測地測量結果로부터 調査된 過去 80年間 韓國에서 地殼의 水平變形
Horizontal Strain of the Crust in Korea for the Past 80 Years from Geodetic Observations

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要 旨

本 硏究에서는 韓國에서 舊三角網(1910-1915)과 정밀1차측지망(1975-1994)을 사용하여 地殼變動量을 계산하고, 地體構造의 일반적인 變形패턴을 幾何學的으로 調査하였다. 본 연구에서는 變形量을 계산하기 위하여 2次元의 無限小 變形모델을 假定하였으며, 水平變形量은 舊座標와 정밀1차 측지망의 精密同時網調整을 自由網調整法에 의하여 최초로 실시하여 一貫性있는 新座標를 사용하여 계산된 測地線의 變化量으로부터 推定하였다.

變形計算結果로부터 1910년부터 1994년까지 累積된 變形量은 平均 $(1.07\pm0.5)\times10^{-5}$ 이고, 이로부터 年變形速度는 $(0.13\pm0.063)\mu$/yr 임을 알 수 있었으며, 變形의 傾向을 보면 變形量이 10 μ 보다 큰 값이 韓半島의 東海岸 地域에 分布하고 있으며, 西部쪽에는 10μ 이하의 값이 分布하고 있는 것으로 나타나 한반도의 동해안에서 地震의 發生頻度가 높은 것을 考慮한다면 본 연구로부터 계산된 結果는 將來의 硏究를 위해 중요한 데이터가 될 것이다. 본 연구에서 얻은 主變形軸의 方向은 全國的으로 77.6° ±13.5° 방향임을 보여주고 있어 韓半島의 地殼은 ENE~WSW방향으로 壓縮狀態에 있음을 알 수 있었으며, 이 結果는 地質學者나 地震學者들의 연구로부터 얻은 結果와 P-軸의 방향이 일치하고 있고, 最大 剪斷變形 理論과 一致하고 있는 것으로 나타났다.

1. Introduction

The main task of geodesy is the determination of the Earth's size, shape and gravity field. Both the Earth's shape and gravity field vary with time under influence such as tectonics, tidal forces, etc.. Studies on the dynamic phenomena of the Earth, especially those of deformation of the crust, play an important role in modern geodesy.

Since the beginning of the 20th century, the study of crustal movement using geodetic measurements have actively been made in relation with earthquake researches in Japan and USA where large earthquakes took place frequently (e.g. Reid, 1911; Tsuboi, 1933).

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In recent, the detection of crustal movement by means of geodetic method has become more active for the researches of tectonics and earthquake prediction (e.g. Savage and Bomford, 1973 ; Bibby, 1968; Komaki, 1993).

Nowadays, space technologies such as Global Positioning System (GPS), Very Long Baseline Interferometry (VLBI), and Satellite Laser Ranging (SLR) are extensively used for the researches of crustal movement with high accuracy (e.g. Kato et al., 1986; Tanaka, 1986; Minster and Jordan, 1987). In Korea, these space techniques are rarely used in the field of geodetic measurement, therefore the detection of crustal movement using space technology remains a future task.

Since 19th century, the Korean peninsula has not experienced destructive earthquake except a few earthquakes of slight damaging. It is, therefore, widely believed that the peninsula is quite free from serious earthquake damages. This is the reason why much attention has not paid upon the earthquakes in Korea.

It is estimated that the historical seismicity of the Korean peninsula has a characteristics of periodical activity, as the activity of historical earthquakes was relatively high in 500~600s, 1200s and 1400~1700s. These facts suggest that considerable accumulation of crustal strains has been progressed steadily in the peninsula. Any study of crustal movement by means of geodetic observations, however, has not been made in Korea until today. To detect the crustal movement, it is necessary to resurveying of geodetic network. To obtain the reliable result, it is also necessary to readjust the old geodetic network and analyze its accuracy, especially for that of triangulation(e.g. Harada, 1967, Komaki, 1995). In Korea the first triangulation network (Basic Geodetic Control Network;BGCN) was established in 1910~1915. The revision survey of the triangulation network had not been made until 1975 when the project of the new Primary Precise Geodetic Network (PPGN) started. The analysis of accuracy of the old triangulation network has also not been carried out in Korea until today, because all original records of triangulation were lost during the Korea war. These facts are the reasons why crustal movement has not been researched in Korea until today.

Since 1975, the PPGN was established by trilateration using EDM instrument during the period of 1975~1994 confirming to economic growth and national needs. Because most of the old geodetic data were lost and different survey methods were used, an inconsistency between the old and the new network is involved. In 1994, the rigorous simultaneous adjustment of the new geodetic network was completed by free net adjustment that minimizes the sum of the squares of displacements.

The horizontal crustal movement was detected using the displacement vectors calculated from the old and the new coordinates. As a result, big errors have unexpectively been brought. Therefore, the reliability of the result is doubtful whether it represents a real horizontal movement. These results are mainly resulted from (1) inconsistency of scale between the new and the old network, (2) insufficient accuracy of angle measurement in the old network, (3) method of successive adjustment of the old network.

If we had the whole observation data of the old triangulation network, more reliable coordinates could be obtained, because the inconsistency of coordinates can be removed by the simultaneous network adjustment. The observation data of the old triangulation network are not available. Among about 1200 triangulation points in the PPGN, only 175 points (14.8%)

were found in normal state. From these reasons, the detection of crustal movement using displacement vectors are not appropriated in Korea. Thus, the displacement vectors at each triangulation point can not be used in the present study.

In the present study, the infinitesimal strain theory is applied because the displacement in the position of the network is very small compared to the size of the network. Being on the infinitesimal strain theory, the calculation of linear strain is made by the comparison of geodetic distance obtained from the old and the new coordinates. In order to calculate the linear strain using the geodetic distance calculated by Gauss mid-latitude formula, the network was divided into several blocks which are included 5~6 normal points obtained from two dimensional digital filtering. Unfortunately, the land uplift was not studied because no levelling data is prepared for providing an accurate data enough in the requirement of this study.

2. Precision Analysis of the New Established Geodetic Network

2.1 Geodetic Works

The National BGCN in the Korean peninsula was mainly established during Japanese occupation. The control network that consisted of triangulation and levelling, was mainly designed to satisfy the control requirements for 1:50,000 topographic mapping and cadastral survey and was set up before the decade of 1920. The works were executed by the Japanese Military Land Survey Department under the direction of the Bureau of Korea Land Survey in the period 1910 to 1915. The triangulation network was constructed of a set of points which have different order from 1st to 4th order and it was also established to provide a precise framework of control point for many low-order surveys such as cadastral mapping.

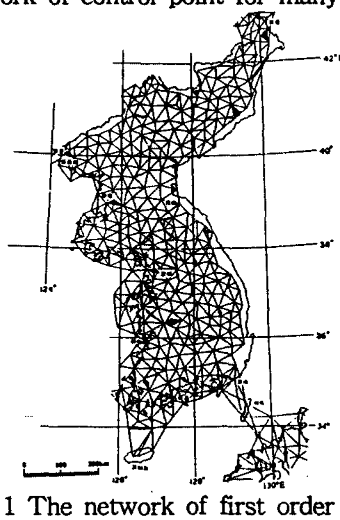

Figure 1 The network of first order triangulation originated from 1910 to 1915

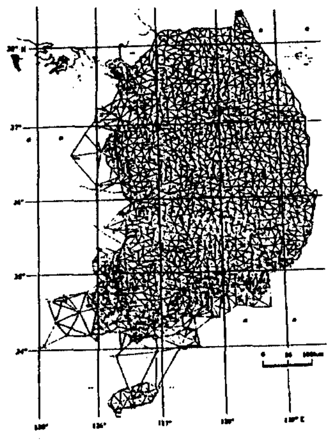

Figure 2 The Primary Precise Geodetic Network established from 1975 to 1994

The reference ellipsoid for the BGCN is the Bessel 1841 whose datum is Tokyo as a fundamental reference point, an origin, to which all other points can be referred. The direct connection between the BGCN and Tokyo Datum was made through Tushima island as shown in Figure 1. In the late of 1930s, it was found that the accuracy of first order triangulation network is equivalent to that of second order triangulation network of Japan. Therefore, resurvey project was attempted to improve the accuracy of control network. In 1943, resurvey could, however, not be continued because Japan had the disadvantage of World War II.

In 1950s, field investigation of triangulation ponts were carried out to repair the triangulation network. It was found that more than 70% of triangulation points and all levelling points were destroyed. Therefore, the survey was dominantly conducted to repair the monument and the base plate stone of triangulation points which were partly destroyed or damaged. In the beginning of 1960s, the geodetic survey was conducted by Korean Government with much difficult problems in social, economical and technical point of view. From the late of 1960s, the survey work was mainly conducted to reconstruct the triangulation network to meet the increasing requirements for public land surveys for various construction works, and for the production of 1:25,000 base map series by photogrammetric method. In this work, a consistency for the accuracy of geodetic network was not carefully regarded.

The results of triangulation and levelling that have still used for the reference of geodetic survey, were originated from Korea Land Survey Project. As mentioned before, taking into account that numerous geodetic information were lost, the task of maintaining accurate official coordinates has been required.

Since 1975, National Geography Institute (NGI) has been established the PPGN based on the number of 1155 points included the existing first and second order triangulation points. The area of the country is approximately 98,000 km^2, so there is one point for each 40 km^2. The PPGN throughout the country is to provide an accurate primary framework for topographic mapping and many low-order surveys. Trilateration, measured mainly with EDM instruments, was applied for the Primary Precise Geodetic Survey(PPGS). Based on the old points, geodetic survey by trilateration has been measured from 1975. In 1994, the PPGS was completed within the whole country and the basic frame of a nationwide which has a consistency, were first obtained by free network adjustment of the PPGN as shown in Figure 2.

2.2 Adjustment and Analysis of the New Geodetic Networks

An adjustment technique of geodetic network is generally classified into three categories, often used in practice; (a) multi-points fixing, (b) one point and one direction fixing and (c) free net adjustment. The (a) method gives a good geometrical strength of network, but the disadvantage is that the observation error as well as the secular variation are shifted to unfixed points. The (b) method has disadvantage that the systematic azimuth error is involved in a large network because a fixed direction is very weak in regard to the rotation of network. In the (c) method, there are no disadvantages mentioned above, but the normal equations B can not be solved, based on the condition, because its determinant is equal to zero; det(B)=0. The condition XX^T=min. is used to solve this problem. Where X is the difference between the new coordinate X_n obtained from network adjustment and the old coordinate X_{n-1}. After completed the geodetic survey, simultaneous adjustment by free-net was carried out for evaluating the accuracy and geometrical strength of network. In case of abnormal points, $X'=X_n-X'_{n-1}$ is used instead of $X=X_n-X_{n-1}$ which is used at normal points. The approximate coordinates X'_{n-1} was obtained from (n-1)th iteration. Therefore, if convergence had not been reached to 0.001 arc second, computation could iterate the entire process. Here three times of iteration were sufficient for the adjustment computation, and the results are shown for not to be dependent on the approximate coordinate used. The observations and network adjustment were followed the Specification of NGI.

The results obtained from free net adjustment is very effective to analysis the standard error of adjusted coordinates and to investigate the geometrical strength of geodetic network because there is no relation with the position of fixed point and direction. To investigate the accuracy of the adjustment computations and to analyze adjustment results, the standard error of coordinates adjusted were computed for all estimated stations.

The mean value of standard error of coordinates obtained is 0.065m and the maximum value is 0.20m. The [trace(Q)/n] value is 0.044m. It is nearly equivalent to that of block adjustment. Figure 3 shows the error ellipses of the position of 1155 triangulation points. The standard error increases toward the marginal part of the geodetic network. The ellipses are all circular form in shape. The displacement vectors at normal points were also plotted as vectorial sums of the coordinate differences as shown in Figure 4. The differences between the two solutions range between 0.2 m and 3.0 m with a mean of 0.81 m and RMS of 1.04 m. The vector of 75 percent is within 1.0 m. The differences in adjusted distances do not exceed 10ppm a requirement that satisfies first order-networks. Figure 3 and 4 shows that the geodetic network is necessary to reinforce the geometrical strength in the eastern demilitarized zone (DMZ) area and the southwestern nearshore area by GPS surveying.

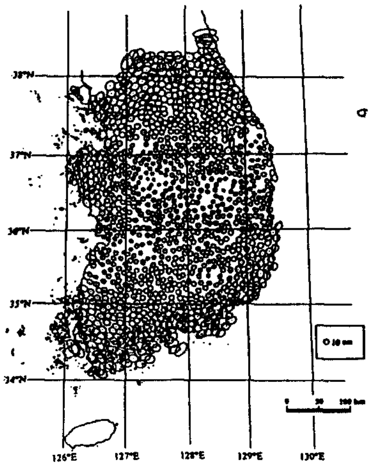

Figure 3 The standard error ellipse of adjusted coordinates obtained from free-net adjustment

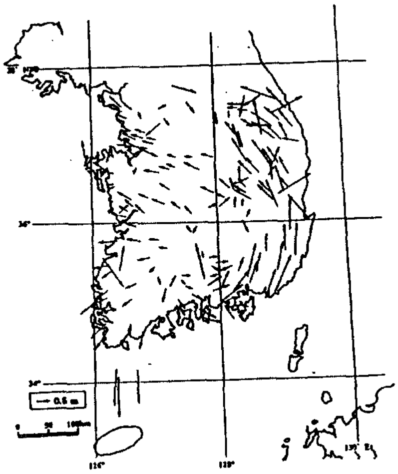

Figure 4 The displacement vectors between the new coordinates obtained from free-net adjustment and the old coordinates

Considering the standard deviation of unit weight, the mean of displacement vector and the distribution of displacement vector, the network adjusted by free network adjustment produced the best available value that is to meet the purpose of maintaining the existing geodetic coordinate system and of upgrading the accuracy of control points. The accuracy of mean position of the first and second order triangulation points is 7.4 cm (relative accuracy : 1/148,000). The rigorous adjustment of the national PPGN of Korea has produced a series of

3.2 Data Processing for Strain Calculation

For the calculation of the horizontal strain using the old triangulation points, it is important to maintain the consistency of precision through the network adjustment. As mentioned before, the BGCN was established by triangulation during 1910~1915. The PPGN consisted of about 1200 points of which the precision is equivalent to that of second order triangulation network of Japan. It is impossible to maintain the consistency of the precision and the scale between both networks because re-adjustment of BGCN can not be performed due to the loses of all documents related with the observations. Therefore, the strain calculation using the old and the new coordinates of the whole triangulation points can not be carried out. The normal points 175 are only available as shown in Figure 5. To calculate the precise strain, the area of about 90,000km^2 was demarcated into 18 blocks as an example shown in Figure 6. The area of each block is taken about 4000km^2~5000km^2 so that more than 5~6 stable points are included in each block. The reason that the area of this size was selected, is to reduce a seemingly strain of the side length by the coordinate error.

In the present study, the horizontal strain is calculated by means of the least square method. In the least square method, two-dimensional digital filtering and the basic criteria were applied to improve the precision of strain.

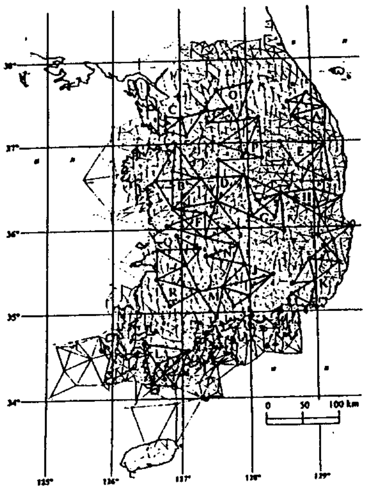

Figure 5 The Distribution of Normal Points Used (175 points)

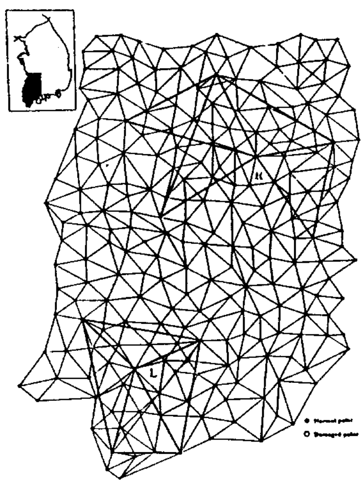

Figure 6 Example of Block Division

(1) Application of Two-Dimensional Digital Filtering Technique

In this study, two dimensional digital filtering technique was applied to eliminate a noisy observations. After applying the filtering to dX, dY components in each block, the appropriate points were acquired for the strain calculation. In some case, filtering was not applied because sufficient points are not available in each block. The strain components are computed for each point of the network by assuming that the strain components at a particular point are affected only by the surrounding points, which are connected by observations to the point at which the strain components are being computed.

In general, linear strain ds is included in the strain in proportion to the side-length, the scale error and the error of side-length caused from the coordinate error within the length of new coordinates which are considered to constitute the best available set of values for the current network. It is expected that these coordinates can be provided the new reference accuracy for space development, crustal movement study, digital mapping, public land survey and cadastal reallocation.

3. Horizontal Strain Patterns in the Korean Peninsula

3.1 Infinitesimal Strains of Homogeneous Body

Any deformed body has an involved history, for it passes from its undeformed stage through various stages before it eventually arrives at its final state of strain. This process is known as progressive deformation. Therefore, at any given instant during progressive homogeneous deformation of a body, there are two kinds of strain quantities that can be specified. There is the strain that relates the instantaneous configuration to the instantaneous change in configuration to the instantaneous configuration. The first of these quantities is the finite strain also called total strain. The second is known as infinitesimal strain also called incremental strain (Means, 1976). In the study of the strain effect in horizontal geodetic networks the infinitesimal strain theory is applicable because the displacement in the positions of the network point is very much smaller compared to the size of the network. The facts that we could use infinitesimal strain theory for our propose makes the derivation of the formulae for strain components very easy, and the formulae themselves become simple. When a line of azimuth is changed its length from r to r' by elastic deformation the strain of this line is expressed as (Jaeger, 1967)

$$E\alpha = \frac{r - r'}{r} = E_{xx}\cos^2\alpha_i + E_{xy}\cos\alpha_i\sin\alpha_i + E_{yy}\sin^2\alpha_i \qquad (1)$$

where r represents the strained length of line, r' represents to the constrained length of the line. Taking into account a triangle, equation (1) can be written for each line of triangle. If simultaneous equation is solved, strain components E_{xx}, E_{xy} and E_{yy} are obtained. These components are generally invariable which is dependent on the coordinates. The horizontal strain of Earth crust is expressed as the two dimensional homogeneous strain if the coseismic change is not taken account.

$$E_1 = \frac{1}{2}(E_{xx} + E_{yy}) + \frac{1}{2}[\ (E_{xx} - E_{yy})^2 + E_{xy}]^{\frac{1}{2}} \qquad (2)$$

$$E_2 = \frac{1}{2}(E_{xx} + E_{yy}) - \frac{1}{2}[\ (E_{xx} - E_{yy})^2 + E_{xy}]^{\frac{1}{2}} \qquad (3)$$

and, the direction of the principal strain axes is expressed as

$$\tan\theta = \frac{E_{xy}}{E_{xx} - E_{yy}} \qquad (4)$$

where θ is the azimuth of principal axis.

Sometimes, dilatation and the maximum shear strain are also used to represent the strain state of the Earth crust. They are

$$\text{Dilatation} \quad \Delta = E_{xx} + E_{yy} \qquad (5)$$

$$\text{Maximum shear strain} \quad \gamma_{max} = E_{xx} - E_{yy} \qquad (6)$$

side 100 km. For example, this error is about 10~20 cm after excluded the low level points among the second order points in Japan (Sato, 1996). Taking into account the length of side 20 km, the strain caused from the error is about 5~10 strain. It can not be ignored when the real strain is calculated. The length of side for the strain calculation was taken about 40~60 km in this study. Therefore, the band width is determined 25 cm when the average length of side is taken 50 km and the strain caused from the error is taken 5 strain.

(2) The Other Criteria for Selecting the High Precision Points

It is estimated that all normal points filtered in each block remain stable. But, it is expected that the large error is involved in the strain obtained from one triangle because the strain must be calculated using the old triangulation points. If it is assumed that the strain is homogeneous within the area of $(50\times50)km^2$, there is no variation of strain although the length of side is moved in parallel.

Among the stable points selected by filtering, high precision points were selected according to the following criteria. First, the points that the displacement vectors are small with the same direction, were selected. These displacement vector is homogeneous because the displacement of the second order points is determined from the first order points that the accuracy is nearly the same. Second, the direction and the size of displacement vector are inconsistently shown due to the error accumulated from the successive adjustment. In statistical point of view, the direction of displacement vector is also differently shown at the boundary area of block. From these reasons, it is possible to evaluate the stable points. Since this criterion is not qualitative, the stable points were determined by referring to $ds/S<30\mu$ based on ds calculated from the length of side 40~60km. This criteria is based on the fact that the linear strain is less than 30μ in Japan.

In order to maintain the consistency of the precision of strain components E_{xx}, E_{xy}, and E_{yy}, 7~9 side-lengths in each block were normally used for the strain calculation. Also, one or two side-lengths in the same direction are only used so that the side-lengths are not biased to the particular direction. To evaluate the bias of the strain components, the diagonal elements of the inverse matrix of normal equation were checked. Finally, 75 of normal points were selected for the calculation of horizontal strain.

To calculate the linear strain, differential formula of length of side is used. Linear strain $E\alpha$ of each side-length is expressed as the linear equation for the strain components, E_{xx}, E_{yy} and E_{xy}. In order to calculate the strain components, we must know the values of side-length S and azimuth A for the corresponding line.

3.3 Distribution of Horizontal Strain in the Korean Peninsula

In the present study the maximum shear strain was only taken into account because the scale error of the old and the new triangulation network is involved in the azimuth of principal axis of strain. Since dilatation involved the scale error, it was not taken into account. In general, error of the coordinates of the second order triangulation is estimated as 15cm. The error results in apparent strain of about 10μ strain in the side-length of 20km. Among 18 blocks, 14 blocks except four blocks including the geodetic lengths in which strain is 10μ has been accepted as the reliable results (see Table 1).

From the results, the strain accumulation during the period from 1915 to 1994 is calculated as $1.07\times10^{-5}\pm0.5\times10^{-5}$ in average. This corresponds to annual strain rate of $(0.13\pm0.055)\mu$ /year. The principal axis of strain in the 77.6° ±13.5° direction which was found in this work can generally be recognized throughout the whole country as shown in Figure 7. This figure is represented the annual strain rates of maximum shear strains of Korea which are obtained by computing from the new and the old triangulation data for a epoch of 80 years.
It shows that the Korean peninsula is featured by compression in a ENE-WSW direction. The annual strain rate in the Korean peninsula is 1/2~1/3 of that of the western part of Honsyu in Japan and the azimuth of the maximum strain axis is significantly different in both country. Here the standard deviations of maximum shear strain were also computed in each block for evaluating the results of strain calculation. According to those results the mean value of the standard deviation is 0.63 ± 10^{-7}/year

Table 1. Summary of strain calculation

No.	$\gamma_{max}(\mu)$	rate/yr	$\sigma(\gamma_{max})$	Az(deg.)	Area	Mark
1	15.1	0.1841	8.2	82.8	A	O
2	9.2	0.1122	3.2	74.9	B	O
3	9.5	0.1159	7.0	76.6	C	O
4	12.3	0.1500	6.1	70.5	D	O
5	14.2	0.1732	4.3	101.3	E	O
6	18.3	0.2232	4.2	57.2	G	O
7	15.8	0.1927	9.1	69.9	H	O
8	12.9	0.1573	7.9	66.9	J	O
9	14.4	0.1756	2.1	81.2	K	O
10	6.5	0.0793	3.5	61.8	L	O
11	4.9	0.0598	2.6	66.8	N	O
12	5.4	0.0659	4.0	77.6	O	O
13	7.6	0.0927	5.2	102.3	P	O
14	3.3	0.0402	2.4	95.8	R	O
AVG.	10.67	0.1301	4.986	77.61		
Rate	0.1314	STD(Az2) 13.46				
No.	$\gamma_{max}(\mu)$	rate/yr	$\sigma(\gamma_{max})$	Az(deg.)	Area	Mark
1	5.3	0.0646	5.7	95.8	F	×
2	21.6	0.2634	10.1	93.4	I	×
3	15.2	0.1854	18.0	70.4	M	×
4	15.8	0.1927	12.9	57.8	Q	×

*. O means accepted and X rejected

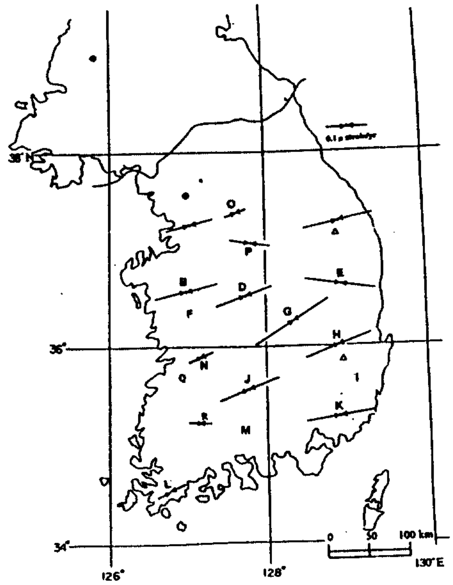

Figure 7 Maximum shear strain distribution in the Korean Peninsula. The length of the line is a measure for the magnitude.

4. Discussion

The study of tectonic movement with use of geological, topographical and seismic data in the Korean peninsula has physically been examined by some seismologists and geologists during the last decade. But no study relating to the tectonic movement using geodetic observation data as well as VLBI, SLR, and GPS data which are recently available in use, has been found yet. Therefore, the purpose of this study is geometrically to estimate the tectonic movement by means of the horizontal strain calculation using the old and the new geodetic observable in the southern part of the Korean peninsula. It is well known that the Korean peninsula is located in the southeastern part of Eurasian plate and is more stable than Japan which is located in the boundary area of Pacific and Eurasian plates. Taking into account such as geological structure, topographic feature and seismic activities, it is also shown that the Korean peninsula is stable except the NEN-SWS trending Yangsan fault and NWN-SES trending Ulsan fault known as the active fault.

In the present study the horizontal strains are calculated using the old triangulation data and the Primary Precise Geodetic Network to estimate the tectonic movement in geometrical point of view. Before the strain calculation, free net adjustment was carried out. Free net adjustment by Choi, J. H. and Choi, Y. S. (1994) was the first adjustment of geodetic network in Korea and it was provided the opportunity for the present study. The standard error of coordinates obtained by free-net adjustment is 0.065 m and the maximum value is 0.20 m. The standard error increases toward the marginal part of the geodetic network. The displacement vectors calculated at normal points show that the mean value is 0.81 m and 75 percent of those are within 1.0 m. It means that the results of free net adjustment provide the sufficient accurate coordinates for the strain calculation.

From the results, the strain accumulation during the period from 1915 to 1994 is calculated as $(10.7 \pm 5.0) \times 10^{-6}$ in average. This corresponds to annual strain rate of $(0.13 \pm 0.063)\mu$/year. The principal axis of strain in the 77.6° ±13.5° direction which was found in this work can generally be recognized throughout the country as a whole (see Figure 7). It shows that the Korean peninsula is featured by compression in a ENE-WSW direction. This agrees with the focal mechanism solution given by Jun (1990) (see Figure 8). With the aid of topographic, geological and geophysical studies, we can see that both directions of principal axis and lineament are composed of 35° ~40° degree. This agree with the theory of maximum shearing fracture.

Considering the focal mechanism solution given by Jun (1990), the distribution of historical and instrumental earthquakes and the frequencies of earthquake, the tectonic movement in the Korean peninsula is apparently shown and the destructive earthquake is expected in the near future.

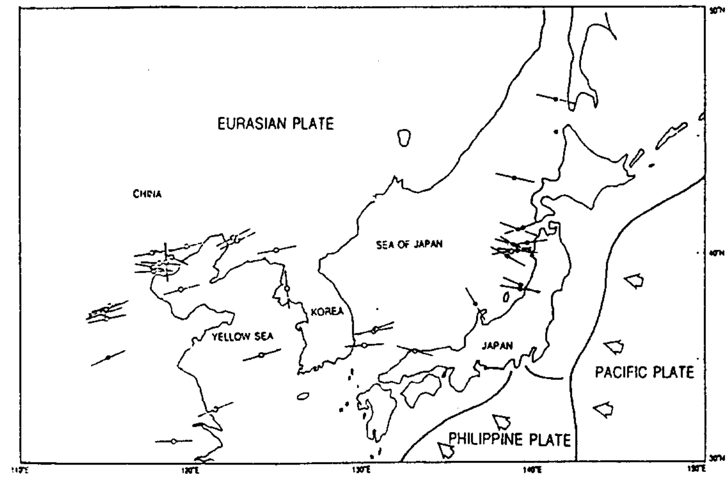

Figure 8 shows the results of focal mechanism solution in and around the Korean peninsula. Focal mechanism solutions of earthquakes show predominant strike-slip faulting with small amount of thrust components. The averaged P-axis is almost horizontal ENE-WSW(N71E) and the T-axis is trending NWN-SES (Jun, 1990).

The recent tectonic of Japan is closely related to the subduction of the Pacific and the Philippine Plate under the Eurasian Plate. Stresses from the boundaries between these plates may cause seismicity of the Korean Peninsula to some degree. However, the mechanisms by which the stresses are transmitted from Japan and Ryukyu arc subduction zones with their complications of back-arc spreading is less apparent than for stress transmission from the Himalayas (Molnar, et al., 1975). Considering that the Korean Peninsula is connected to China geologically, the source mechanism of large earthquakes occurring in the peninsula may be similar to that of those in China.

The annual strain rate in the Korean peninsula is 1/2~1/3 of that of the western part of Honshu in Japan and the azimuth of the maximum strain axis is significantly different in both country. Figure 9 shows the results of Honshu area given by Sato (1974) and Figure 10 shows the P-axis distribution of western Japan given by Tsukahara and Kobayashi (1991).

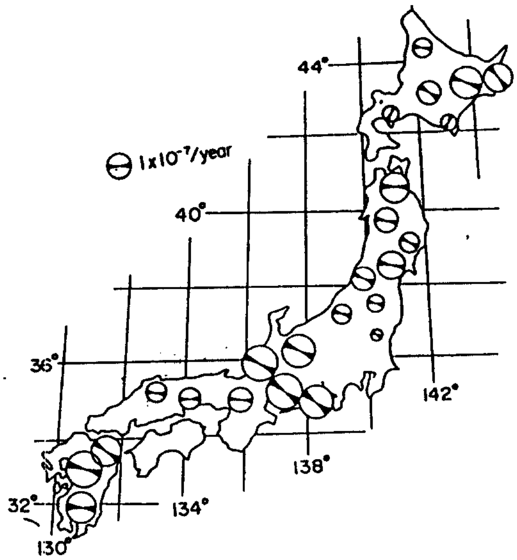

Figure 9 Annual Rate of Horizontal Strain in Japan Obtained from the Result of the First Order Triangulation (after Sato, 1974)

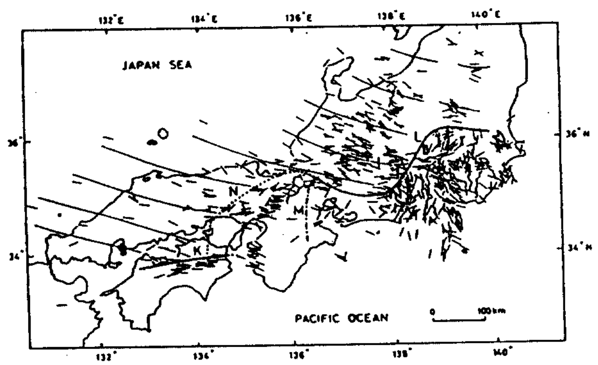

Figure 10 P-axis Distribution of Western Part of Honshu Area (after Tsukahara, Kobayashi, 1991)

Considering the present results, the western part of Honshu shown in Figure 9 and 10, it can be estimated that a northeastward continuation of the Tsuhima fault in the Korea strait into the southwestern part of East Sea is situated.

Since 1995, GPS and VLBI observations by GSI in Japan and NGI in Korea have been performed to establish the regional site. For detecting the crustal movement by 1 year GPS observation, GSI analyzed a nation-wide GPS continuous monitoring network with more than 100 sites by fixing the position of Tsukuba International Geodynamic Service (IGS) site. This result gives about 5 cm/year relative movement by compression in both countries. From several evidences as mentioned already, the general strain patterns in and around the Korean peninsula is featured by compression in the NEE-SWW direction and NNW and SSE extension.

5. Conclusions

In the present study the horizontal strains are calculated using the BGCN data and the PPGN to estimate the tectonic movement in geometrical point of view. Before the strain calculation, the first rigorous simultaneous adjustment of PPGN was carried out by free net adjustment in Korea and has produced a series of new coordinates which are consistent among themselves. It is provided the opportunity for the present study. The preliminary investigation on crustal movement in Korea was carried out by using the data obtained from the geodetic network adjustment. Some of important conclusions that deduced from the present study can be summarized as follows:

(1) The standard error of coordinates obtained by free-net adjustment is 6.5cm and the maximum value is 20cm. The standard error increases toward the marginal part of the geodetic network. The displacement vectors calculated at normal points show that the mean value is 81cm and 75% of those are within 1.0m. It means that the results of free net adjustment provide a sufficient accuracy coordinates for the strain calculation.

(2) The trend of strain shows that larger values than 10μ are distributed in the area along the Eastern coast and smaller values than 10μ are distributed in the western part of the peninsula. If we consider the difference of strain between Eastern coast area and Western area in statistic point of view, this result can be given. As regard of the shortage of sample points, the reliability of this result is deteriorated. If we consider the high frequencies of earthquake in the seashore of East sea, the results obtained from the present study are important data in the future.

(3) From the results, the strain accumulation during the period from 1915 to 1994 is calculated as $(10.7 \pm 5.0) \times 10^{-6}$ in average. This corresponds to annual strain rate of $(0.13 \pm 0.063)\mu$/ year. The principal axis of strain in the $77.6^{\circ} \pm 13.5^{\circ}$ direction which was found in this work can generally be recognized throughout the whole country. It shows that the Korean peninsula is featured by compression in a NEE-SWW direction. The direction of P-axes deduced agrees with the result of seismic interpretation given by Jun (1990).

(4) With the aid of topographic, geological and geophysical studies, we can see that both directions of principal axis and lineament are composed of 35~40 degree. This agrees with the theory of maximum shearing fracture.

(5) Comparing to the principal strain in Japan, the annual strain rate in the Korean peninsula is 1/2~1/3 of that of the western part of Honshu in Japan and the azimuth of the maximum strain axis is significantly different in both country.

This study shows that the strain is varied about 0.1/yr in the Korean peninsula. It seems that the variation is large with respect to the recent earthquake activities, but considering the records of historical earthquake, this velocity can be obtained. The strain rate in the western part of the peninsula is diffferent from that in the eastern part. It has a possibility due to earthquake activity.

Since 1995, GPS and VLBI observations by GSI in Japan and NGI in Korea have been performed to establish the regional sites. These observations give about 5 cm/year relative movement by compression in both countries. The permanent GPS observation is necessary to monitor the regional and continental crustal movement. Some of conclusions mentioned above may also lead to better understanding of the crustal movement in East Sea.

Reference

1. Bibby, H.-M.(1975),"Crustal Strain from Triangulation in Marlborough", New Zealand. Techonophysics 29 (1-4), Elsevier, pp. 529-540.
2. Brunner, F.-K., R. Coleman and B. Hirsch (1981), "A Comparison of Computation Methods for Crustal Strains from Geodetic Measurements". Tectonophysics 71, Elsevier
3. Chen, R.(1991), "On the Horizontal Crustal Deformations in Finland", Report of the Finnish Ggeodetic Institute 91:1, Helsinki.
4. Choi, J.-H. and Y.-S. Choi (1994), "Precise Determination of the Geodetic Primary Framework of Korea". Journal of the Korean Society of Geodesy, Photogrammetry and Cartography, vol.13, No.1, pp.1-12.
5. Fujii, Y. and K. Nakane (1982), "Horizontal Crustal Movements in the Kanto-Tokai District. Japan, as deduced from Geodetic Data". Techonophysics 97, Elsevier, pp. 115-140.
6. Harada, T.(1967), "Precise Readjustment of Old and New First Order Triangulation, and the Result in Relation with Destructive Earthquakes in Japan", Bulletin of the Geographical Survey Institute, Vol. 12, No. 3, pp. 5-53.
7. Harada, T. and M. Shimura (1978), "Horizontal Deformation of the Crust in Western Japan Revealed from First-Order Triangulation Carried Out Three Times". Techonophysics 52, Elsevier, pp. 469-478.
8. Jaeger, J.-C.(1967), "Elasticity, Fracture and Flow, with Engineering and Geological Applications". Methuen, London.
9. Jun, M.-S.(1990), "Source Mechanisms of Shallow Earthquakes in the Western Sea of Japan and their Tectonic Implication", Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science 285, Uppsala University, Sweden, pp. 1-30.
10. Jun, M.-S.(1990), "Tectonic Implication of Shallow Intraplate Earthquakes in and around the Korean Peninsula", Journal of Uppsala University, Sweden.
11. Komaki, K.(1993), "Horizontal Crustal Movements Revealed by Geodetic Measurements-Applications of a New Method for Estimating Displacement Vectors", Journal of the Geodetic Society of Japan, Vol. 39, No.4, pp. 387-410.
12. Kyung, J.-B., K.-S. Oh, K.Oike(1996), "Paleoseismological Approach in the Southeastern Part of the Korean Peninsula". 1996 Symposium on Seismology in East Asia, Proceedings, pp.38-47.
13. Lee, K.-H., et al.(1985), "Studies on the Seismic Risk of the Korean Peninsula(I)". The Journal of the Geological Society of Korea, Vol. 1, No. 4, pp. 227-240.
14. Mittermayer, E.: A Generalization of the Least-Square Method for the Adjustment of Free Network, Bulletin, Geodesique 104 (1972), pp.139-157.
15. Murata, I, et al.: Crustal Deformation Measurements with GPS around the Suruga Bay, Central Japan, Proceedings of the Japanese Symposium on GPS (1993), pp. 17-22.
16. Rapp, R. H.: Geometric Geodesy, Vol. 1, Department of Geodetic Science, The Ohio state University, Columbus, Ohio (1979).
17. Sato, T.: On the Adjustment of Free Networks, Journal of the Geodetic Society of Japan, Vol. 30, No. 3 (1984), pp. 175-197 (in Japanese).
18. Sato, H and H. C. Sheu: Crustal Movement and Seismic Activity in Eastern Taiwan. Journal of the Geodetic Society of Japan, Vol. 37, No.2 (1991), pp. 165-173.
19. Sato, H., M. Kosuga: Secular Crustal Strain in Eastern Taiwan and its neotectonic Implication, Neotectonics: An International Journal of Crustal Dynamics, Vol.1 (1986), pp. 61-74.
20. Sheu, H. C., H. Sato: Crustal Movement of Eastern Taiwan and its Tectonic Significance, Journal of the Geodetic Society of Japan, Vol. 30, No. 3 (1984), pp. 213-227.
21. Tsukahara, H. and Y. Kobayashi: Crustal stress in the central and western parts of Honshu, Japan, Earthquake, Vol. 2, No.44 (1991), pp. 221-231.