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44. *Electrical Conductivity of Strained Rocks. The Third Paper. A Resistivity Variometer.*

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Summary

A resistivity variometer by which changes in the earth resistivity can be continuously observed in the field is constructed. A field test at Aburatsubo proves that the variometer can record changes in the resistivity associated with the earth strain caused by tidal loading. It is found that the rate of resistivity change amounts to the order of 10^{-3} in contrast to the strain of the order of 10^{-6}. Further refinement of the variometer may lead to observation of pure earth-tide, premonitory strain before an earthquake and so on by the present method.

1. Introduction

It has been proved by the laboratory experiments as reported in the previous papers[1),2)] that the rate of resistivity change of sedimentary rocks is far larger than the mechanical strain applied to the rock specimens. It is therefore suggested that there might be a possibility of detecting an extremely small strain by measuring changes in the electric resistivity even in the field. As the writer dealt with in the first paper[1)], a preliminary experiment on measuring resistivity changes due to tidal loading had been made by Yokoyama[3)] with some success. In view of the development of electronics in recent years, it is believed that a much more accurate measuring technique, which would possibly be applied to a routine observation, could be advanced.

What follows is the writer's work of continuously observing changes in resistivity at a near-coast station where extension and contraction of

1) Y. YAMAZAKI, *Bull. Earthq. Res. Inst.*, **43** (1965), 783-802.
2) Y. YAMAZAKI, *Bull. Earthq. Res. Inst.*, **44** (1966), 1553-1570.
3) I. YOKOYAMA, Read at the monthly meeting of the *Earthquake Research Institute*, March 18, 1952.

the ground caused by tidal loading were also observed. In Section 2 will be described how to measure extremely small changes in resistivity in the field. Some preliminary results will be presented in Section 3 together with the results of simultaneous observation of earth's strain and sea level. Additional discussion about the plausibility of the changes in the resistivity thus disclosed will be made in Section 4.

2. Outline of the resistivity variometer

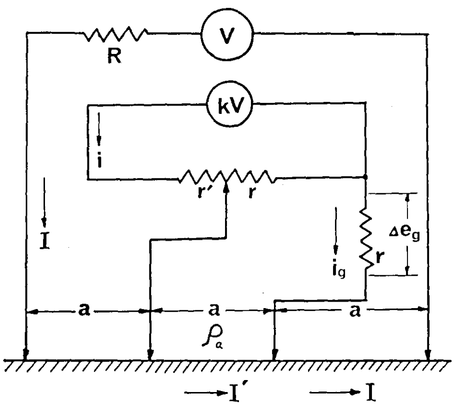
2-1. *Measuring circuit*

The measuring technique is much the same as the four-pole method as has been described in Subsection 2-1 of the first paper. Four copper electrodes, 10 mm in diameter, plated with silver are buried in holes 10 cm deep. From the outer two electrodes, a 67 c.p.s. alternating current is driven into the ground. The voltage picked up by the inner two electrodes is balanced by a voltage taken from the secondary winding of a transformer of which the primary circuit is connected to the 67 c.p.s. oscillator.

Fig. 1 is a schematic representation of the measuring circuit. In the first paper[1)] the circuit was analyzed and it was concluded that Δe_g, an output voltage deviating from the equilibrium state, is proportional to the change in the apparent resistivity which is denoted by ρ_a provided changes in electrode distance a is disregarded. A relation such as

$$\Delta\rho_a = 2\pi a \Delta e_g / I' \qquad (1)$$

therefore holds good, ρ_a, a, e_g and I' being measured in units of Ω-cm, cm, mV and mA respectively.



$$\Delta\rho_a = 2\pi a \frac{\Delta e_g}{I'}$$

Fig. 1. Equivalent circuit for the four electrode method.

2-2. *Construction of the resistivity variometer*

A block-diagram of the present device as named the resistivity variometer by the writer is shown in Fig. 2. A quartz oscillator with an appropriate power amplifier provides a very stable power source of 67 c.p.s. alternating current,

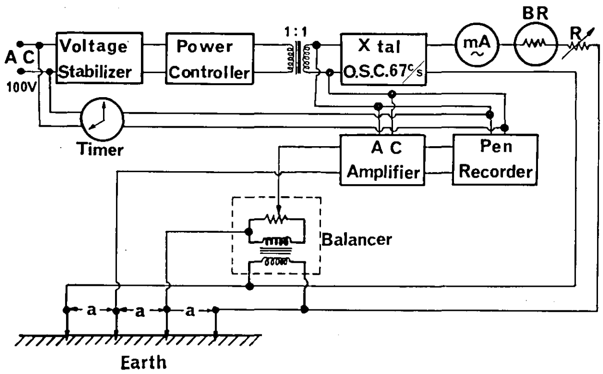


Fig. 2. Schematic diagram of the apparent resistivity observation by the four electrode method.

the frequency and voltage accuracies being 10^{-5} and 10^{-4} respectively. Use of an odd frequency alternating current is important for rejecting stray currents of 50 or 60 c.p.s. commercial alternating current as well as those from man-made disturbance sources such as railways. This is the reason why the writer made use of a 67 c.p.s. alternating current which is incommensurable to the commercial frequencies. A 100 mA current at 250 V is adopted for the actual observation.

Most of the voltage appearing between the inner two electrodes is cancelled by the balance circuit. A very small voltage at the output of the circuit as denoted by Δe_g in the last subsection is then led to an a.c. amplifier which is equipped with a mechanical filter sharply tuned at 67 c.p.s. Having a Q amounting to 20.6, the filter being quite powerful for rejecting unwanted signals. No difficulties are experienced in amplifying the signals passed through the mechanical filter to a voltage easily recorded by a pen-writing recorder.

The most difficult point of the present measuring system is how to choose the electric potential of various parts of the system relative to the ground. In electronics, it is customary to make the potential of each chassis equal and to earth the chassis. It is not possible in the present system, however, to earth the amplifier because the input of the amplifier is already connected to the ground. There may be a number of ways of avoiding the difficulty. A possibility is to make the whole system electrically independent of that of the ground by taking the power source from the commercial alternating current through a transformer. It should be borne in mind, however, that the commercial line is earthed somewhere, so that some interference between the commercial and the 67 c.p.s. alternating currents might be introduced to the system through the inner electrodes which are buried in the ground.

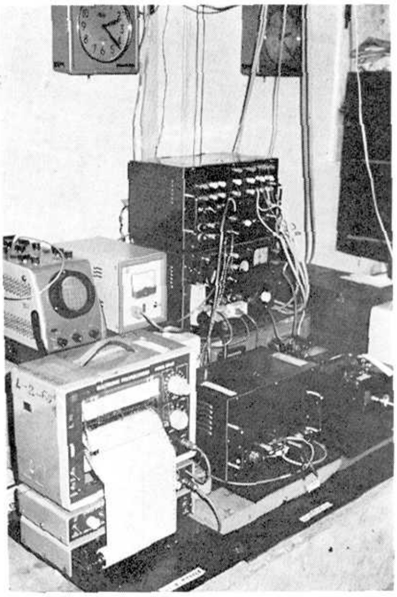


Fig. 3. Resistivity variometer

Another possible way may be to introduce the input voltage to the amplifier through a coupling transformer. In that case, it is possible to earth the amplifier. At the moment, the writer is tentatively using the former method and is encountering noises of which the cause has not been made clear. The interference as mentioned in the last paragraph would certainly play some role in inducing the noises. The writer should like to improve in the future the measuring system by trying whichever methods may be effective for reducing the noises.

Fig. 3 shows the set of amplifier, recorder, oscillator and so on which consists of the resistivity variometer.

2-3. *Sensitivity of the resistivity variometer*

Let us suppose that a practicable electrode distance amounts to 1 m and that the limit of detecting Δe_g is one microvolt, the limit of detectable $\Delta \rho_a$ is calculated from (1) as $6\times10^{-3}\,\Omega$-cm. As the resistivity itself amounts to a few kiloohm-cm or larger for actual measuring sites, the detecting limit of the rate of resistivity change amounts to the order of 10^{-6} or smaller.

Although it is no difficult matter for present-day electronics to amplify a voltage of one microvolt by a factor of 120 db, the actual sensitivity is controlled by the signal-to-noise ratio. For the present model of the resistivity variometer, however, the noise level is so high that the limiting sensitivity of detecting the rate of resistivity change is no less than the order of 10^{-4} or so. The writer has not been able to examine convincingly the cause of the noises yet. It is hoped in a future observation to make the noises drastically smaller.

2-4. *Observation site*

Observations of crustal deformation have been conducted by Hagiwara and others[4),5),6),7),8)] at the Aburatsubo Geophysical Observatory of the Earthquake Research Institute over a 20-year's period. The extensometers as well as tiltmeters there record the strains of the order of 10^{-6} caused by tidal loading. Since the writer has been undertaking fairly detailed experiments on rock samples taken from Aburatsubo, the first test of the resistivity variometer is aimed at discovering possible changes in the earth resistivity associated with the strain caused by the tidal loading at the Aburatsubo Observatory.

The electrodes are put in a cave close to the underground gallery where the extensometers and tiltmeters are at work. The distance between the entrance of the cave from the shore-line amounts to some 10 m, while the floor of the cave is about 3 m high above the mean sea level. Figs. 4 and 5 respectively show the sketch map around the

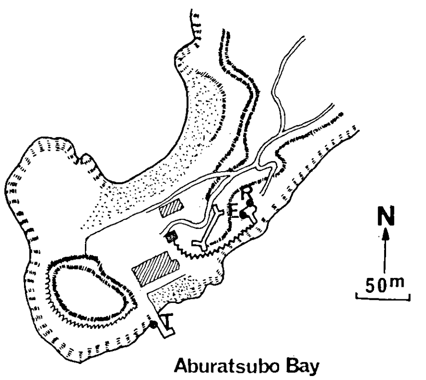


Fig. 4. Sketch map of the observation site.
R: Resistivity variometer.
E: Electronic extensometer.
T: Tide gauge.

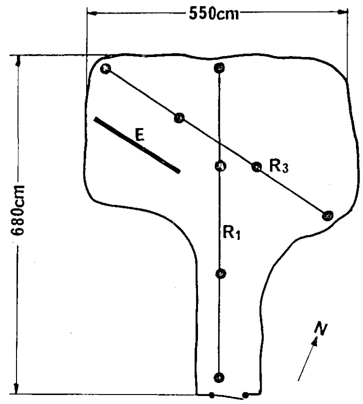


Fig. 5. Electrode arrangements in the cave. An electronic extensometer E is set parallel to the R_3 arrangement.

4) T. HAGIWARA, T. RIKITAKE and J. YAMADA, *Bull. Earthq. Res. Inst.*, **26** (1948), 23-26.

5) T. HAGIWARA, T. RIKITAKE, K. KASAHARA and J. YAMADA, *Bull. Earthq. Res. Inst.*, **27** (1949), 35-38.

6) T. HAGIWARA, T. RIKITAKE, K. KASAHARA and J. YAMADA, *Bull. Earthq. Res. Inst.*, **27** (1949), 39-44.

7) T. HAGIWARA, K. KASAHARA, J. YAMADA and S. SAITO, *Bull. Earthq. Res. Inst.*, **29** (1951), 455-468.

8) T. HAGIWARA, and K. KASAHARA, *Bull. Earthq. Res. Inst.*, **29** (1951), 557-561.

observation site and the plan of the cave.

Observations of changes in the resistivity are made for three sets of electrodes, two on the ground floor and one buried in the ceiling. The directions of the lines connecting the electrodes and the electrode distances are indicated in Table 1.

Table 1. Electrode arrangements and apparent resistivities.

No.	Direction	Electrode distance (m)	Place	Resistivity (Ω-cm)
1	N 14° W	2.1	Floor	2.37×10^3
2	N 28° W	2.4	Ceiling	1.90×10^3
3	N 81° W	1.6	Floor	2.24×10^3

The optical extensometers having been set in the three directions, N 25°W, N 81°W and N 22°E say, comparison between the strains and the rate of resistivity change is readily made. An electronic extensometer has been later set beside the No. 3 electrodes by courtesy of Professor Kasahara and others. Dr. Aida and others set up portable tide-gauges at the request of the writer, so that the resistivity changes are easily compared to the changes in sea level.

3. Observed results

Fig. 6 indicates an example of simultaneous observations of the

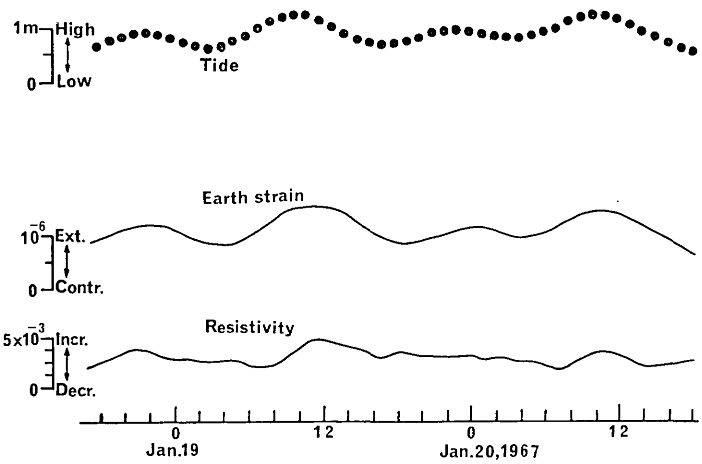


Fig. 6. Simultaneous records of the apparent resistivity, the earth strain and the sea level.

changes in sea level, the extension and contraction as observed by an extensometer in the N 81°W direction and the resistivity change in the same direction as observed by the present variometer. It is interesting to note that marked parallelism can be observed between the three curves.

When the sea level gets high, the ground surface extends to the direction concerned because of the bending of the ground due to the tidal load. Such an extension of the ground then gives rise to an increase in the electric resistivity there. The relation between the strain and the change in the resistivity agrees with the results of experiments[1),2)] on rock specimens taken from exactly the same place where the resistivity variometer is at work. The present observation also confirms what was reported by Yokoyama[3)] many years ago on the basis of a crude experimental technique.

Probably the most important and interesting point of the present result is the fact that the rate of resistivity change amounts to the order of 10^{-3} in contrast to the mechanical strain amounting to the order of 10^{-6}. The fact that the ratio of the rate of resistivity change to the mechanical strain amounts to 10^3 multiplied by a factor as revealed by the laboratory work is also confirmed in the actual field.

Rate of resistivity change $\Delta\rho_a/\rho_a$ versus strain $\Delta L/L$ plots for the hourly values during a period from Jan. 18 to 20, 1967 are shown in Fig. 7. Although we observe some scatterings of the points, an

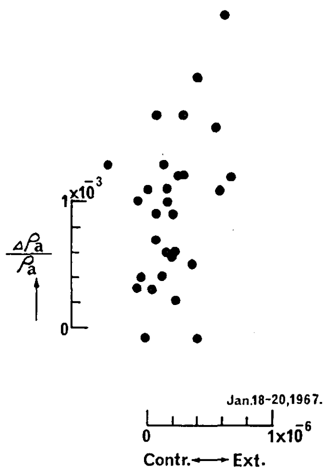


Fig. 7. $\Delta\rho_a/\rho_a$ versus earth strain relation as plotted using the data read every two hours.

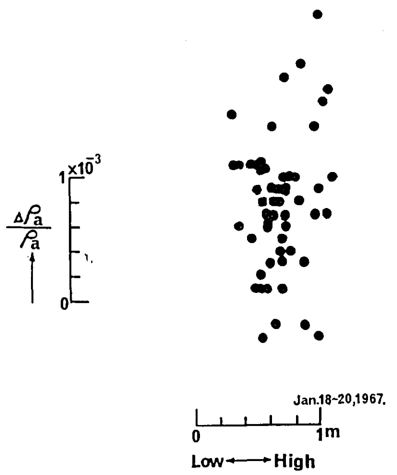


Fig. 8. $\Delta\rho_a/\rho_a$ versus sea level relation as plotted using the hourly readings.

approximately linear relationship between both the quantities seems to be established. The mean value of $\Delta\rho_a/\rho_a/\Delta L/L$ is estimated as 2.5×10^3, a value approximately the same as that obtained by the laboratory experiments for a small strain of the order of 10^{-5}.

Fig. 8 indicates similar plots for the sea level and the rate of resistivity change. We observe that the change in $\Delta\rho_a/\rho_a$ amounts to some 10.1×10^{-3} for one meter change of sea level.

Similar observations of changes in the resistivity have also been made for electrode-sets Nos. 1 and 2. Changes of more or less similar extent have been brought out. The change in resistivity for the No. 3 arrangement being almost exactly in phase with those in sea level and ground strain, a slight difference, however being noticed for the No. 1 electrodes. No detailed analysis on this point has yet been worked out. The changes in resistivity as found by the No. 2 arrangement, i.e. an electrode-set provided at the ceiling of the cave, strongly suggests that the resistivity change observed may not be caused by the effect of the sea-water which could penetrate below the cave because the majority of electric currents flow in rocks above the ceiling in this case.

A seiche of approximately 10 cm in amplitude and 13 min. in period sometimes prevails in Aburatsubo Bay. Rapid-run records of the changes in resistivity involve changes having a period approximately the same as that of the seiche although such changes are clearly picked up only after applying a numerical low-pass filter to the original records in order to eliminate the noises. It is interesting to note that even an earth strain as small as 10^{-7} produced by a small tidal load due to the seiche is detected by the resistivity variometer. A detailed study on the resistivity change caused by the seiche will be undertaken in a later paper.

4. Discussion

It has been feared that the changes in the earth resistivity as observed by the resistivity variometer are caused by the effect of the high-conducting sea-water immersing the ground because the measuring site is close to the shore-line. That this is not the case could be concluded from the following.

(1) The ratio of the rate of resistivity change to the earth strain observed approximately agrees with that for the rock specimens taken from exactly the same place.

(2) The resistivity change is observed not only by the electrode sets put on the floor but also by those provided on the ceiling of the cave. Most of the currents are thought to flow in the ceiling rock of a few meters in thickness and so very little current flows in the underground layer filled with sea-water.

(3) At the time of high tide, the underground level of the sea-water becomes also high although some delay behind the actual tide could possibly be expected. It is therefore expected that the top surface of the high-conducting layer moves close to the electrodes and so an apparent decrease in the resistivity should be observed for a high-tide period. In reality, we observe an increase in the resistivity when the sea level rises. The observed fact disproves the hypothesis that the resistivity change is caused mostly by the influence of the sea-water.

(4) An electric prospecting in the N 60°W direction in front of the cave was conducted at the time of medium tide in order to see the underground structure. An apparent resistivity versus electrode distance curve as shown in Fig. 9 is then obtained. Probably one of the most

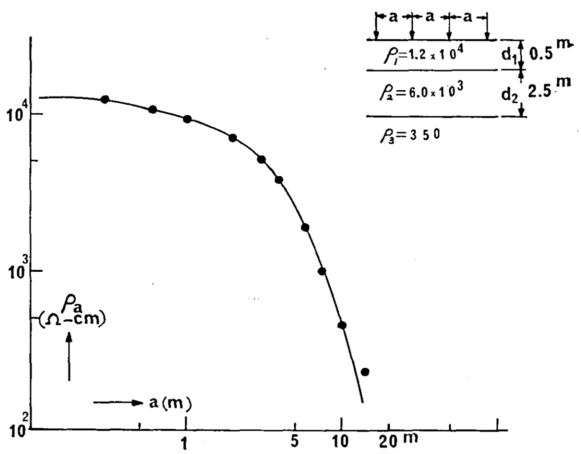


Fig. 9. Changes in ρ_a (apparent resistivity) with a (electrode distance) as revealed by the electric prospecting in the N 60°E direction.

likely structures that can be concluded from the prospecting would be the one as indicated in Fig. 9 in which $d_1=0.5$ m, $d_2=2.5$ m, $\rho_1=1.2\times10^4\Omega$-cm, $\rho_2=6.0\times10^3\Omega$-cm and $\rho_3=3.5\times10^2\Omega$-cm. Judging from the resistivity value, the third layer seems to be filled with sea-water.

The apparent resistivity measured on the ground surface with an electrode distance a is given by

$$\rho_a=\rho_E\left[1+4\sum_{k=1}^{\infty}Q^k\{1+4k^2(d_1+d_2)^2a^{-2}\}^{-1/2}-2\sum_{k=1}^{\infty}Q^k\{1+k^2(d_1+d_2)^2a^{-2}\}^{-1/2}\right], \tag{2}$$

in which

$$\left.\begin{aligned}\rho_E&=(d_1+d_2)/(d_1/\rho_1+d_2/\rho_2)\ ,\\ Q&=(\rho_3-\rho_E)/(\rho_3+\rho_E)\ .\end{aligned}\right\} \tag{3}$$

Changes in the apparent resistivity with those in $D(=d_1+d_2)$ are shown in Fig. 10 for two values of electrode distance a. d_1 is assumed to take on a constant value, 0.5 m say, in the calculation.

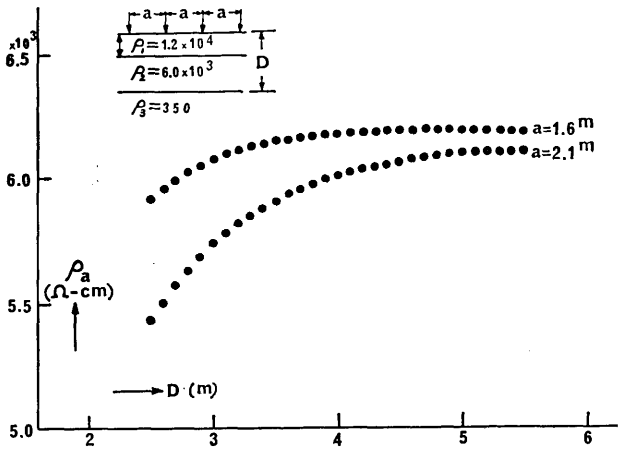


Fig. 10. Expected changes in the ρ_a (apparent resistivity) when the depth of the third layer changes as calculated for the two values of electrode distance a.

It is seen from the curves in Fig. 10 that a change in the apparent resistivity amounting to some 2 Ω-cm should be observed for 1 cm displacement of the top surface of the third layer. Judging from the permeability of the rocks composing the measuring site as reported in the second paper[2] and from the period of tide, it is supposed that the upheaval and subsidence of the underground water level would not be greatly different from that of the tide. The phase difference between them would also be small.

Should the present variometer be observing apparent changes in the resistivity due to the displacement of the underground water level, the above discussion makes us suppose a very large change probably twice the order of magnitude larger than the actually observed one. It is concluded, therefore, that what we are observing is the change in the resistivity of the top layer wherein the major part of electric current is flowing.

5. Conclusions

It is proved that a resistivity variometer as described in the above could possibly be used for detecting small changes in the earth strain in actual fields although further improvements, especially in making the noises smaller, would be required for a high-sensitivity observation. In Subsection 2–3 it has been argued that the limit of sensitivity could in theory be of the order 10^{-6} in measuring the rate of resistivity change. As the rate of resistivity change amounts to some hundred times as large as the mechanical strain for sedimentary rocks, it would be possible to detect a strain as small as 10^{-8} by the present method provided the signal-to-noise ratio is sufficiently large. It is hoped in the future to set up the resistivity variometer somewhere of great distance from the sea-coast and to see whether or not a pure earth-tide is detected.

If the variometer is proved stable enough, it would also be a good idea to set it up at a place where earthquakes of fair magnitude are frequently experienced. It would be of utmost importance and interest to investigate into the possible premonitory anomalous strain before an earthquake.

In conclusion the writer would like to express his hearty thanks to Professor Rikitake under whose supervision the present work has been conducted. Professors Kasahara, Kajiura, Dr. Aida, Messers Hagiwara, Uzawa, Wako, Takahashi, Sasaki and Koyama, to whom the writer also wishes to extend thanks helped the writer in providing the extensometer, tide-gauge and other necessary data. Part of the expense for the present work has been defrayed from a fund given to Professor Rikitake from the Ministry of Education.

44. 岩石変形と電気伝導度変化 (第三報) 比抵抗変化計の試作

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堆積岩を変形させると岩石の比抵抗変化率 $\frac{\Delta\rho}{\rho}$ は，岩石の受ける歪 $\frac{\Delta L}{L}$ にくらべてつねに大きく，この両者の比，増倍率 $\frac{\Delta\rho}{\rho}\Big/\frac{\Delta L}{L}$ は，岩石の種類，含水率 w, $\frac{\Delta L}{L}$, などに左右される，もし岩石が電気的に均質なものならば $\frac{\Delta\rho}{\rho}$, $\frac{\Delta L}{L}$, とも同程度の値をしめすはずである.

しかし岩石が第一報にて名づけた A 型のような，特殊な電気伝導機構をもつたものならば，電導性の水分がふくまれている多数の孔隙の体積が，圧縮により急減するから，見かけの電気伝導が異常に大きくなるものと考えられる.

この岩石の $\frac{\Delta\rho}{\rho}$ がつねに $\frac{\Delta L}{L}$ よりも大きいという室内実験結果から，地殻の微小変形を歪，そのもので測定するよりも，増倍率がすでに含まれていると考えられる大地の比抵抗を観測したほうが，感度がよい地殻歪の測定ができるのではないかと考え，このための比抵抗変化計を試作した.

海岸に近い場所では潮汐変化に対して，土地の伸縮がある．この場所で大地の比抵抗を連続観測すれば，伸縮，潮汐との比較測定が出来るはづである.

観測をおこなつた場所は油圧試験機による圧縮実験で著しい増倍率をしめした，火山礫凝灰岩 (Lapilli tuff) でおもに構成されている油壺地殻変動観測所付近の横穴において，1967 年 1 月から四電極法により連続観測をはじめた.

測定結果は $\frac{\Delta L}{L}$ が 10^{-6} 位であるに対し，大地の比抵抗の変化率 $\frac{\Delta\rho_a}{\rho_a}$ は 10^{-3} 位で変わり，$\frac{\Delta\rho_a}{\rho_a}$ は潮汐荷重による土地変形についても，$\frac{\Delta L}{L}$ より大きな値をしめすことを立証した.

また $\frac{\Delta\rho_a}{\rho_a}$ が透水性の岩石の中に海水の浸透によりおきるのではないかとの点につき，電極を横穴の天井に配列して同様に連続観測をおこなつたが，やはりおなじような変化をしめした.

油壺湾にはときに周期 13 分位の静振がおき，その振幅は 10 cm 位で，潮汐の 1/10 位である．この静振による地殻歪は 10^{-7} 位であるが比抵抗変化計の早まわし記録によつても静振でおきたと考えられる $\frac{\Delta\rho_a}{\rho_a}$ を検出した.