mathbf{n}$ is the number of observations and $\mathbf{m}$ is the rank of coefficient matrix $\mathbf{A}$. The solution satisfies

$$\sum_{i=0}^{p} \mathbf{\Delta_i = 0} \quad , \qquad \sum_{i=0}^{p} \mathbf{R_i = 0} \quad , \qquad (15)$$

where $\mathbf{p}$ is the number of selected quasi-stable points. As for how to select the quasi-stable points, first we apply a free network adjustment in which the center of gravity of the whole network is assumed unmoved. Inspection of the result by this preliminary adjustment enables us to find which points are relatively stable and adopt them as quasi-stable points. For more details about inner constraints technique and the quasi-stable point method, the readers are recommended to refer to Zhou (1980), Yu and Yu (1983), Zhange et al. (1985), Koch (1988), and Xia and Fujii (1992).

3- Results Deduced from Levelling Data:

Levelling data employed here comprise first-order levelling measurement carried out by the Geographical Survey Institute (GSI.). The total length of the levelling routes is about 3,500 km. The levelling routes are shown in Fig. 4. Fig. 5 shows the survey epochs. Although there are three epochs of levelling data for the network in Figure 5 before 1965 (one epoch was carried out from 1895 to 1902, the second was observed from 1933 to 1943, and the third one was carried out from 1956 to 1961), only data after 1965 are adopted because the intervals of levelling before 1965 are too long and not suitable for the adjustment with velocity model.

It is required that there are at least two epochs of levelling observation for an interval where crustal movements can be supposed to be linear when the velocity model is adopted to perform least squares adjustment. In the Tohoku levelling network case, we have 4 completed epochs of levelling data, with each surveyed during 1966-1969, 1973-1977, 1978-1983, 1983-1986 respectively. In addition to the above, one epoch not completed yet, started in 1994.

Even though closing errors of some loops (loop **III**, **IV**, **IX** in epoch one, loop **II**, **XII** in epoch two, loop **VI**, **VII**, **XIII** in epoch four) are beyond the error limitation of first-order levelling observation ($2\sqrt{S}$ in mm where S is the length of the levelling loop in km), these data were adopted for network adjustment (Table 1). This is because we have only limited number of repetition of levelling in these cases. Also we expect that a velocity model will reduce loop closing errors to some extent if they are due to the ongoing crustal movement during each epoch.

We rearranged the levelling data epochs into three intervals in time sequence: interval **I** from 1966 to 1977, interval **II** from 1973 to 1981, and interval **III** from 1978 to 1995. The intervals **I, II, III** are 12, 9, and 17 years respectively. It is assured that there are at least two epochs of data for each levelling line in each interval. Therefore, it is possible to estimate the rate of vertical movement from each interval of data.

In this way, least squares adjustment was performed for three intervals of levelling data separately and the parameters of heights and the rates of vertical movement were estimated. The standard deviations of observation for 1 km levelling route for interval **I**, **II**, and **III**, are 4.31 mm, 4.88 mm, and 4.54 mm, respectively. Generally, the unit standard deviation of all interval is large compared with the accuracy requirement of first-order levelling network. This suggests that the extraordinarily large closure errors (see Table 1) were possibly caused by normal observation errors and not by epoch error.

Based on the estimated values of the rates of vertical movement, the contour maps of movement during the three intervals were charted in Fig. 7. Fig. 8 shows the standard deviations of the estimated rates of vertical movement. In general, the standard deviations of the estimated rates of the three intervals are large. The estimated rates of vertical movement at ten tidal stations deduced from levelling with those deduced from sea level data are listed in Table 2.

4- Results Deduced from Both Levelling and Tidal Data :

In the previous section, we selected some so-called quasi-stable points and assumed that the sum of their movement rates equal to zero in order to solve the reference datums. In this section, tidal data will be combined with levelling data to perform least squares adjustment.

Table 1. Closure errors of levelling loops in Tohoku district. The unit is mm.

<table>
<tr><th>Survey No.&
Duration</th><th>1
1966-1969</th><th>2
1973-1977</th><th>3
1978-1981</th><th>4
1983-1986</th><th>5
1994-1995</th></tr>
<tr><td>Loop I
(75 km)</td><td>7.7</td><td>—</td><td>16.0</td><td>—</td><td>—</td></tr>
<tr><td>Loop II
(259 km)</td><td>18.7</td><td>35.9</td><td>21.1</td><td>11.8</td><td>—</td></tr>
<tr><td>Loop III
(586 km)</td><td>50.4</td><td>3.5</td><td>6.7</td><td>7.9</td><td>—</td></tr>
<tr><td>Loop IV
(495 km)</td><td>73.9</td><td>4.5</td><td>14.5</td><td>39.8</td><td>50.8</td></tr>
<tr><td>Loop V
(380 km)</td><td>40.4</td><td>26.5</td><td>14.4</td><td>9.8</td><td>—</td></tr>
<tr><td>Loop VI
(494 km)</td><td>28.9</td><td>22.7</td><td>1.8</td><td>48.7</td><td>—</td></tr>
<tr><td>Loop VII
(375 km)</td><td>0.5</td><td>29.0</td><td>1.3</td><td>48.7</td><td>1.4</td></tr>
<tr><td>Loop VIII
(156 km)</td><td>4.2</td><td rowspan="2">17.4</td><td rowspan="2">5.0</td><td>37.9</td><td>—</td></tr>
<tr><td>Loop IX
(244 km)</td><td>42.3</td><td>13.2</td><td>—</td></tr>
<tr><td>Loop X
(322 km)</td><td>13.6</td><td>33.3</td><td>26.2</td><td>7.4</td><td>1.4</td></tr>
<tr><td>Loop XI
(328 km)</td><td>6.5</td><td>61.4</td><td>33.3</td><td>74.3</td><td>—</td></tr>
<tr><td>Loop XII
(400 km)</td><td>19.6</td><td>72.5</td><td>9.4</td><td>30.1</td><td>—</td></tr>
<tr><td>Loop XIII
(512 km)</td><td>25.7</td><td>40.8</td><td>21.3</td><td>56.8</td><td>78.6</td></tr>
<tr><td>Loop XIV
(122 Km)</td><td>24.2</td><td>10.7</td><td>7.2</td><td>11.3</td><td>—</td></tr>
</table>

In section (2-1), rates of vertical movement at all the concerned tidal stations were estimated from sea level data. However, these estimated linear rates should not be used as the fixed values for readjustment of the levelling network, because the rate of vertical movement changes from period to period as is seen in Fig. 6. For this reason, the rate of vertical movement of the three intervals of levelling data were estimated from the divided linear rates of change sea level shown in Fig. 6 by dashed lines.

We tried two types of readjustment, one assuming a known tidal station and the assuming with five known tidal stations. As for the "one station" solution, we chose the rate of vertical movement at Asamushi station as known value, because this station is located in the area of quasi stability and, moreover, the data quality is good in both length and noise. The reestimated rate of vertical movement from data interval **I**, **II**, and **III** are approximately the same as those obtained in free net solution. For the second case, five tidal stations at Hachinohe, Kamaishi, Nezugaseki, Oga, and Fukaura were used, because these stations are well distributed around the network and have long enough sea level data. The reestimated rates of vertical movement from data intervals **I**, **II**, and **III** are shown in Fig. 9.

5- Comparison of the Results Deduced from Levelling and Tidal Data:

Levelling and tidal observations are two independent measurement techniques dealing with the vertical crustal movements. If both of them are dealt with properly, the deduced rates of vertical movement from them should be consistent with each other.

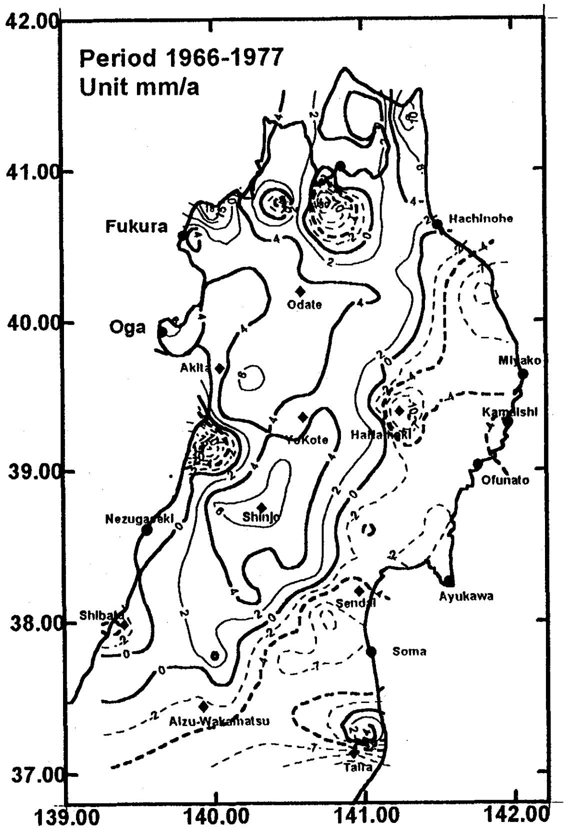


Fig. 7(a)

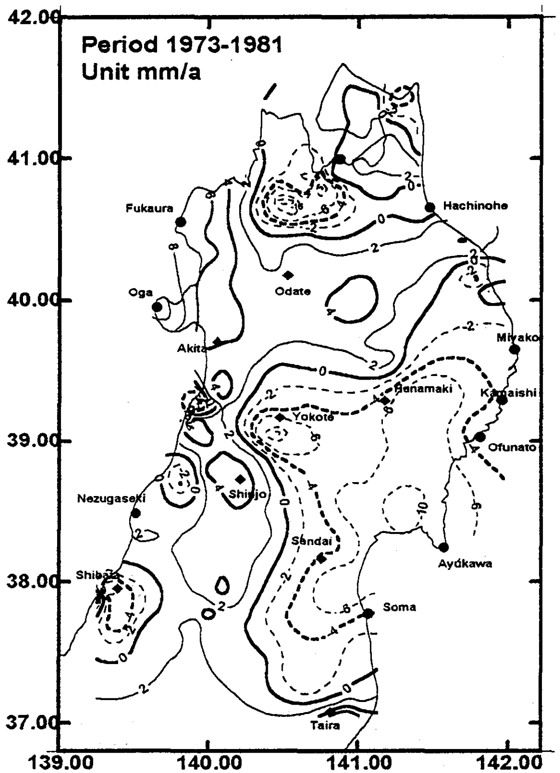


Fig. 7(b)

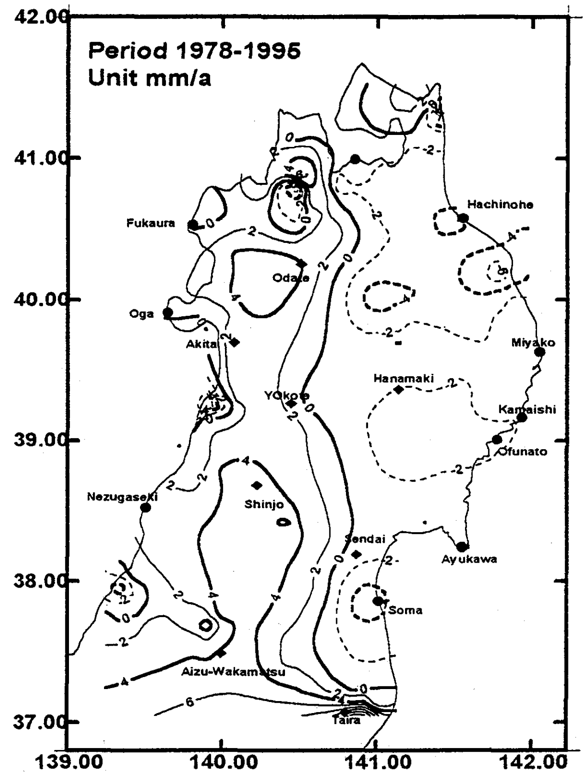


Fig. 7(c)

Fig. 7. Contour maps of the rate of vertical crustal movement in the Tohoku district. (a), (b), and (c) are based on the results of free network adjustment techinque with respect to time interval 1966-1977, 1973-1981, and 1978-1995, respectively. The unit is mm/a.

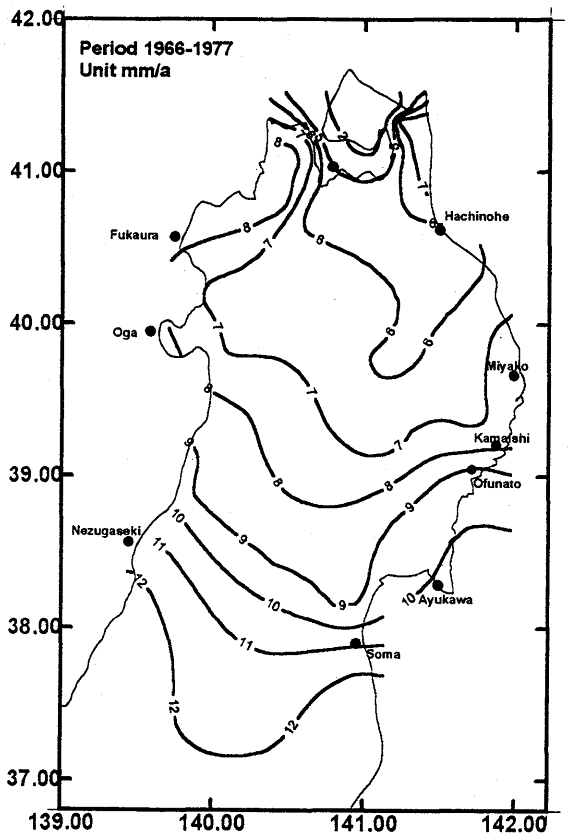

Period 1966-1977
Unit mm/a
Fukaura
Oga
Nezugaseki
Hachinohe
Miyako
Kamaishi
Ofunato
Ayukawa
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Fig. 8(a)

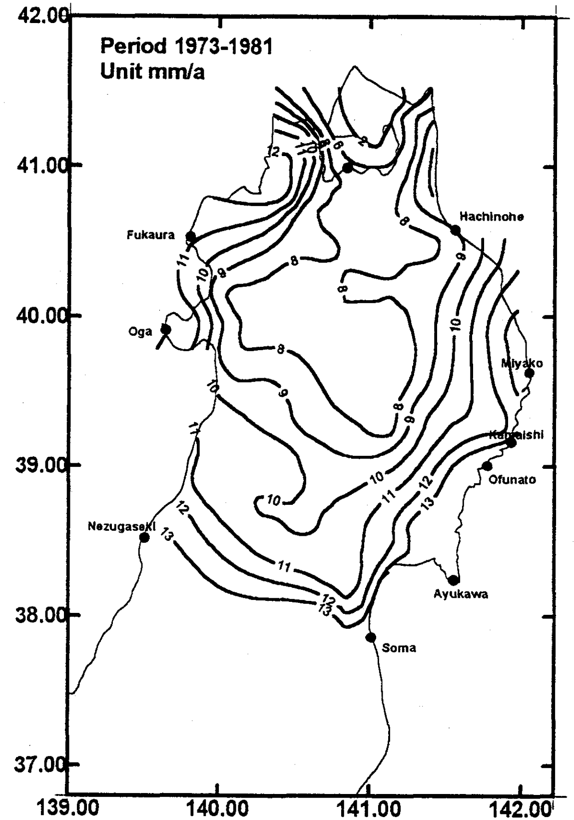
Period 1973-1981
Unit mm/a
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Fig. 8(b)

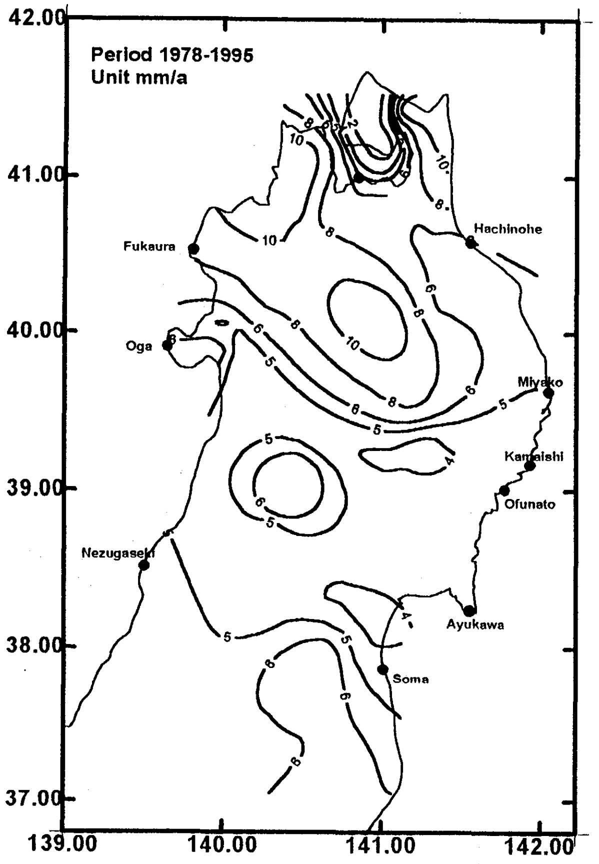


Fig. 8(c)

Fig. 8. Contour map of standard daviation of estimated rate of the vertical movememt by free adjustment technique. The panels (a), (b), and (c) correspond to those in Fig. 7, respectively. The unit is mm/a.

In Table 2, the estimated rate of vertical movement at 11 tidal stations from both levelling data and tidal data are listed. It can be seen that most of the rates of vertical movement at tidal stations deduced from sea level data and from levelling data are consistent with each other. This consistency of the results suggest that, first, the method of processing both tidal and levelling data may be appropriate as far as the present accuracy is concerned, and second, both data can be combined to study the vertical crustal movement with consistency. The latter one is of much importance, because the levelling data gives us information about a large region but discrete in time, while tidal data give us information continuously in time but at few distant stations.

Note, however, that the rate of crustal movement may not be necessarily constant, but some periodical crustal movement variations could exist (Nishi, 1985). Suppose amplitude of periodical variation is large. Then, if accidentally old levelling bservations is carried out when periodical variation reached the top and new one at the time of bottom, the estimated rate of vertical movement from these two levelling observations would be significantly different from the longer term linear rate of movement there.

Table 2. The comparison between the rates f vertical at Tidal Stations obtained from sea level data and levelling data. Positive sign indicates uplift.

Period No. & Duration	(I) 1966-1977		(II) 1973-1981		(III) 1978-1995	
	Tidal Data	Levelling	Tidal Data	Levelling	Tidal Data	Levelling
Asamushi						
Rate mm/a	-0.80	0.47	-1.80	0.05	-0.70	-1.20
S.D. cm/a	±0.06	±0.55	±0.20	±0.70	±0.04	±0.55
Hachinohe						
Rate mm/a	0.04	1.20	3.58	1.28	1.70	-4.20
S.D. cm/a	±0.17	±0.50	±0.19	±0.80	±0.11	±0.50
Miyako						
Rate mm/a	-6.10	-6.37	-3.30	-2.75	-3.40	-2.56
S.D. cm/a	±0.13	±0.72	±0.18	± 1.13	±1.2	± 0.42
Kamaishi						
Rate mm/a	-8.80	-6.73	-6.70	-4.83	-5.70	-3.20
S.D. cm/a	±0.24	±0.72	±0.14	±1.17	±0.10	±0.42
Ofunato						
Rate mm/a	-6.70	-4.93	-5.20	-3.77	-3.60	-2.51
S.D. cm/a	±0.12	±0.90	±0.17	±1.26	±0.09	±0.47
Ayukawa						
Rate mm/a	-5.10	-3.90	-10.30	-11.64	-2.60	-1.06
S.D. cm/a	±0.04	±1.00	±0.17	±1.28	±0.09	±0.43
Soma						
Rate mm/a	------	-----	-1.80	-4.46	-5.10	-4.90
S.D. cm/a	------	-----	±0.19	±1.26	±0.08	±0.47
Nezugaseki						
Rate mm/a	0.01	-1.00	-1.37	0.96	-1.81	2.56
S.D. cm/a	±0.20	±1.12	±0.15	±1.30	±0.10	±0.52
Oga						
Rate mm/a	4.30	5.54	2.40	5.76	2.10	1.04
S.D. cm/a	±0.2	±0.81	±0.03	±1.19	±0.19	±0.57
Fukaura						
Rate mm/a	3.80	4.58	2.60	5.60	0.14	0.68
S.D. cm/a	±0.13	±0.83	±0.19	±1.10	±0.01	±0.95
Ominato						
Rate mm/a	-----	-----	------	-----	-.0.30	0.31
S.D. cm/a	-----	------	-----	-----	±0.04	±0.31

Tidal data may be used to correct such effect because tidal observation is carried out continuously for a long time. Although, the variability of tidal data is much larger than levelling due to many environmental effects, the usage of filtering and areal average of the monthly mean sea level would significantly improve variability of sea records (Kato and Tsumura, 1979). Table 2 shows that the accuracy of the vertical rate deduced from tidal data is much better than that from levelling data. Tidal data at Ayukawa station is a good example to support the above interpretation. The monthly mean sea level data at Ayukawa suggests that it has been subsiding through the whole period, but the subsidence accelerated obviously during 1973 to 1981 and after 1981 it slowed down again. The estimated vertical rates of the three levelling intervals also suggests the existence of that accelerated subsidence. From this comparison, we may be able to conclude that monthly mean sea level data can be used as the absolute datum to the vertical crustal movement there.

In Table 2, there are exceptions at Hachinohe and Nezugaseki where the rates of vertical movement during interval **III** are opposite and their difference is significantly large between levelling and tidal data. Leveling data at Hachinohe suggests that it uplifted with 1.2 mm/a in intervals **I** and **II**, and changed to subsidence of 4.2 mm/a in interval **III**. However, the sea level data suggest continuous uplift through the whole period, though its rate seems to have slightly changed.

In Nezugaseki, levelling data shows large uplift in the interval **III,** while the sea level data suggest subsidence in the same period. Judging from Fig. 6, land subsidence seen in sea level data in inherent at Nezugaseki. The differences between the vertical rates of levelling and tidal data during interval **III** at both Hachinohe and Nezugaseki are approximately the same. There might be some kinds of unknown systematic errors in the levelling data which cause the bias of the estimated rates of vertical movement.

In order to make unknown systematic errors minimum, it might be suitable to use as many fixed tidal sites as possible in the network adjustment. For this purpose, the three intervals of levelling data were once again adjusted taking all of the vertical rates deduced from five tidal stations as fixed in Fig. 9. Comparing Fig. 7 with Fig. 9, we see a difference in the results as for the Hachinohe area and Nezugaseki area. This stems from the constraint of vertical movements at Hachinohe and Nezugaseki using sea level data instead of levelling only.

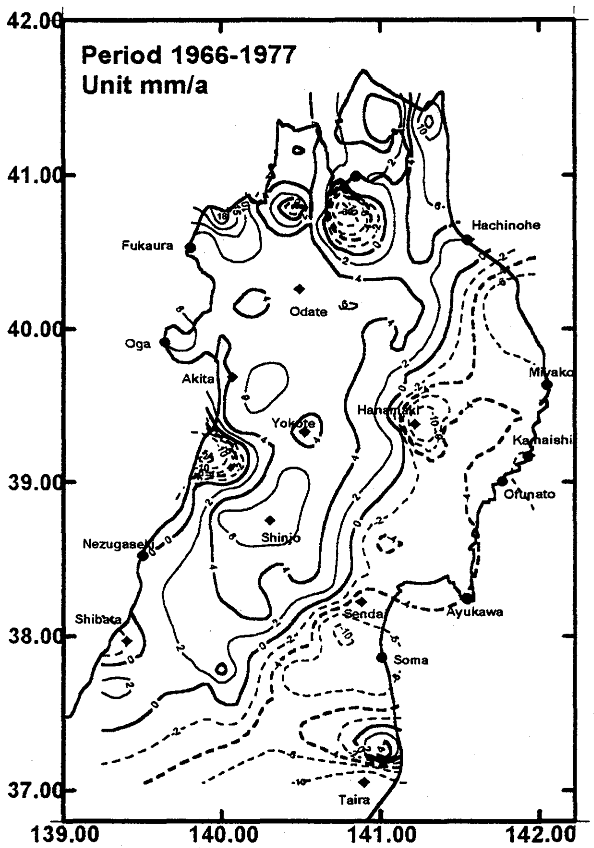
Summing up from the comparisons of various net adjustment algorithms described so far, it seems best to rely on the multiple stable tidal stations as absolute datum for the levelling data.

6- Characteristics of the Contemporary Vertical Movement in Tohoku District:

Fig. 9 shows the final results of spatial distribution and temporal change of the vertical movement in Tohoku district.

As already pointed out by many investigators (Dambara, 1971; Kato, 1979; Ishii et al, 1981; Miura et al, 1989) the most fundamental features, subsidence of the pacific coast, uplift of the north Japan Sea coast and the southern part of district, are unchanged by the present study. However closer look of the obtained results may provide us with more detailed picture of vertical crustal movements in this district.

The area along Miyako, Kamaishi, and Ofunato (Sanriku coast) were in a state of subsidence with approximate rate of 8 mm/a during interval **I**, **II**, and reduced to about 4 mm/a later.


Period 1966-1977
Unit mm/a
Fukaura
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Odate
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Miyako
Yokote
Hanamaki
Kamaishi
Ofunato
Nezugaseki
Shinjo
Shibata
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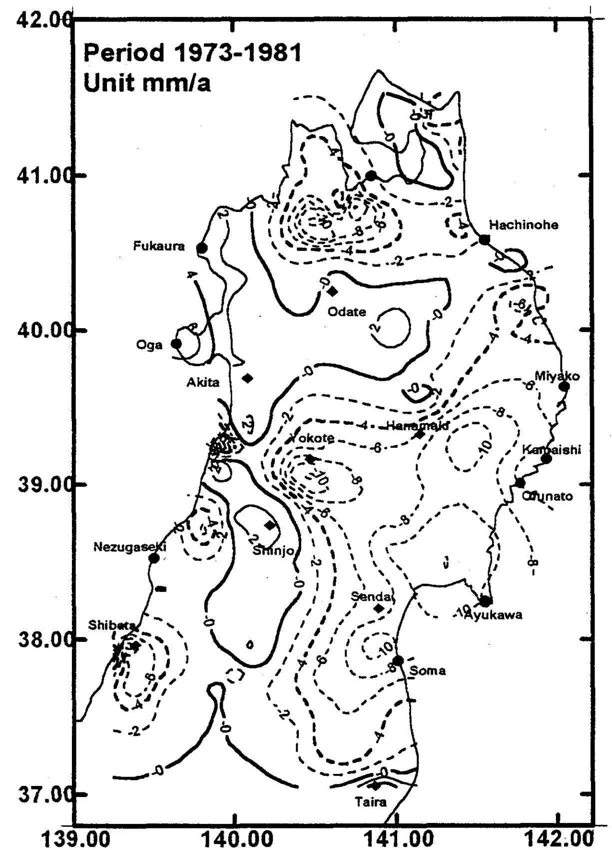
Fig. 9(a)


Period 1973-1981
Unit mm/a
Fukaura
Hachinohe
Odate
Oga
Akita
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Hanamaki
Yokote
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Fig. 9(b)

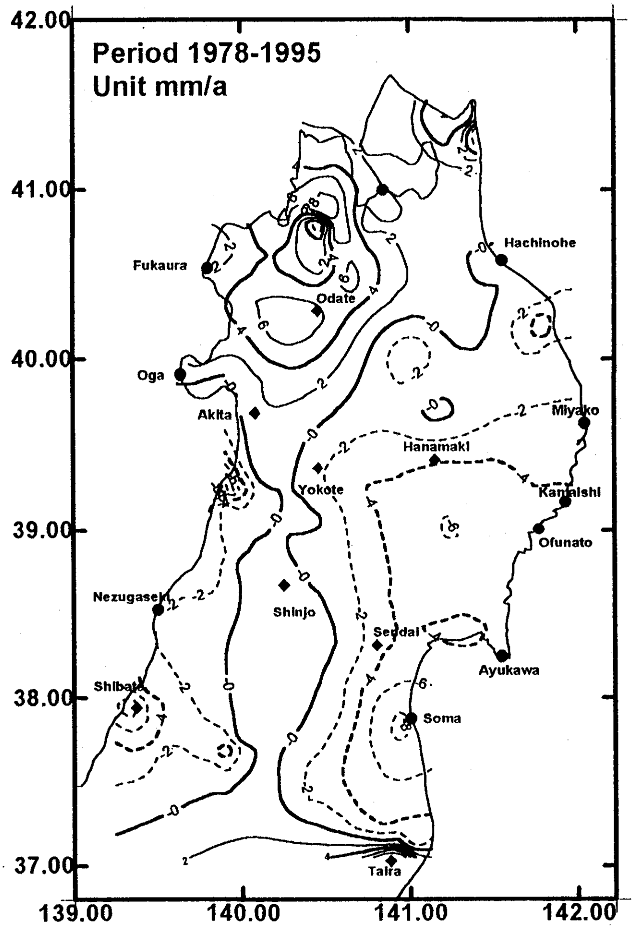

Fig. 9(c)

Fig. 9. Contour maps of the rate of vertical crustal movement in the Tohoku district. (a), (b), and (c) are based on the rate of vertical movement of Hachinohe, Kamaishi, Nezugaseki, Oga, and Fukaura tidal stations with respect to time interval 1966-1977, 1973-1981, and 1978-1995, respectively. The unit is mm/a.

The area around Ayukawa was in a state of subsidence with a rate of 4 mm/a during the first interval, and increased to 10 mm/a during the second interval, and then once again reduced to about 4 mm/a during the third interval. Rapid subsidence in the second interval may be due to co-seismic subsidence by the Miyagi-oki earthquake of 1978 (Seno et al., 1980; Kato, 1983).

A remarkable local subsidence around Aomori city seems to be regarded as an artificial deformation caused by pumping of ground water (Miura, 1982; Miura et al, 1989). The rate of subsidence during the first interval is 35 mm/a. But it reduced to 18 mm/a during the second interval and became uplift at a rate of about 4 mm/a during the third interval. This change of vertical deformation rate may be due to the control of pumping out of groundwater in this area.

There is another local subsidence area along the southern Japan Sea coast. This subsidence is regarded as co-seismic deformation (rate of subsidence during interval I was 24 mm/a) due to the Niigata earthquake (1964, M=7.5) which occurred very close to the coast (Abe, 1974). Subsidence rate decreased gradually with time (12 mm/a , 10 mm/a during interval **II**, **III** respectively).

On the other hand, there is a significant uplift around the northwestern part of the Tohoku district, north of Fukaura area, rate of which amount to 18 mm/a during interval **I**. This region is close to the source area of the 1983 Japan Sea earthquake (M=7.7). The abnormal land uplift was considered to be a precursor of the above earthquake (Fujii, 1973; Miura et al, 1989). This uplift extended southward making a large uplift area but the rate is changed with time (rate during interval **II**, **III** are 4 mm/a, 8 mm/a, respectively).

Uplift is also seen near Shinjo, where its rate was 6 mm/a during interval **I** (about 70 km in diameter), reduced to 2 mm/a during interval **II** and further reduced to 0.5 mm/a during the third interval. Miyamura and Mizoue (1964) suggested that this trend of uplift might reflect an up-warping movement of island arc, although the reduced rate with time diminishes the plausibility of this suggestion.

Rapid local subsidence of 16 mm/a is recognized at the southeastern end of Tohoku district (north of Taira area) during the first interval. This may be due to the effect of mining at Zyoban mining region (Kato, 1979). This subsidence changed to uplift gradually and extended westward forming a large uplift area , rate of uplift during interval **II** and **III** became 4 mm/a and 10 mm/a respectively. Though this phenomena might be due to crustal visco-elastic rebound or buoyant recovery by inflow of underground water after the close of the mine, further study is needed to clarify its mechanism.

In addition, there is a significant large local subsidence around Hanamaki area (about 250 km from Japan trench axis) during interval **I** with a rate of 10 mm/a. During interval **II**, a similar subsidence is seen in Yokote basin with a rate of 12 mm/a. As to whether there is any relation between these two subsidences and whether these subsidences should be considered as due to the subducting pacific plate, or should be considered as just local subsidences, more detailed study is required.

7- Conclusion:

The vertical crustal movements in the Tohoku district have been studied by a new adjustment technique. The technique employs a velocity model that allows crustal deformations between epochs. Moreover, we studied various algorithms such as free net adjustment, single and multiple tidal stations for absolute datum for levelling, and found that the last one is best. The present study thus combined levelling data with tidal data to discuss the crustal movements in the Tohoku district from 1966 up to date. Based on the results of the analysis, some conclusions on the crustal movement in this area and also some notes on the analysis technique are given.

The characteristics of the vertical movements in the Tohoku district are quite complicated in the studied period. On a long term, the Pacific coast subsided and the north Japan Sea coast uplifted, as already pointed out by Kato (1979), Ishii (1981), Miura (1982), and Miura et al. (1989). The rates of these movements, however, change from time to time. Moreover, a similar accelerated subsidence at Hanamaki area during the first interval is seen in Yokote basin during the second interval.

The rate change in the north of Taira area in the recent 30 years is outstanding. As to whether it has any tectonic meaning or not, further study is required.

The present study showed that the tidal records provide accurate constraint as absolute datum for adjusting levelling data. This is especially important where tectonic deformation is rapid and complicated. To realize accurate adjustment, many tidal stations with high quality of data and long history are indispensable. By this way, the rate of vertical crustal movement using the least squares adjustment is most reliable.

Finally, special attention should be taken into account when we use the dynamic adjustment (velocity model), to express the vertical movement of each bench mark. The suitable intervals should be fitted to the tectonic activity of study area. The present case is performed on the assumption that the crustal movement in the Tohoku district is linear with time for three intervals, 11, 9, 17 years respectively, and acceptable results are obtained. However, temporal change of vertical movements in tidal record suggest that shorter term crustal deformation might exit. Therefore more frequent repetition may be necessary to get more accurate results.

Acknowledgment

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