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19. *Electro-Optical Measurement of Horizontal Strains Accumulating in the Swarm Earthquake Area (1).*

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Abstract

Since October, 1965, the authors repeated Geodimeter surveys for a base-line net in Matsushiro and observed horizontal strain accumulation successfully. The following are the conclusions drawn from them:

1) Strain, which predominates in the NS-direction, accumulated most actively during the period of November-December, 1965. Mode of the strains as represented by the principal axes harmonizes surprisingly well with the seismic force system there.

2) Accumulated strain energy reached an amount comparable to that of seismic energy.

These sorts of information seem to suggest an inseparable relationship of the earth's strain to the seismic activity.

1. Introduction

Recent development of the electro-optical distance measuring technique opened a new and reliable way of observing horizontal strain accumulation in the earth. Since 1963, the Earthquake Research Institute has been carrying out a research project for the neotectonics in Japan, in which the authors have participated for the purpose of introducing the above new technique for studies of crustal deformations. They preferred instruments of the electro-optical type as represented by a Geodimeter to purely electronic types for the former's superiority in instrumental accuracy, and repeated observational tests on base-line nets which were constructed at several localities of geotectonical interest.[1] Successful results from these experiments seemed to prove the usefulness of the system of field observations thus tested.

Last autumn, when the Institute worked out a program of field

1) K. KASAHARA and A. OKADA, "Observations of crustal deformations by use of an electro-optical distance measuring device (1)," Read at the Monthly Meeting of the Earthquake Research Institute, May 25, 1965.

expeditions for the Matsushiro swarm earthquakes, the authors planned a series of Geodimeter surveys as a part of it. They believed that the nature of the seismic event would be understood more concretely by taking the data of horizontal strain accumulation into account.

2. Field work

2.1. Construction of base-line nets

The Matsushiro net. Proper selection of the locality for base-line construction is the first serious step in the surveys. Besides good visibility along the proposed base-line, many other conditions must be taken into consideration for the best results. Particularly difficult is the point selection of a Geodimeter station, since it requires convenience for transportation as well as being a short distance from an electric power line. Through the authors' experiences in the past, they learnt that the most effective base-line length for their device is 2–4 km so that high relative accuracy of measurement and good S/N ratio may be secured under average atmospheric conditions in Japan.

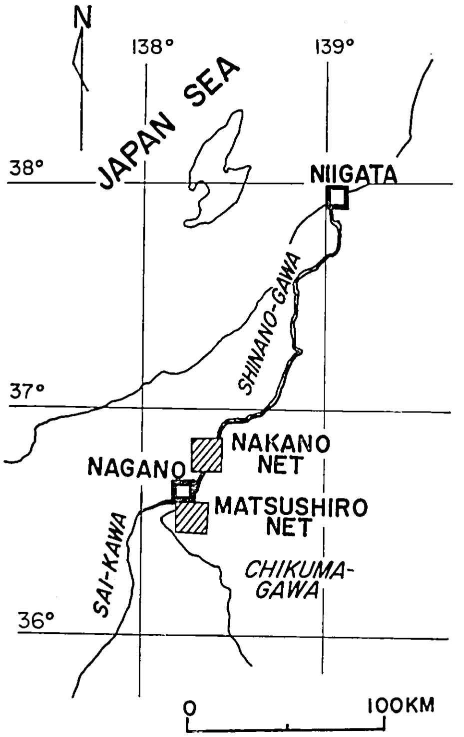

Fig. 1. Index map of the surveyed areas.

After considerations on these conditions as well as on all the available information about the event, the authors spread their first net over the Matsushiro area in early October, 1965 (Fig. 1). Fig. 2 illustrates the detailed arrangement of the base-lines thus constructed. A Geodimeter station was set up at the top of Minakami-yama, a small hill located at the center of the seismic area. Three reflecter stations, Zozan, Nishiterao and Sorobeku, were distributed around it forming three base-lines of 2.4–3.2 km length as shown in Fig. 2. Station marks with stainless steel rods at their center were newly constructed at these sites except for Zozan where a con-

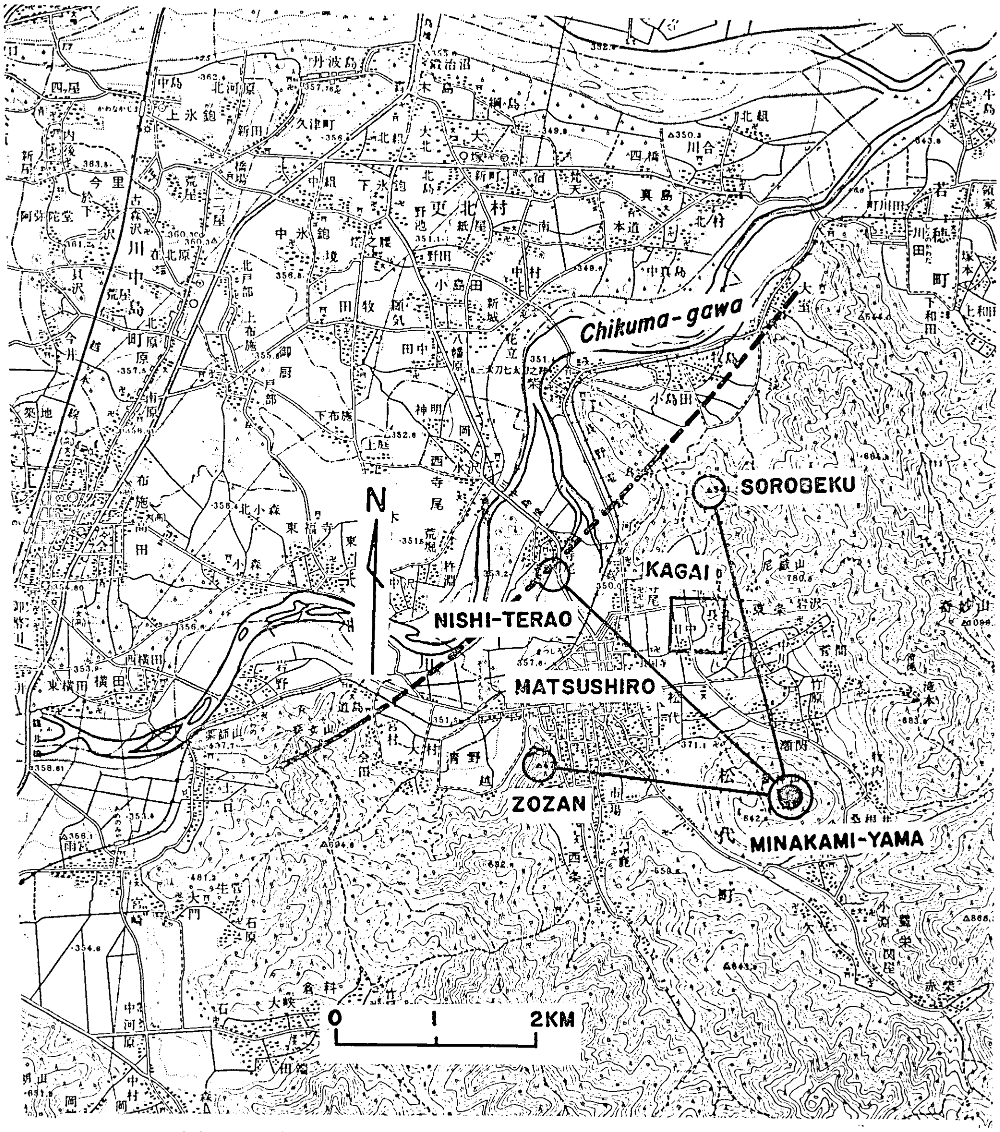

Fig. 2. Arrangement of base-lines for the Matsushiro net.

ventional stone-mark for the GSI's (Geographical Survey Institute) triangulation station was available for the present surveys.

Between the base-lines to Nishiterao and Sorobeku, three additional base-lines of shorter length (ca. 150 m) were constructed in the Kagai area, where a developing surface breakage was noticed by local people (Fig. 2).

The Nakano net. The second net adjacent to Nakano city (Fig. 1)

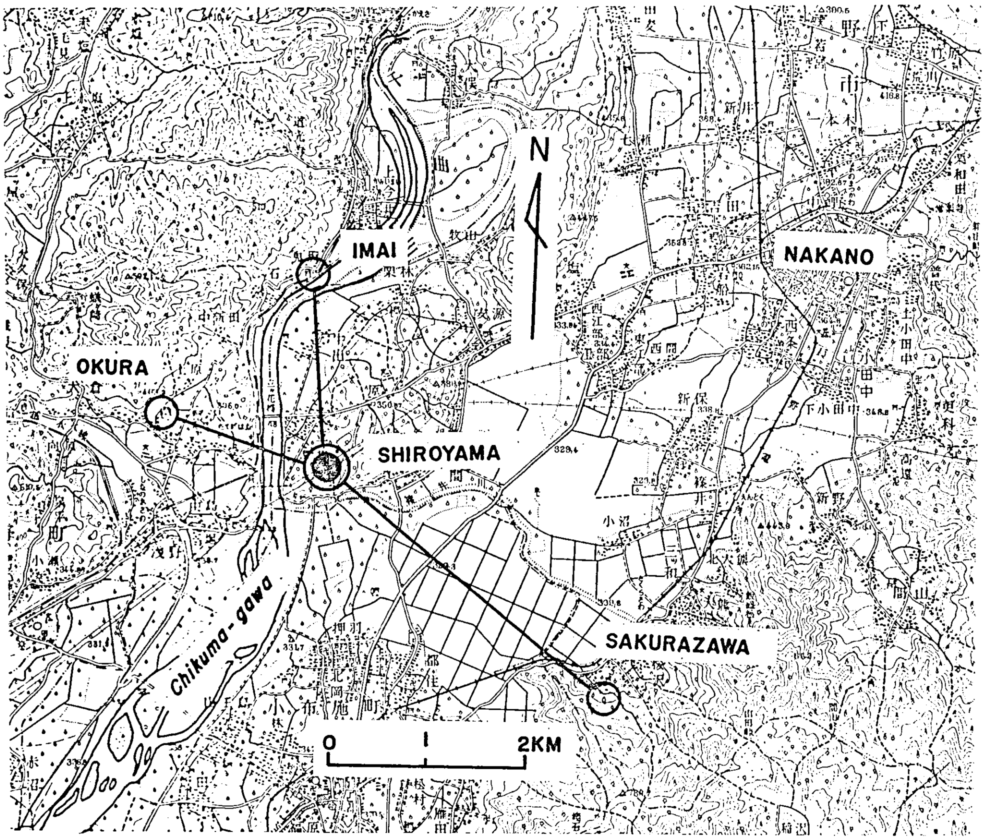

Fig. 3. Arrangement of base-lines for the Nakano net.

was constructed in February-March, 1966 as it seemed necessary to extend our surveys outside the Matsushiro area. Precise leveling by a GSI party discovered recently an abnormally high rate of land upheaval there.[2] Although it was uncertain whether the event was a portent to an approaching catastrophe, various sorts of observation were newly started in this area to collect further information about the possibility of future seismic activity there. Fig. 3 illustrates the arrangement of three base-lines which form a Y-shape with its central station at Shiroyama.

2.2. Repetition of surveys

The surveys were made for four times up to the present time. Periods required for these were as follows:

2) T. DAMBARA and I. TSUBOKAWA, Read at the Monthly Meeting of the Earthquake Research Institute, January 25, 1966.

Survey I	October 5–10, 1965 ,
Survey II	November 14–18, 1965 ,
Survey III	December 8–13, 1965 ,
Survey IV	March 1–9, 1966 .

As stated above, the survey on the Nakano net was started very recently, just after survey IV. Accordingly, results from the Nakano net will be dealt with in the next report after repeating the further surveys for comparison.

The surveys were made with a Geodimeter Model IV (AGA X590315) aiming seven-element corner reflectors placed at the reflector stations. Following our standard scheme of operation, measurements of the three base-lines were carried out simultaneously. That is to say, after completing one or two sets (each set involving twelve readings of distance) of measurements for the first objective, the Geodimeter was pointed to the second reflecter. This procedure was repeated cyclically for one or more nights until several sets of satisfactory data were accumulated for the respective base-lines. Thin lines as indicated "distance before correction" in Fig. 4 illustrate the results thus obtained.

Atmospheric pressure, temperature and humidity were also observed frequently at the master station in order to correct the distance readings for the atmospheric conditions along the light paths. Following the manufacturer's instruction, the atmosphere of $-6.0°C$ and 760 mmHg was taken as the standard for the present correction. For the distances of our present observations, the correction term fell on the range of $+80 \sim +120$ mm as shown in Fig. 4.

Thick lines at the top of the same figure are the distances after correction. Broken lines drawn horizontally across the thick solid lines indicate the mean distance readings for the respective period of surveys (see also Table 1). Scattering of the data around the mean value (the values in Table 1 are associated with their probable errors) is mostly less than ± 6 mm. This figure is very satisfactory as for the overall error under the present conditions, because the instrumental error specified by the manufacturer is $\pm[10\,\text{mm} + 2 \times 10^{-6} \times (\text{Distance})]$ and the error of the tripod's setting is less than ± 5 mm.

Considerably large scattering of data is noticed, however, on the data from survey II. As is evident from Fig. 4, the atmospheric correction of ordinary sense does not reduce the short-period disturbances efficiently. For the purpose of improving the correction technique the

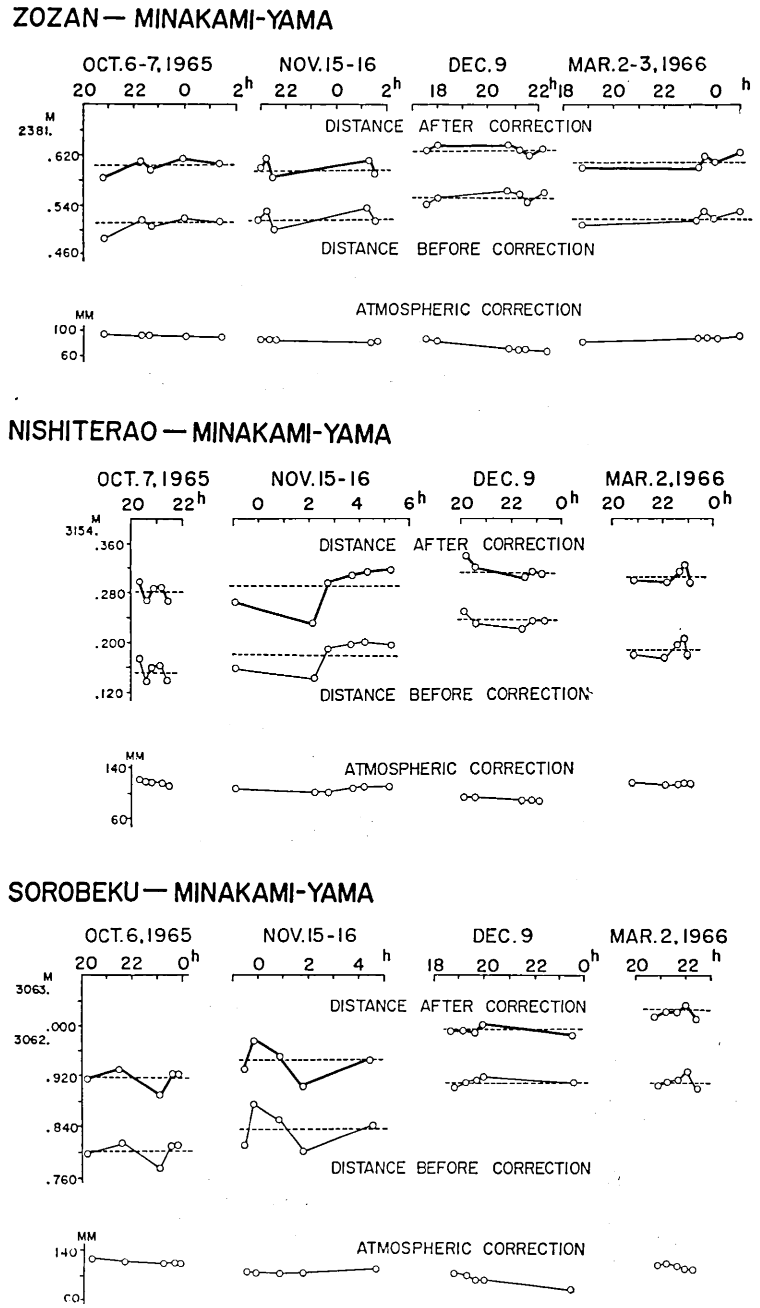

Fig. 4. Variation in base-line lengths observed by repeated surveys (Matsushiro).

Table 1a. Base-line lengths observed by repeated surveys.

Survey No.	Date	Zozan	Nishiterao	Sorobeku
		m mm	m mm	m
I	Oct. 6-7, 1965	2381.612±3	3154.286±5	3062.912± 4
II	Nov. 15, 〃	.602±6	.293±8	.938±10
III	Dec. 9, 〃	.624±2	.318±4	.994± 2
IV	Mar. 2, 1966	.609±3	.310±4	3063.025± 3

Table 1b. Changes in the base-line lengths.

	Zozan	Nishiterao	Sorobeku
	mm	mm	mm
II-I	−10	+ 7	+26
III-I	+12	+32	+ 82
IV-I	− 3	+24	+113

authors conducted meteorological observation supplementally at the reflecter stations during survey III. Unfortunately, however, they did not observe any significant difference between the base and reflecter stations, so that no reasonable explanation was provided for the above-stated fluctuation. By taking the present scattering into account, the authors consider that the observed changes in base-line lengths (Table 1b) would be safely assigned for the overall errors of about ±10 mm (ca. 3×10^{-6} of the base-line lengths).

3. Discussion

3.1. Linear strains along the base-lines

Fig. 5 illustrates accumulation of linear strains along the three baselines. The authors derived them from the data in Table 1b on the assumption that the strains were zero when the surveys were started in last October and the earth has been strained since then.

It is noticeable that the strain in the EW-direction is inactive as represented by the uppermost curve, whereas the strain along the Sorobeku base-line, representing the NS-strain, is outstanding. The most active event is observed during the period (III–II), when the strain accumulated as much as 20×10^{-6} in one month. Activity of the present period seems to be verified by the data from the Nishiterao base-line, which also shows the highest strain rate during this period. It must be remembered that the highest seismic activity was also experienced late in November,

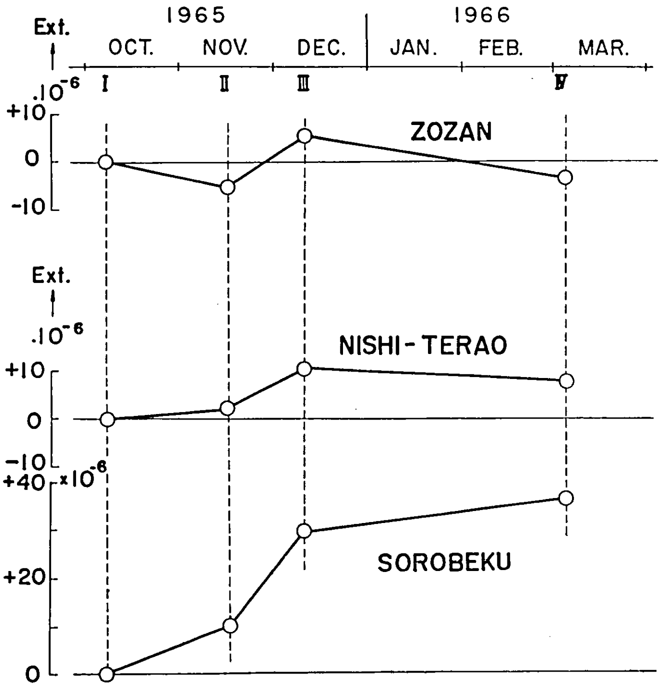

Fig. 5. Accumulation of horizontal strains (Matsushiro).

as proved by the occurrence of a strong shock ($M=4.9$) and an increased number of felt and unfelt shocks that followed it.[3] As a total, the strain accumulated in the past five months reached 40×10^{-6} on the Sorobeku base-line, 10×10^{-6} on the Nishi-terao base-line, and approximately zero on the Zozan base-line.

3.2. Principal axes of strain

As we have assumed uniformity of strains in the Matsushiro area, it is possible to compute the principal axes of strains and other strain components by dealing with the above-stated data as a plane-strain problem. Results of the computation are schematically drawn in Fig. 6, in which the direction and the amplitude of the axes are given for the various period of strain accumulation. As indicated by thick solid lines, the strain is most tensional in the NS-direction reaching 50×10^{-6} during

3) THE PARTY FOR SEISMOGRAPHIC OBSERVATION OF MATSUSHIRO EARTHQUAKES and THE SEISMOMETRICAL SECTION, EARTHQUAKE RESEARCH INSTITUTE, "Matsushiro Earthquakes Observed with a Temporary Seismographic Network. Part 1," *Bull. Earthq. Res. Inst.*, **44** (1966), 309-333.

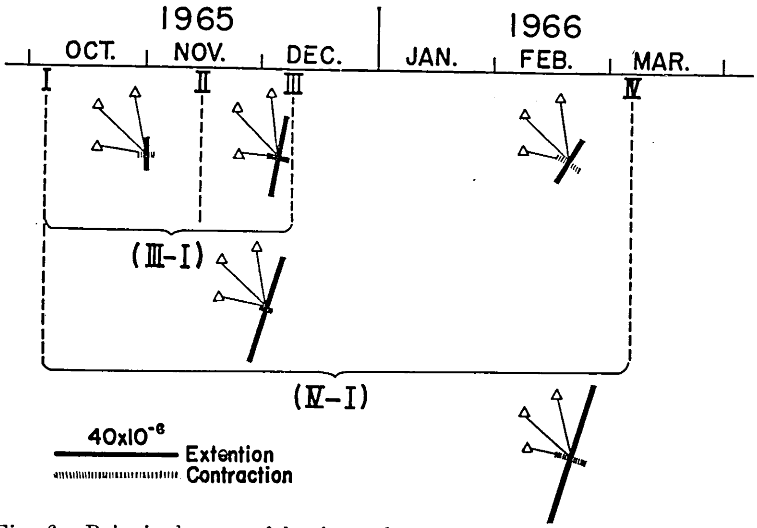

Fig. 6. Principal axes of horizontal strains computed for various periods of the repeated surveys (Matsushiro). Small triangles illustrate reflecter stations, schematically.

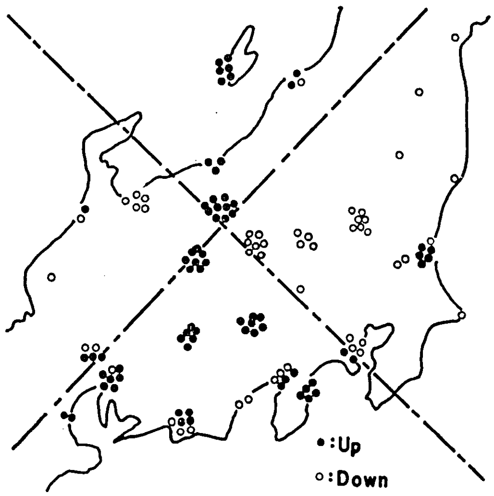

Fig. 7. Superposed plots of the polarity of P-waves from several major earthquakes in Matsushiro.[4]

the whole period.

Strain in the direction perpendicular to it is much less than the major axis, sometimes showing contraction as indicated by thick broken lines. Directions of the axes do not change from time to time, suggesting stable stresses as the origin of the present event. A more interesting

4) M. Ichikawa and T. Ishikawa, *Annual Meeting, Seismological Society of Japan,* May, 25, 1966.

relation is noticed between directions of the principal axes in Fig. 6 and the systematic distribution of the first P's polarity of the major Matsushiro earthquakes in Fig. 7. Superposed plots of the first P's polarity being explained by a pair of the nodal lines, we may attribute these major shocks to sudden release of compressional stress in the EW-direction or of tensional stress in the NS-direction. Stresses of these types are in good harmouy, in either case, with the distribution of the principal axes as mentioned above.

3.3. Strain energy

It would be useful for further studies of the event to estimate how much energy loss (or gain) was associated with the deformations. Precise treatment of it seems impossible at present due to the lack of basic data, such as distribution of strains and mechanical properties in the medium,

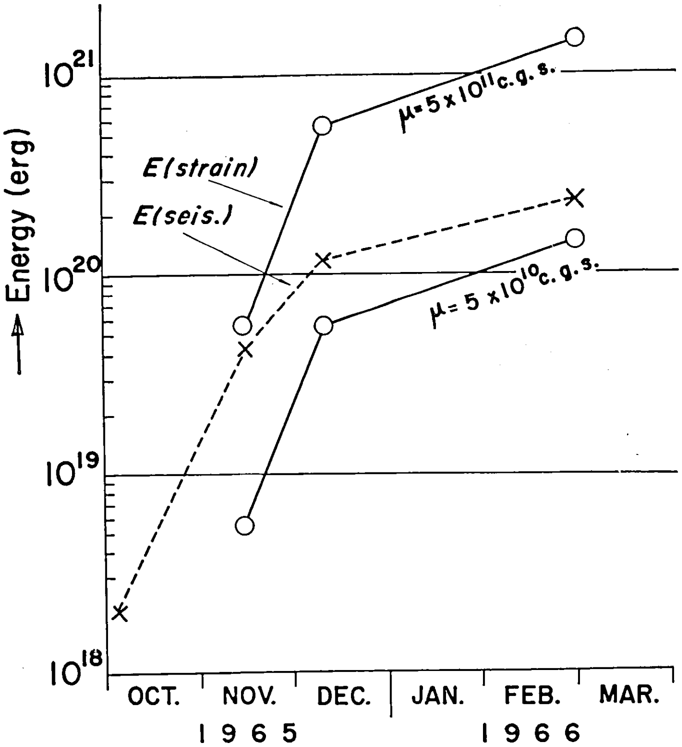

Fig. 8. Comparison of the seismic energy with the strain energy (cumulative sum).

Fig. 9. Geodimeter station at the top of Minakami-yama.

Fig. 10. Operation of a Geodimeter in the night.

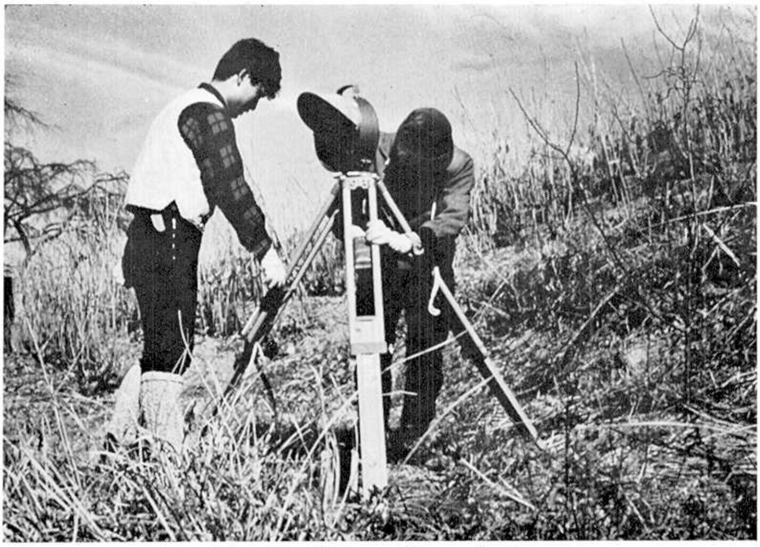

Fig. 11. Set-up of a reflector.

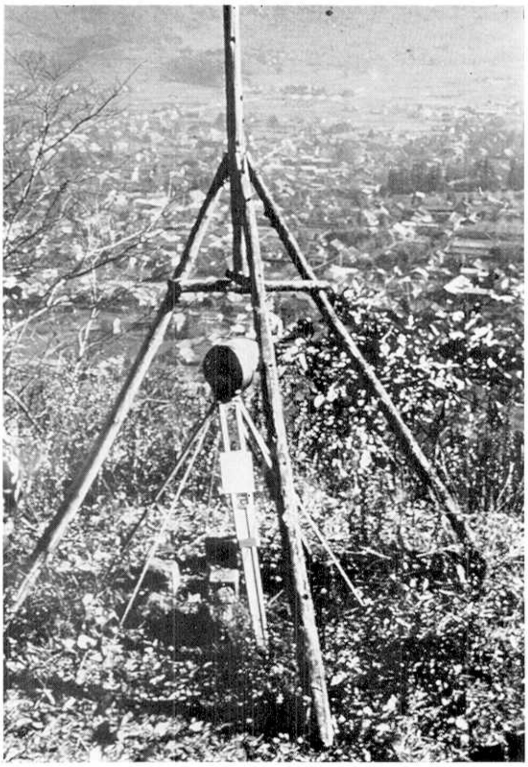

Fig. 12. Reflector station (Zozan).

and the strains which initially existed there. However, an approximate estimate of the energy would be practicable by taking a model as simple as possible. Let us assume, for instance, that a certain volume, V of an elastic medium is subject to a uniform linear strain, ε. Then the total strain energy, E (*strain*) is given by the well-known formula, as follows:

$$E\ (strain)=\tfrac{1}{2}\mu\varepsilon^2 V\ ,$$

where μ is an elastic constant.

Assumption on the simple strain would be acceptable, because the patterns in Fig. 6 seems to indicate uniaxial surface extension developing to a fixed direction (NNE-SSW). Accordingly we may reasonably put the respective amplitude of the accumulated major axis (Fig. 6) into ε. We then take two possible values for μ, 5×10^{10} and 5×10^{11} c.g.s., to draw the lines in Fig. 8, where the initial value of ε of last October was assumed as zero. V is taken as 3.3×10^{17} c.c., which is approximately equal to the volume of the seismic active part of the earth.

Broken lines in the same figure represent cumulative sum of seismic energy at the time of respective survey derived from the data by T. Hagiwara et al..[5] Reflecting the high seismic activity of last November, the time rate of energy accumulation is much higher in the second period than in the others. Accumulation of E (*strain*) takes on a similar development in time, reaching 2.5–25×10^{20} ergs this month. It is interesting to see that the two independent parameters, E (*strain*) and E (*seis.*), agree well with one another. We must be careful to draw a definite conclusion from this single evidence, but we may tentatively stress the belief that the strain pattern inside the volume does not change much from that observed on the earth's surface.

3.4. Miscellaneous discussion

The authors experienced two strong shocks on November 15 and December 9 when they were operating the Geodimeter in the field. However, they did not observe any significant change in the base-line length though they examined the data about the moments of shocks carefully.

4. Conclusions and acknowledgement

Since October, 1965, the authors repeated Geodimeter surveys for a base-line net in Matsushiro and observed horizontal strain accumulation

5) *loc. cit.*, 3).

successfully. Following are the conclusions drawn from them:

1) Strain predominates in the NS-direction and accumulated most actively during the period of November-December, 1965, when we experienced the highest activity of swarm earthquakes in the past six months.

2) Mode of strains as represented by the principal axes harmonizes surprisingly well with the seismic force system there.

3) Accumulation of strain energy was studied on the basis of a simplified model of the strained earth and was compared with seismic energy accumulation with satisfactory agreement.

4) The authors experienced some strong shocks during surveys. However, they did not discover any significant change in the base-line length.

Recently, they constructed the second net in the Nakano area. Results from this will be reported in the next paper together with further discussion on strains in the Matsushiro area.

This survey was carried out with the cooperation of many people. The authors are grateful to the General Affairs Section of the Matsushiro Town Office, the Health Section of Nakano City Office, the General Affairs Section of Toyono Town Office and Mr. Muto of the Minakami-yama Shrine, who kindly offered their services for the surveys. Messrs Koichi Sasaki and Shigeo Matsumoto of the Earthquake Research Institute have participated in the present work from the beginning. The authors would like to acknowledge with thanks the useful assistance by them as well as by Messrs Muturo Sibano, Tamotsu Daikubara and Kiyoshi Suzuki who also cooperated with the authors in the course of the present study.

19. 群発地震活動に伴う地殻変動の観測 (1)

地震研究所 {笠原慶一 / 岡田惇

(1) まえがき

光波による精密基線測量を同一測線に対して反復実施することにより微小な地殻変動を検出することが可能である．地震研究所を中心に実施中のネオテクトニクス研究計画の一環として，筆者らは光波測量をこの研究分野に導入する試みを続けてきた．その結果，基線の設定や測定の方法，測定結果の精度などについてある程度の見通しが得られるに至つた．

昭和 40 年 8 月 (1965) 以来松代町附近に発生した群発地震の綜合調査が計画されるにおよび，地殻の水平変動の検出を目的としてジオデメーター IV 型による光波測量が立案された．これにもとづき長野県松代町附近（第 1 図）において昭和 40 年 10 月以来 4 回の測量が実施されたのである．その後，昭和 41 年 3 月になつて松代町北方の中野市附近にも基線が増設された．いずれ再測量される予定である．本文では主として松代での観測結果と，それから推定される地殻の水平変動の様子を報告し，群発地震の特性との関係についても若干の考察を加えた．

(2) 観　測

松代基線—第 2 図に示すように松代町皆神山々頂を中心として可候（そろべく）基線，西寺尾基線，象山（三等三角点）基線を設けた．三基線の長さは 2〜3 km である．昭和 40 年 10 月 5〜10 日に基線網設置および第 I 回の観測が行われ，以後 11 月 14〜18 日に第 II 回，12 月 8〜13 日に第 III 回，昭和 41 年 3 月 1〜9 日に第 IV 回目の測定が行われた．ジオデメーターの主観測点は皆神山々頂に置き，扇状の基線の端点には特殊反射鏡（七素子型）を置いてある．夜間観測により，基線毎に毎回 5〜7 セットの測定が繰返された．皆神山測点においては補正のため気圧，気温，湿度の観測も並行して行われた．I〜IV 回の測定から得られた基線長，気象補正値および補正を行つた基線長は第 4 図に示す通りである．ただしこの基線長は高度補正を行わない 2 点間の空間の長さを表わしている．第 4 図中の点線は各回観測に対する平均値を示し，その数値は第 1 表に記してある．

中野基線—松代町北方約 30 km の中野市周辺（第 3 図）にも昭和 41 年 3 月新らしく基線を設置した．これは昭和 40 年 12 月に行われた国土地理院による水準測量の結果，豊野町—中野市間に異常隆起地帯が発見され，地震活動の可能性が心配された事情による．今後反復測定を実施する予定である．

(3) 測定基線長の変化

第 1 表に見られるように，松代における I〜IV 回の観測結果は各方向について特徴ある変化を示している．すなわち，東西方向の基線（皆神山—象山）については比較的変化量が小さいが，南北方向の基線（皆神山—可候）は一方的な伸びを示し，北西方向の基線（皆神山—西寺尾）は両者の中間の変化を示している．これら基線長の変化量より各方向に対する土地歪を求め，第 I 回の測定値を基準として変動進行状況を示したのが第 5 図である．これら土地歪の量は，皆神山から象山や西寺尾に向う方向に対しては 10×10^{-6} 以下であるのに対し，可候（北方）は約 40×10^{-6} を示していることが注目される．

以上の変動が地震活動の最盛期であつた 11〜12 月に最も著るしかつた事実は，歪の消長と地震活動との密接な関係を物語るものと思われる．

(4) 歪主軸の方向

三方向に対する歪量が観測期間毎に得られたので，それぞれの時期に対する水平歪の主軸値と方向を計算することができる．この結果を示したのが第 6 図であつて，主軸の方向がほぼ南北に一定し

ていることが注目される．これは松代地震群中の顕著な地震数個に対して求められた初動分布が，やはり東西圧縮（または，南北伸長）の集積歪力の存在を暗示している事実に調和するものであつて極めて興味深い．

(5) 歪エネルギーと地震エネルギー

震源域は水平断面が長軸 12 km，短軸 7 km の楕円で，深さが 5 km のひろがりと見積られる．第6図の結果にもとづいて歪の型式を一方向の伸びと近似し，それが上記震源域に一様に存在していると仮定すれば，各期間中に蓄積された歪エネルギーを次式によつて概算することができる．

$$E\,(strain)=\frac{1}{2}\mu\varepsilon^2 V\,,$$

ただし，μ: 弾性定数 ($5\times10^{10}\sim5\times10^{11}$ c.g.s.),
ε: 歪量,
V: 体積.

第 8 図の実線で示したのは昨年 10 月，すなわち第 I 回基線測量当時の歪をゼロとして，それから起算した歪エネルギーの変化状況である．一方，破線は別の研究者によつて計算された地震エネルギーの放出積算量 (9 月基準) にもとづいて，われわれの測量実施時期における積算量をよみとつたものである．両者が量的にも，また時間的変化の傾向においても，かなりよく一致している点が注目される．これだけの資料から断定するのは困難であるが，前提となつた諸仮定がそれ程無理なものでないこと，従つて地表で測定された歪がほぼそのままで地下のある深さまで及んでいることを暗示するものかも知れない．

(6) むすび

松代地域における光波測量を反復した結果，基線長の変化を検出することができた．結論として次の諸点が指摘される．

1) 南北方向に対する伸びが卓越し，特に 11～12 月の間に大きな変動が進行したようである．これは地震活動の消長によく対応する．
2) 水平変動の歪主軸は松代地震群の発震機構によく調和している．
3) 簡単な模型に基づいて算出した歪エネルギーの変化状況は地震エネルギーの放出状況とほぼ同じ傾向にあり，量的にも一致する．これは，地中の歪状態が地表で測定されたものと同程度であることを意味するものかもしれない．
4) 測定中に震度 IV 程度の地震に遭遇する機会は二度あつたが，その前後における測定結果に特異な変化は認められなかつた．

以上のことは松代における群発地震の性状および地質構造の解析に多くの示唆を与えるものであろう．

謝　　辞

本調査が順調に実施できたのは，多くの方々の御協力によるところが多い．なかでも松代町役場には総務課を通じて，中野市役所には保健課を通じて，また豊野町役場には総務課を通じて，それぞれ作業に対する便宜を提供していただいた．松代基線網の中心点を置いた皆神山々頂では，皆神山神社の武藤氏にいろいろお世話になつた．

地震研究所の佐々木幸一・松本滋夫両氏は全期間を通じて筆者らと共に本調査に従事され，柴野睦郎・大工原保・鈴木喜吉の各技官もしばしばこれに協力された．その他，松代地震調査に関係する多くの方々からも有益な助言・協力をいただき，調査の進行に大いに役立つた．

以上記して謝意を表する次第である．