BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
Vol. 43 (1965), pp. 783-802

50. *Electrical Conductivity of Strained Rocks.*
The First Paper.
Laboratory Experiments on Sedimentary Rocks.

By Yoshio YAMAZAKI,

Earthquake Research Institute.

(Read July 20, 1965.—Received July 30, 1965.)

Summary

Changes in the resistivity of tuff specimens are measured by a four-pole method and a bridge method. Simultaneous recordings of the change in the resistivity and the deformation of rock specimen make it clear that the rate of change in the resistivity of a pumice tuff specimen from Oya, Tochigi Prefecture, is of the same order as the strain and that the rate of a lapilli tuff specimen from Aburatsubo, Kanagawa Prefecture, is extremely larger, $10^2 \sim 10^3$ times say, than the strain. The latter result supports Yokoyama's preliminary observation in situ. Yokoyama, who measured changes in the resistivity of the ground by tidal loading, reported an unusually large rate of change in the resistivity which approximately agrees with the rate as measured by the present laboratory experiment. Crude theories of electric conduction in such a material as tuff specimen are advanced. It is also pointed out that the electrical means as advanced here could possibly be applied to measuring extremely small changes in the earth's strain.

1. Introduction

Much effort has so far been made in observing changes in the earth's strain especially in relation to occurrences of earthquake. Although geodetic means such as repetition of triangulation and levelling, observation by tiltmeter, extensometer and the like seem to be the most promising for observing the earth's strain, attempts to detect changes in the earth's strain by electric and magnetic methods have also been made.

Unlike magnetic methods which have been drawing much attention of geophysicists for many years, it appears to the writer that little work has been conducted on the relationship between changes in the electric properties of the earth and the earth's strain. As far as the writer is aware of, the only work along this line was reported by I. Yokoyama[1] who observed changes in the electrical resistance of the ground by tidal loading at Aburatsubo Geophysical Station where an observation by extensometers had been under way all the time. He made use of an apparatus almost the same as that for an ordinary electric prospecting. An electric current of a few tens of cycles per second was driven into the ground through two of the four equally spaced electrodes. The voltage appearing between the inner two electrodes was then potentiometrically balanced by the voltage which was taken from the generator through a transformer. When the earth's resistance slightly changes, the equilibrium breaks down, so that, if an appropriate circuit is provided, the deflection of a galvanometer can be made proportional to the changes in the resistance. In such a way Yokoyama reported that the earth's resistance changed with a lunar period. A comparison between the changes in the earth's resistance, the linear strain parallel to the line on which the electrodes were placed, and the sea level suggested that the rate of the changes in the earth's resistance was larger than that of the earth's strain by $10^2 \sim 10^3$ as can be seen in Fig. 1. It was feared,

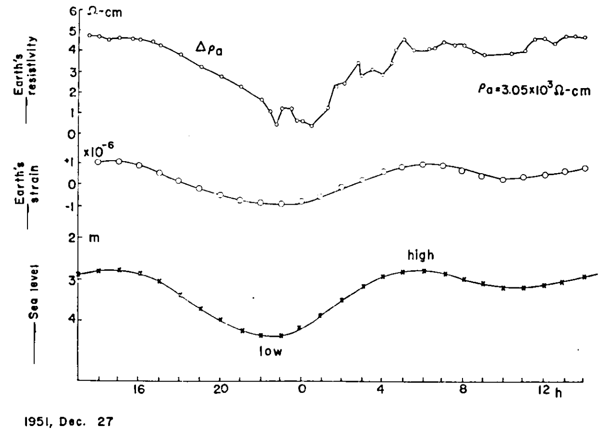

Fig. 1. Yokoyama's observation on the change in the earth's resistivity caused by tidal loading at Aburatsubo. The resistivity itself was measured as $3.05\times10^3\Omega-$cm. The earth's strain was measured by an extensometer and is also shown together with the sea level.

---

[1] I. YOKOYAMA, Read at the monthly meeting of the *Earthquake Research Institute*, March 18, 1952.

however, that the influence of sea-water, which is highly conducting, could be very large because the observation point was very close to the sea shore, only a few tens of meters say, and the rocks around there were highly permeable. Because of adverse circumstances no more observations have been added to Yokoyama's one since then. It has consequently been doubtful whether or not the changes in the earth's resistance as observed by Yokoyama were free from the effect of sea-water. But the point that the apparent rate of change in the earth's resistivity might be $10^2 \sim 10^3$ times as large as the mechanical strain has been considered very important.

Professor T. Rikitake suggested to the writer that the result obtained by Yokoyama might have an important bearing on the detection of changes in the earth's strain by an electric means. This is the reason why the writer takes up a basic study of changes in the electrical resistance of rocks which are strained. First of all, it is aimed at measuring changes in the electrical resistance of rocks in a laboratory.

As the writer would like to apply later the measuring techniques to observations at a field station, a four-pole method like Yokoyama's one was adopted although some other ways were also made use of when necessary. In Section 2 of this paper will be reported the changes in the resistance of a pumice tuff specimen subjected to a bending together with the measuring technique. Meanwhile similar changes of the same rock specimen which is compressed by a loading will be reported in Section 3. The results of experiments of a similar sort for rock specimens taken from Aburatsubo will be described in Section 4. In Section 5 will be advanced crude theories of electric conduction through a porous medium such as tuff specimens in relation to the present experiments.

2. Bending test

2.1 Four-pole method

Although a usual way of measuring electric resistance at a low frequency is to insert it in one of the branches of a bridge circuit as will be done in a measurement described in the following section, a four-pole method similar to the one used for an ordinary electric prospecting is first developed for the present experiment because the writer aims at applying the measuring techniques to observations of changes in the earth's resistance at a field station after completing laboratory experiments.

Four tungsten wire electrodes, 0.5 mm in diameter, are buried in holes drilled 5 mm deep along a centre line of one side of a rock specimen having a size of 92 cm × 14 cm × 8.7 cm. In order to achieve good electric contact between the electrodes and the specimen, silver paste is put in the holes. A 65 c.p.s. generator that is driven by a synchronous motor is used for making an electric current flow into the specimen through the outer two electrodes. The voltage used is 350 volts, while the current driven into the specimen ranges from 10 to 20 mA.

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 winding is led to the generator. As can be seen in a circuit diagram (Fig. 2), the balance is achieved by adjusting a variable resistance R_3.

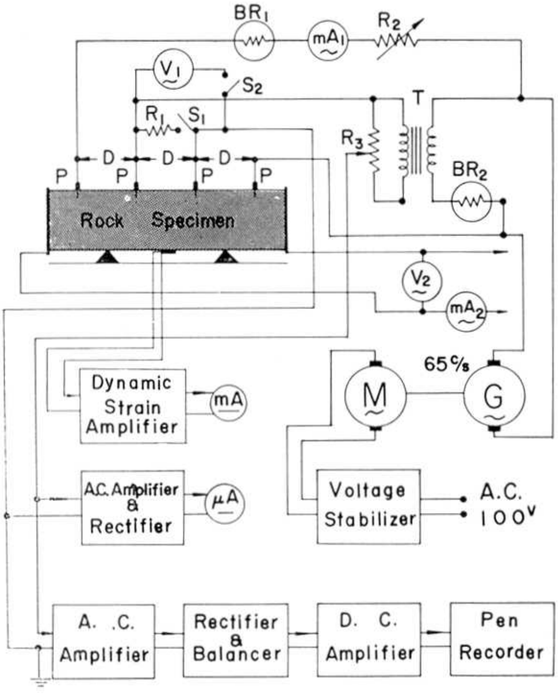

Fig. 2. Schematic diagram of the bending experiment by a four-pole method.

In the case of an actual experiment, the system is almost balanced when no load is applied to the specimen. After loading a small voltage appears at the output of the circuit because of the change in the apparent resistivity of the rock specimen. That voltage (65 c.p.s.) is then amplified by an a.c. amplifier approximately by a factor 1.3×10^5 and rectified. A certain part of the a.c. voltage thus obtained is potentiometrically cancelled out by a voltage taken from a battery, so that, after being amplified by a d.c. amplifier, we can easily record the voltage by a pen-writing recorder.

2.2 Theory of the circuit

An equivalent circuit of the measuring network would be the one as shown in Fig. 3. The theory of circuit analysis leads to

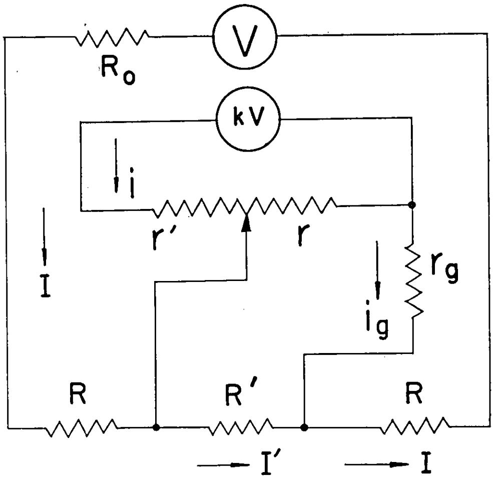

Fig. 3. Equivalent circuit for the four-pole method.

$$I=I'+i_g\,, \tag{1}$$

$$i_g r_g+(i+i_g)r-I'R'=0\,, \tag{2}$$

$$V=I(R_0+2R)+I'R'\,, \tag{3}$$

$$kV=ir'+(i+i_g)r\,, \tag{4}$$

where k is a constant proper to the transformer.

If I' is eliminated from (1) and (2), we obtain

$$i_g=\frac{ir-IR'}{r_g+r+R'}\,. \tag{5}$$

The potential drop e_g between both the ends of r_g is then given as

$$e_g = \frac{ir - IR'}{1 + (r+R)/r_g}\,. \tag{6}$$

Since r_g is the input impedance of an a.c. amplifier, a relation $r_g \gg r, R$ holds good. e_g is therefore given by

$$e_g = ir - IR'\,, \tag{7}$$

which is almost zero for a balanced state. In (4) we can ignore i_g because it is extremely small, so that we obtain

$$i = \frac{kV}{r + r'}\,. \tag{8}$$

When R_0 is assumed to be larger than R and R', we can approximately neglect R and R' getting

$$V = IR_0\,. \tag{9}$$

Putting (9) into (8), we obtain

$$i = \frac{kIR_0}{r + r'}\,. \tag{10}$$

Introducing (10) into (7), we are then led to

$$e_g = \left(\frac{rkR_0}{r + r'} - R'\right) I\,, \tag{11}$$

from which a small change in e_g is obtained as

$$\Delta e_g = -I\Delta R' + \left(\frac{rkR_0}{r + r'} - R'\right)\Delta I\,. \tag{12}$$

Since the coefficient of ΔI on the right-hand side of (12) is nearly zero around the equilibrium state, a small deviation of e_g from the balanced state is approximately given as

$$\Delta e_g = -I\Delta R' (= -I'\Delta R')\,. \tag{13}$$

A ballast lamp inserted in the actual circuit also serves for making ΔI small. Hence we may safely assume that Δe_g is proportional to $\Delta R'$.

As is well known in the case of an electric prospecting by four-pole method in a semi-infinite medium, the apparent resistivity in units of Ω-cm is given by

$$\rho_a = 2\pi D V_0 / I_0\,, \tag{14}$$

where D is the distance in cm between the electrodes, V_0 the voltage in V picked up by the inner two electrodes and I_0 the electric current in mA. (13) can be rewritten with the present notations as

$$\rho_a = 2\pi DR'I'/I\,. \tag{15}$$

If I' is eliminated from (15) with the relation (1), (15) becomes

$$\rho_a = 2\pi DR'(I-i_g)/I\,. \tag{16}$$

When the system is nearly balanced, it has been shown that e_g and consequently i_g are very small, so that, ignoring i_g, we approximately obtain

$$\rho_a = 2\pi DR'\,. \tag{17}$$

We therefore have

$$\varDelta\rho_a/\rho_a = \varDelta R'/R' + \varDelta D/D = -\varDelta e_g/IR' + \varDelta D/D\,, \tag{18}$$

where IR' may be replaced by $I'R'$ because i_g can be neglected as before. It is hence seen that the ratio of $\varDelta e_g$, which is the voltage impressed at the imput impedance of the a.c. amplifier, to the voltage between the inner two electrodes can be correlated with the rate of change in the resistivity by

$$\varDelta\rho_a/\rho_a = -\varDelta e_g/I'R' + \varDelta D/D\,. \tag{19}$$

The rate of change in the resistivity is thus estimated from that in the output voltage appearing at the end of a high resistance r_g provided $\varDelta D/D$ is known. It should be borne in mind, however, that no capacitance is included in the analysis. The effect of capacitance cannot be neglected if an alternating current of a higher frequency is used for the measurement.

2.3 Effect of the finite size of the specimen on the resistivity

The relation indicated in (14) holds good only for a four-pole method in a semi-infinite medium. As the present experiment is made for a finite specimen, the resistivity measured is rather an apparent resistivity ρ_a. In order to estimate ρ from ρ_a, an experiment to measure ρ itself is undertaken as described in the following.

After polishing both the ends of a specimen, plane copper electrodes are attached there with the aid of a binding agent. Electric contact between the specimen and the electrodes is made almost perfect by use of silver paste. A 65 c.p.s. a.c. voltage V_0 which is measured by a valve voltmeter, is applied to these plates and electric current I_0 is then measured by an a.c. milliammeter. When the length and the area of a cross-section of a rectangular specimen are denoted by L and A, the resistivity is given by

$$\rho=\frac{V_0}{I_0}\frac{A}{L}, \tag{20}$$

while ρ_a is obtained by the four-pole method as described in Subsection 2.1.

An example of size-effect experiment is shown in Fig. 4 in which changes in ρ_a, ρ and size-effect coefficient $K(=\rho_a/\rho)$ are shown as functions of the electric current intensity. In this particular experiment, the specimen size is 92 cm × 14 cm × 8.7 cm and the electrode distance $D=25$ cm. Although ρ_a and ρ exhibit slight decreases as the current intensity increases for an unknown reason, K takes on a value around 30. It has little physical meaning to compare ρ_a to ρ plotted against an abscissa which indicates the intensity of current flowing through the plate electrodes for the present experiment and the one through the rod electrodes for the four-pole experiment because the distributions of current through the specimen are different from one another. No discussion about the changes in K with the current intensity is therefore tried here. It sounds reasonable, however, that a four-pole method applied to a finite specimen apparently gives a much higher resistivity because the path of electric currents is highly restricted. In Table 1 are indicated the values of K for different electrode distances.

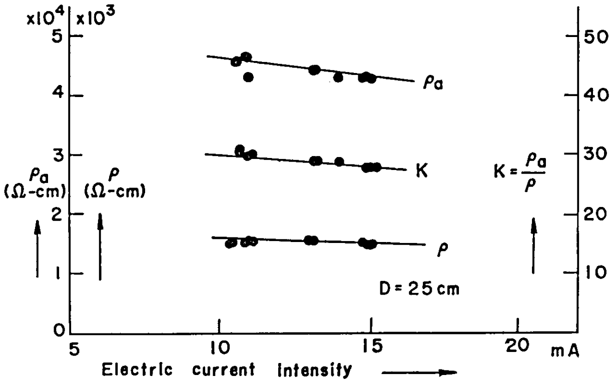

Fig. 4. Apparent resistivity (ρ_a), true resistivity (ρ) and size-effect coefficient (K) plotted against the electric current intensity. The electrode distance is 25 cm.

Table 1. Dependence of size-effect coefficient K on electrode distance D. A pumice tuff specimen (92 cm × 14 cm × 8.7 cm) is used. The electric current intensity is 12 mA.

D (cm)	K
20	24
22.5	31
25	34

2.4 Loading experiment and deformation of the specimen

The rock specimen is supported by two iron prisms which are placed on a heavy iron platform as schematically shown in Fig. 5. In order to apply a weight to the specimen, a bakelite plate of 8 cm width is placed at the centre. The weight that is suspended by chains from the ceiling is then put on a brass plate placed on the bakelite plate which prevents the electric leakage. Special caution is taken to put the weight on the plate as quietly as possible.

The strain caused by the loading is measured by a *Shinko Tsushin Type DS6/PX* dynamic strain amplifier. Strain gauge elements are attached to parts of the specimen as can also be seen in Fig. 5. As the gauge is sensitive to temperature change, effort is made in keeping the room temperature constant during an ex-

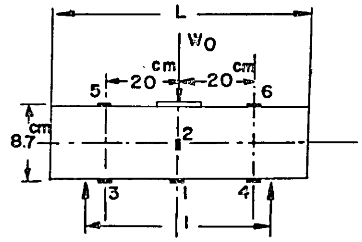

Fig. 5. Schematic view of the bending experiment. Strain gauge elements are attached at points 1, 2, 3, 4, 5, and 6. A weight W_0 is applied on a bakelite plate at the centre of the upper side of the specimen.

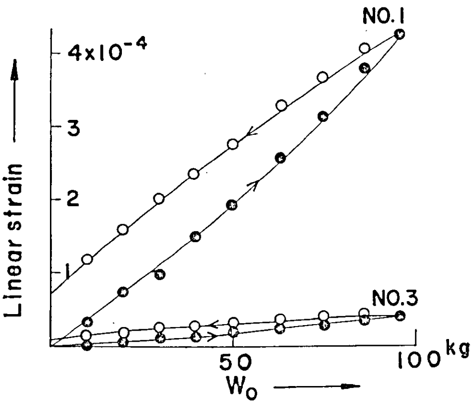

Fig. 6. Changes in linear strain at points Nos. 1 and 3 with increase and decrease of the weight. Solid and hollow circles are the results during the increase and the decrease respectively. The weight W_0 is increased or decreased every one minute.

periment.

Examples of strain values for successive loadings are shown in Fig. 6 in which the changes in strain at elements Nos. 1 and 3 are illustrated. The weight is increased stepwise every one minute. Probably the rate of loading is too large for attaining equilibrium states, so that this is the reason why we obtain hysteresis curves like those in Fig. 6. It is observed, however, that the post-loading strain at zero weight gradually diminishes as time goes on and so the permanent deformation is extremely small. Young's modulus and Poisson's ratio of a pumice tuff specimen which is used for the experiment in the following subsection is estimated respectively as 0.6×10^{11} dyn/cm^2 and 0.19 from the present experiment.

2.5 Relationship between changes in the resistivity and strains

According to the methods as described in Subsections 2.1 and 2.4, both changes in the resistivity of rock specimens and strain are simultaneously recorded with two pen-writing recorders. An example of the records for a pumice-tuff specimen from Oya, Tochigi Prefecture is schematically shown in Fig. 7. For this particular experiment the specimen size is 92 cm × 15 cm × 8.7 cm, the electrode distance 25 cm, the electric current flowing into the specimen through the outer electrodes 9.2 mA, the voltage between the inner electrodes 12.9 V and the weight 138 kg. The strain is measured at point No. 1 which has been shown in Fig. 6. It is regrettable that the paper speeds for the two recorders

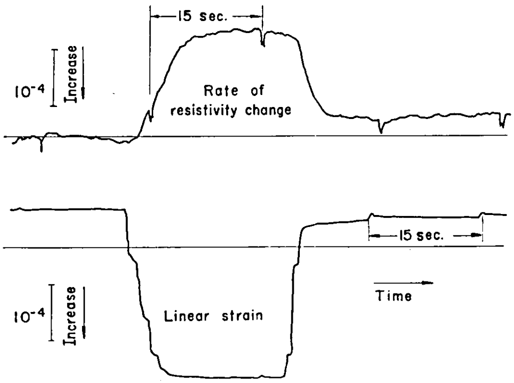

Fig. 7. Schematic records of the rate of resistivity change and the linear strain as observed by a bending experiment for a pumice tuff specimen from Oya.

are slightly different from one another. It is hoped, however, that time marks provided by a clock serves for looking for the corresponding parts of the records.

Since the weight is so heavy that it is difficult to give a sudden loading, some irregularities in the strain curves cannot be avoided unless a more sophisticated and expensive device for loading is made use of. It is observed, however, that the change in the resistivity lags a little behind that in strain although no argument about the time-constant is intended to be made in this paper. Taking both the steady values of the change in the resistivity and the strain, a value for the rate of resistivity change amounting to -1.6×10^{-4} per 10^{-4} in strain is obtained in this particular case. In the estimate, $\Delta D/D$ is estimated from a relation

$$\Delta D/D=-\frac{WL_0}{Ea^2b}, \tag{21}$$

where W is the weight applied at the central line, L_0 the distance between the supporting prisms and E Young's modulus as before, a and b denote respectively the thickness and width of the specimen. It turns out, however, that $\Delta D/D$ is smaller than $\Delta e_g/I'R'$ by a factor 10 or so. Although the resistivity decreases in association with the extension at point No. 1 of the bottom plane of the specimen, it is not clear whether or not the true resistivity decreases in association with an extension at the bottom because the upper half of the specimen must be subjected to a contraction. Actually the strain gauges at points Nos. 5 and 6 indicate a contraction, while it is also proved that point No. 2 is a neutral point where no strain takes place. In order to make this point clear, a series of compression experiments are undertaken as will be described in the following section.

While bending experiments are repeated, it has been noticed that the rate of change in the resistivity depends on water-content of the specimen. The rate of change seems to take a high value for a wet specimen and a small one for a dry specimen. Although no detailed study on this point has been made yet, the rate of change as obtained from the bending experiments covers a range from -0.9 to -1.7×10^{-4} per 10^{-4} in strain for the same specimen. As rocks at an actual field site would have a fairly high water-content, it is very important to study the relationship between rate of change and water-content. Such a study will be reported in a following paper.

3. Compression test

3.1 Test by the four-pole method

Schematic diagram of the arrangement for a compression experiment is indicated in Fig. 8. Points 1, 2, 3 and 4 are the points where the elements of the strain gauge are attached. At their symmetry points 1′, 2′, 3′ and 4′ on the reverse sides of the specimen are also attached the elements which are connected in series with the corresponding elements of the front sides in actual measurements. In such a way slight unbalance of loading can be averaged out.

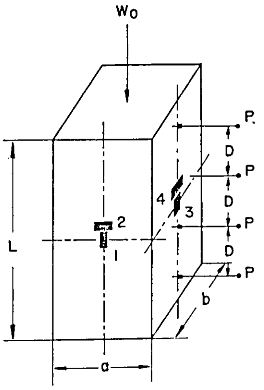

Fig. 8. Schematic view of the compression experiment. Strain gauge elements are attached at points 1, 2, 3, and 4. A weight W_0 is applied on a bakelite plate on the top side of the specimen.

In a compression experiment, it is obvious that all parts of the specimen are subjected to a contraction in the direction of loading. Unlike the bending experiment, therefore, there appears no ambiguity between change in the resistivity and strain. A pumice-tuff specimen similar to the one which has been used for the previous test is also used. The only difference is its size which, in the case of the present test, is 40.3 cm × 13.9 cm × 9.1 cm.

The four-pole technique is first applied to the experiment. A weight for loading heavier than the previous bending test, 138 kg say, is needed in order to have a strain of the order similar to the previous case.

Simultaneous recordings of changes in the resistivity and strains provide records similar to that in Fig. 7. As a result of a series of experiments, the rate of resistivity change is obtained as $-(0.5\pm0.2)\times10^{-4}$ per 10^{-4} in strain. The effect of $\Delta D/D$ which is given by an expression similar to (21) is also taken into account in this case. However, it is again confirmed that such an effect is unimportant. Although fairly large scatterings of the rate are observed, a part of the errors are believed to be caused by the fact that the condition of the specimen is not always constant. It is noticed that the rate of change in the resistivity seems likely to decrease as the specimen gets dry. As is the case for the bending test, the effect of water-content on rate of change in the resistivity should be examined.

3.2 Test by a bridge method

In order to check the results obtained by a four-pole method, changes in the resistivity are further measured by a bridge method. The specimen to which two plane electrodes are attached at its ends is inserted in one of the branches of a bridge as schematically shown in Fig. 9. After balancing the circuit, a small voltage appearing at the output due to the loading is amplified and recorded by a pen-writing recorder as was done in the case of previous experiments. A circuit analysis proves that the output voltage is proportional to the change in the resistance. As the resistivity is given by

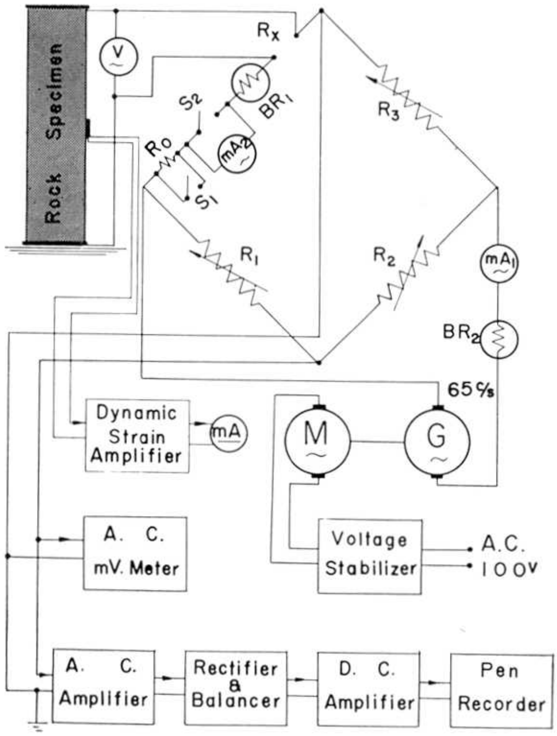

Fig. 9. Schematic diagram of the compression experiment by a bridge method.

$$\rho = RA/L\,, \tag{22}$$

where R is the resistance, A the cross-section area and L the length of the specimen, the rate of change in the resistivity is estimated by

$$\Delta\rho/\rho = \Delta R/R + \Delta A/A - \Delta L/L = \Delta R/R - (1-2\sigma)\Delta L/L\,, \tag{23}$$

where σ denotes Poisson's ratio.

An example of the simultaneous recordings of changes in strain and resistivity is shown in Fig. 10. Although some drift and noise are observed on the record, there is no doubt about the fact that the resistivity changes as the specimen is compressed.

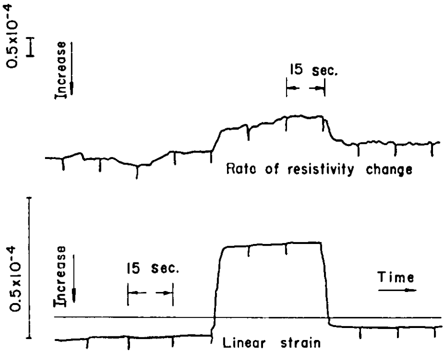

Fig. 10. Schematic records of the rate of resistivity change and the linear strain as observed by a compression experiment for a pumice tuff specimen from Oya.

The rate of change in the resistivity observed by the bridge method roughly agrees with that by the four-pole method. For instance, -1.0×10^{-4} per 10^{-4} in strain is obtained by the former, while the latter gives -1.5×10^{-4} per 10^{-4} in strain. These experiments being made on different days, the effect of water-content is unknown. It is only possible to say that the rate of change in the resistivity observed by the two methods agrees with one another in its order.

4. Experiments on lapilli tuff from Aburatsubo

In order to check the preliminary results obtained by Yokoyama[1], a series of compression test is made for a lapilli tuff specimen taken from Aburatsubo. Yokoyama's experiment was made in a gallery dug in a formation composed of the lapilli tuff.

A 20cm×7.1cm×7.2cm specimen is used for the experiment. Changes in the resistivity is in this case measured by a bridge method only. As can be seen in an example as shown in Fig. 11, the rate of change in the resistivity is found to be surprisingly large

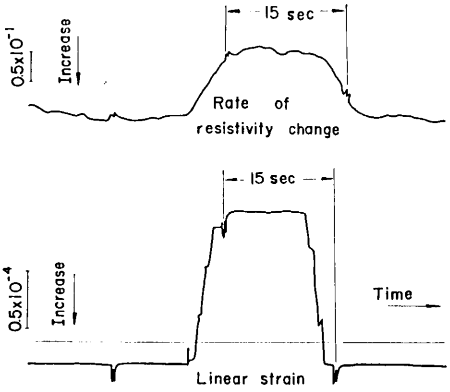

Fig. 11. Schematic records of the rate of resistivity change and the linear strain as observed by a compression experiment for a lapilli tuff specimen from Aburatsubo.

for the present specimen. $\Delta\rho/\rho$ is estimated as -0.65×10^{-1} per 10^{-4} in strain. Although the reason why such a large rate of change in the resistivity is observed for the present specimen is not quite clear, the present result supports Yokoyama's one of which the large change in $\Delta\rho/\rho$ with a lunar period has been suspected to be caused by an effect of sea-water.

The specimen used for the present experiment is more porous than the pumice tuff specimen described in Section 2. The water-content by weight is estimated as 24.6 per cent when the experiment is made. Young's modulus and Poisson's ratio of a lapilli tuff from Aburatsubo is estimated as 0.13×10^{11} dyn/cm^2 and 0.28.

5. Discussion

The present series of experiments on tuff specimens make it clear that there are at least two types of rock in its electrical aspect when strained. Let us call the first one as revealed by the pumice tuff from Oya the O-type. For this type of rock, the rate of change in the resistivity is of the same order as the mechanical strain. Meanwhile, rocks of the A-type represented by the lapilli tuff from Aburatsubo exhibit an enormously large rate of change in the resistivity when they are strained.

It is hard to calculate mechanisms of electric conduction for such materials of complicated structure as rocks experimented here. But the writer thinks that a mixture of air and solid particles of rock may be a possible model for fairly dry rocks although the air, which may contain vapour and ions, is not quite insulating in this case. Assuming spherical particles, Maxwell[2] obtained a formula for the apparent conductivity of such a mixture as

$$\sigma_D=\sigma_A\frac{3-2p(1-\sigma_A/\sigma_S)}{3\sigma_A/\sigma_S+p(1-\sigma_A/\sigma_S)}\,, \tag{24}$$

where σ_A is the conductivity of air, σ_S the conductivity of solid and p the porosity. Mutual interaction between particles is completely ignored in such a model. A reasonable assumption $\sigma_A \ll \sigma_S$ leads to a simplified expression such as

$$\sigma_D=\sigma_A(3-2p)/p\,, \tag{25}$$

---

[2] J. C. MAXWELL, *A Treatise on Electricity and Magnetism.* 3rd ed. ii, 1 (1904). Oxford.

which can be rewritten in terms of resistivity as

$$\rho_D=\rho_A p/(3-2p)\,, \tag{26}$$

from which we obtain

$$\frac{d\rho_D}{\rho_D}=\frac{3}{3-2p}\,\frac{dp}{p}\,. \tag{27}$$

If it is assumed that the volume of solid does not change, the rate of change in the porosity can be correlated to that in the volume by

$$\frac{dp}{p}=\frac{1-p}{p}\,\frac{dV}{V}\,, \tag{28}$$

so that (27) reduces to

$$\frac{d\rho_D}{\rho_D}=\frac{3(1-p)}{p(3-2p)}\,\frac{dV}{V}\,. \tag{29}$$

As the porosity of actual rocks would be 0.2 or so, $d\rho_D/\rho_D$ is of the order the same as dV/V. According to the experimental results, such a model may be qualitatively applicable to a fairly dry state of an O-type rock. A theory of change in the resistivity of a little more wet rocks of the O-type will be advanced in a following paper.

A similar theory for a rock saturated by water leads to an expression for the apparent conductivity such as

$$\sigma_W=\sigma_w\frac{3-2p(1-\sigma_w/\sigma_S)}{3\sigma_w/\sigma_S+p(1-\sigma_w/\sigma_S)}\,, \tag{30}$$

where σ_w is the conductivity of water which is much larger than σ_S. The condition that $\sigma_w \gg \sigma_S$ leads to

$$\rho_W=\rho_w(3-p)/2p\,. \tag{31}$$

and

$$\frac{d\rho_W}{\rho_W}=-\frac{3(1-p)}{p(3-p)}\,\frac{dV}{V}\,. \tag{32}$$

(32) indicates that the change in the resistivity is positive for a decrease in the volume. Since it is shown by the experiments that the change in the resistivity is negative for a decrease in the volume, the model assumed does not work even for a rock of the O-type. In order to account for the experimental results for a wet state, therefore, a theory based on another model, in which mutual interaction between the particles contained is necessarily taken into account, should be

developed. The writer fears that it would be no easy matter to advance such a theory though a very crude attempt will be made in the following.

Let us think of a permeable rock. Such a rock could be represented by a model in which spherical holes filled by conducting water are arranged in such a manner as shown in Fig. 12. Denoting the distance between the neighbouring spheres by D, we assume that N spheres are contained in a distance L, so that we obtain

$$D=L/N. \tag{33}$$

It is assumed that the neighbouring spheres are slightly overlapping. When the material is subjected to a comression, the degree of overlapping increases. The intersection of the two neighbouring spheres forms a circle of which the area is given by

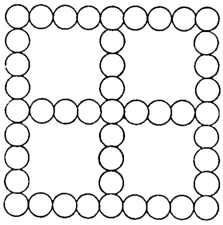

Fig. 12. A schematic model for electric conduction for the A-type rock. Chains of spheres, which are slightly overlapped with one another and filled with conducting water, are assumed.

$$S=\pi r^2\left(1-\frac{D^2}{4r^2}\right), \tag{34}$$

in which r is the radius of the sphere.

When an electric current flows in a direction parallel to a chain of such spheres, the electric resistance could be, to a crude degree of approximation, assumed to be inversely proportional to S provided the resistance of water filling each hole is very small. The resistance is hence given by

$$R=\frac{k_1}{r^2-L^2/4N^2}. \tag{35}$$

while the resistivity becomes

$$\rho=\frac{k_2}{(r^2-L^2/4N^2)L}, \tag{36}$$

where k_1 and k_2 are constant.

We then have

$$\frac{d\rho}{\rho}=K\frac{dL}{L}, \qquad K=-\frac{r^2-\dfrac{3}{4}\dfrac{L^2}{N^2}}{r^2-\dfrac{1}{4}\dfrac{L^2}{N^2}}. \tag{37}$$

It is seen from (37) that K takes on a fairly large value when the difference between r and $L/2N$ is small. For instance, K amounts to 10^3 when $r=1.001\,L/2N$. We therefore see that the change in the degree of overlapping between the spheres as possibly expected in association with a deformation of a rock specimen may lead to a large rate of change in the resistivity although the model should be more refined in order to reach a better understanding of an unusually large rate of the change in the resistivity as found for a rock of the A-type. It would be useful to measure permeability of rock specimen for studying the conduction mechanism for such a rock.

It has been noticed in the course of experiments that the rate of change in the resistivity becomes larger as the water-content of a specimen increases. The crude theories of conduction in the above being advanced only for dry and saturated states, it is therefore difficult to apply the theories to an intermediate state. The writer hopes, however, that the effect of water-content on the rate of change in the resistivity will be studied both experimentally and theoretically in a following paper.

6. Conclusion

Techniques for measuring a small change in the resistivity of rock specimen are advanced. Four-pole method and bridge method are both used. The former may also be applied to a measurement at a field station.

Applying the techniques to rock specimens subjected to bending or compression, it is established that the resistivity changes in association with deformation of specimen. As far as two tuff specimens already experimented are concerned, there seem to be two types of rock. For a pumice tuff specimen from Oya, Tochigi Prefecture, the rate of change in the resistivity amounts to the order the same as the mechanical strain. Meanwhile, an extremely large rate of change in the resistivity is observed in the case of a lapilli tuff specimen from Aburatsubo, Kanagawa Prefecture. The writer named the former the O-type and the latter the A-type.

Although crude theories are developed in Section 5, it is hard to understand well conduction mechanisms through the rocks. Especially the unusually high rate of change in the resistivity for rocks of the A-type seems difficult to understand. However, it is suggested in Section

5 that such a high rate could be caused by an interaction of some sort between water particles contained in a permeable rock specimen.

It is extremely interesting that a high rate of change in the resistivity of rocks as observed by Yokoyama's experiment in situ is confirmed by the laboratory experiment. Since the rate of change in the resistivity is $10^2 \sim 10^3$ times as large as the mechanical strain for rocks of the A-type, it might be possible to apply the technique to measuring extremely small earth strains. Such a measurement at a field station will be undertaken in the near future.

The present study was started by the suggestion of Professor Rikitake. The writer wishes to express his sincere thanks to him for the advice given to the writer in the course of the study. The writer has also been helped by colleagues in the Divisions of Geophysics and Geology of the Earthquake Research Institute to whom the writer's hearty thanks are also due. Part of the expense for the present study was defrayed from a fund given to Professor Rikitake by the Ministry of Education.

---

50. 岩石変形と電気伝導度変化 (第一報)
(堆積岩についての室内実験)

地震研究所 山崎良雄

地殻に作用する歪力によつて，地殻を構成する物質の電気伝導度が変化するであろうという議論に対して一つの観測がある．

それは横山　泉により 1951 年から 52 年にわたり，神奈川県三浦市油壺附近でなされたものである．この観測によると，観測点近くの潮汐の変化により地殻の伸縮がおこり，この伸縮が 10^{-6} 程度変るとき，地殻の電気伝導度，すなわち比抵抗が 10^{-3} の割合で変化することが観測された．つまり地殻の伸縮に対しての比抵抗変化率は $10^2 \sim 10^3$ 倍に達することとなる．

この観測結果を確かめるために，室内実験を二種類の堆積岩について行ない，以下の諸点があきらかになつた．

(1) 大谷産，軽石凝灰岩 (Pumice tuff) の荷重実験

軽石凝灰岩の適当な大きさのものを岩石試料とし，これを横において，岩石試料の上部中央点に 138 kg の垂直荷重を掛ける曲げ実験，および岩石試料を縦において，上部に同じ 138 kg の垂直荷重を掛ける圧縮実験の二実験を行なつたが，いずれも岩石試料の歪と比抵抗変化率との間には，大きな違いはなかつた．この実験において岩石試料にながす交流電流の値が，垂直荷重にともなつておきる比抵抗の変化率に影響があるということが，わかつたが，これについてはもつと数多くの岩石試料について，くわしく実験をすすめなくては量的なことはいえない．なお，圧縮実験においては，曲げ実験とおなじ方法の四電極法，岩石試料を四辺で構成するブリッジの一辺にいれるブリッジ法の二つの方法で，同一の岩石試料について実験を行なつたが，これらの二つの方法で得られた垂直荷重と，比抵抗変化率との関係はかなりよく一致した．

(2) 油壺産，火山礫凝灰岩 (Lapilli tuff) の荷重実験

横山　泉の観測結果を室内実験で確かめるために，油壺の火山礫凝灰岩の露頭から，大きさ 20 cm ×7.1 cm×7.2 cm の試料を切り出して，室内実験により垂直荷重による岩石試料の歪と，比抵抗変化率をブリッジ法により求めた．この場合には岩石試料の比抵抗変化率の歪に対する比は数百倍にも達し，横山　泉の行なつた観測のときとほとんど同程度の値を示したことは興味あることである．

最後に上記の実験結果の解釈について，若干の議論を行なつた．