THE SEISMIC ELECTRIC EFFECT[1]

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ABSTRACT

The seismic electric effect is the name which has been given to the variation of earth resistivity with elastic deformation. An account is given of the use of this effect in recording seismic waves. The recording circuit employs a direct current sent through the ground by means of a storage battery and spaced electrodes, and the changes in current due to seismic disturbances are recorded. An analysis of the noise appearing in the recording circuit is given and methods of reducing the noise level are described. The results of measurements on the magnitude of the effect are given, and the sensitivity obtainable with the seismic electric method is compared with that given by an electromagnetic pickup.

The possibility that there might exist a variation of earth resistivity with elastic deformation was first suggested by Louis Statham and L. W. Blau of the Humble Company. They pointed out that, if the effect existed, it might be used to provide an entirely new method of picking up the seismic energy in reflection and refraction shooting. By a suitable arrangement of electrodes it would be possible to obtain a current distribution in the earth involving almost any desired volume of earth. Since the resistivity at any point in this volume would vary, as a function of time, with the elastic strain at that point, the variation in effective impedance between the two groups of electrodes would be the integral, throughout the volume, of the seismic disturbance as a function of time. Due to the very high apparent velocity (along the surface) of the reflected waves as compared to waves of less penetration, the method would offer a possibility of discriminating against the shallow waves and in favor of the reflections.

This effect, the variation of the earth resistivity with elastic deformation, which has been termed the seismic-electric effect, has been investigated as to causes, magnitude and possibilities of use.

A schematic diagram of the circuit used in recording the seismic electric effect is shown in Fig. 1A. For simplicity, only two electrodes A and B are shown, although either of these may be a multiple electrode earth contact. A direct current is passed through the earth between these electrodes by means of a storage battery in series with the primary of a transformer. The secondary of the transformer is connected through an amplifier to an oscillograph and the signals are

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recorded as in ordinary reflection shooting. Fig. 1B represents the equivalent input circuit in which R represents the effective ground resistance, Z is the impedance looking into the transformer primary, and I is the direct current flowing in the circuit. The resistance R is assumed to vary with time as

$$R = R_0 + \Delta r(t)$$

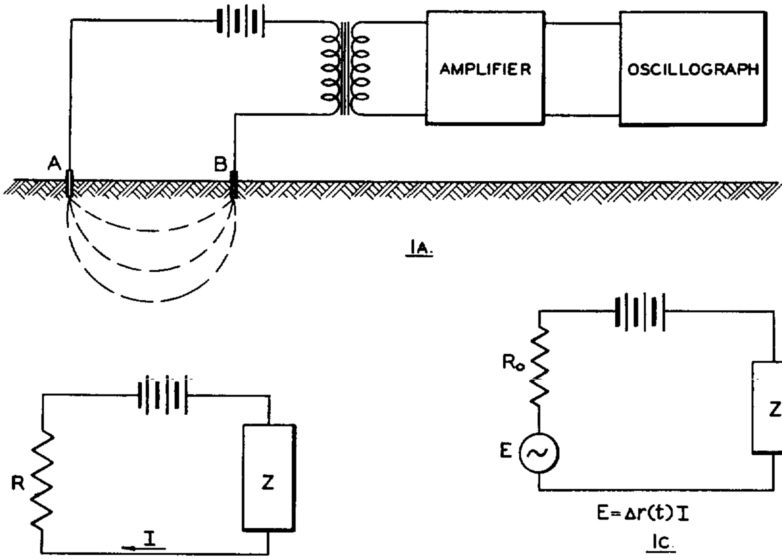


FIG. 1.
SCHEMATIC OF SEISMIC ELECTRIC EFFECT RECORDER & EQUIVALENT INPUT CIRCUITS.

where $\Delta r(t)$ is very small compared to R_0. This circuit is approximately equivalent to that of Fig. 1C where the effect of the variation in resistance is represented by a series generator of voltage $\Delta r(t)I$ and internal impedance R_0. Thus the signal voltage effective in the input circuit is given by the product of the instantaneous value of the resistance variation and the magnitude of the direct current flowing through the ground.

Noise voltages which originate in the input circuit may be divided into two classes: Noises due to resistance changes other than the seismic electric effect, such as variations in contact resistance; and noises due to currents already flowing in the earth which produce a fluctuating potential difference between the electrodes. The first type of noise increases linearly with the ground current so long as the current is not raised to such a high value that the unwanted resistance fluctuations cease to be independent of the current. The second type of noise voltage is independent of the ground current and is a function only of the location, separation, etc., of the electrodes. In addition, it has been found that for large values of current a third noise voltage component must be included. This component is negligible for small values of current but increases rapidly as the current is raised above a certain value. Apparently this source of noise is associated with chemical action at the electrode.

Thus an expression for the noise voltage may be written

$$E_n = IR_n + E_g + G(I)$$

where I is the ground current, R_n represents resistance fluctuations other than those due to the seismic electric effect, E_g represents the noise voltage picked up due to natural or artificial earth currents, and $G(I)$ is a term included to take care of the very rapid increase of noise with ground current when the current becomes too high.

These noise components are illustrated in Fig. 2 where it is seen that at very low currents E_g is the important component; as the current is increased IR_n becomes the important component; and for very large values of current $G(I)$ becomes the principal source of noise. Since the signal voltage varies linearly with the ground current, that is

$$E_s = \Delta r I$$

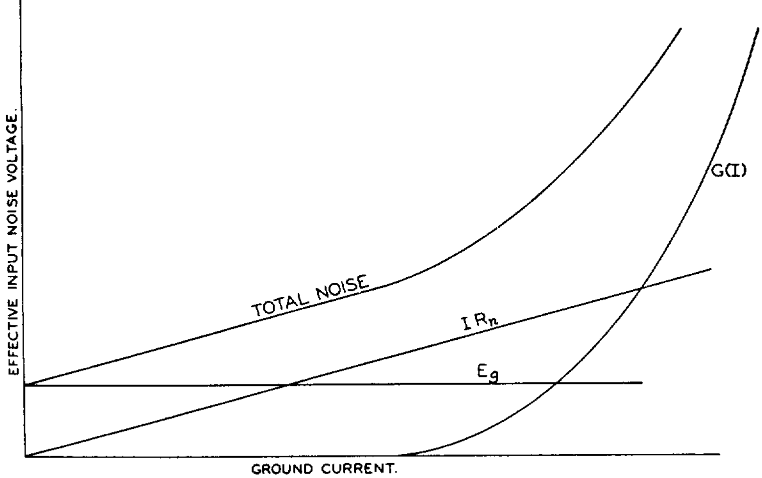
it is evident that the best signal to noise ratio is obtained in the region where the IR_n term is the principal noise component and that in this region the ratio is

$$\frac{E_s}{E_n} = \frac{\Delta r}{R_n}.$$

The first experiments with electrodes showed that any kind of metal rods driven into or buried in the earth gave an intolerably high noise level due to fluctuating contact resistances. A much quieter earth contact was finally obtained by drilling holes in the ground with a hand auger, filling the holes with a salt solution to serve as an electrolyte, and placing the electrode in the solution. The electrodes used were cylinders of copper or zinc about $3\frac{1}{2}$ inches in diameter and 3 to 6 inches in length. Electrodes of this type were used in all subsequent work.

Measurements were made, with two such electrodes, on noise as a function of electrode separation. The results are shown on Fig. 3. Line A represents the equivalent input noise voltage for various distances between electrodes. It is evident that in this case the noise increases linearly with distance between electrodes. This indicates that the noise comes from ground currents which are distributed in such a way that the potential gradient is very nearly constant over the area involved. This would be expected to be the case if the earth

FIG. 2.
ILLUSTRATION OF NOISE COMPONENTS IN SEISMIC ELECTRIC RECORDER.



is homogeneous, and the source of the disturbance is not a local source near the electrodes. If this is true, it should be possible to balance out the voltage picked up in this way by using the arrangement *B*, where three electrodes are set in a straight line, the center electrode being equidistant from the two outside electrodes. The two outside electrodes are connected together and are of one polarity while the center electrode is of the opposite polarity. With an arrangement of this type the noise dropped to the value indicated by "B" on Fig. 3 when the distance between outside electrodes was 50 feet. Five electrodes in line gave a noise voltage indicated by "C" on Fig. 3. Any number of electrodes may be used in a balanced arrangement, it being necessary only to space the electrodes so that the vector sum of all the lines correcting positive electrodes to negative electrodes is zero. It thus appears that when only two electrodes are used the E_n term is relatively large and increases linearly with electrode separation. With a balanced arrangement the E_n term can be reduced considerably.

The results of measurements on the variation of noise with ground current are shown on Fig. 4. In this case a three electrode balanced circuit was used so that the E_n term should be small, and the IR_n term should be the important one. It will be noted that the noise increases linearly with the current and has a very small value at zero

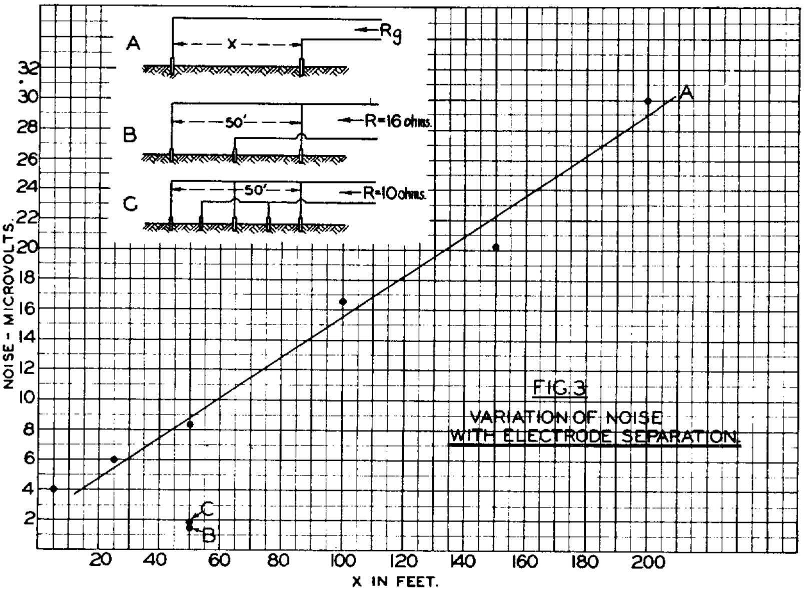


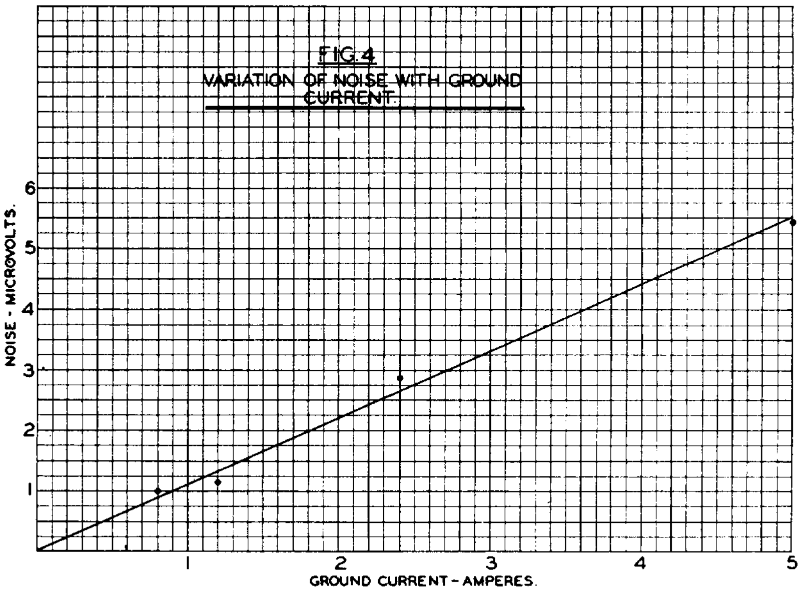
FIG. 3
VARIATION OF NOISE WITH ELECTRODE SEPARATION.

current as would be expected, since the noise at zero current should be the value of E_n.

As has already been shown, the effective input signal voltage is given by

$$E_s = \Delta r I.$$

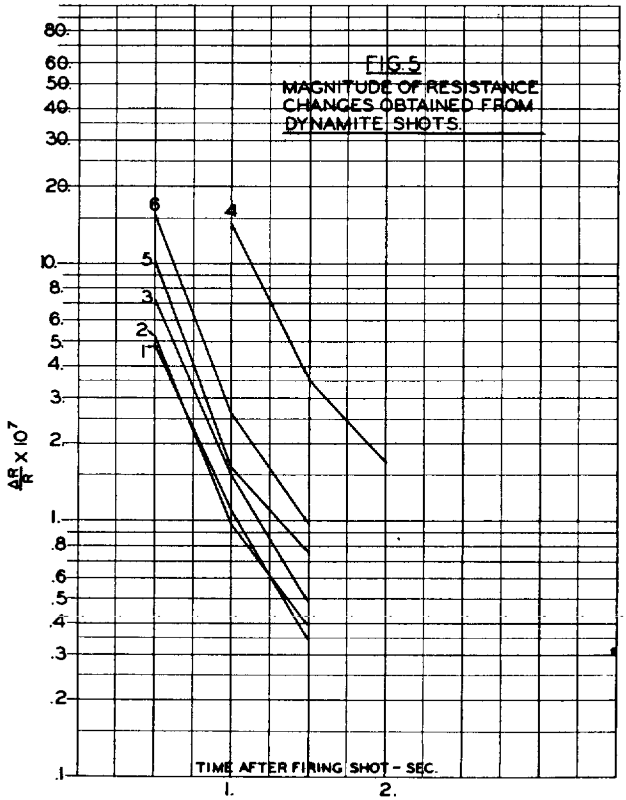
The value of Δr, and hence of the signal voltage, varies with time in exactly the same way as the ground motion. By inserting a low impedance generator of proper frequency and known voltage in the input circuit and comparing the amplitude recorded from this input to that obtained on the record of a dynamite shot, the magnitude of E_s may be determined at various times on the record. The magnitude of the ground current may be measured by a series ammeter and the ground resistance determined by the *IR* drop across the electrodes. Thus Δr and R may be determined and the ratio $\Delta r/R$ computed. This ratio is, of course, a function of time along the record, and for any particular set-up will vary with the size of the charge in the same way as the ground motion. Fig. 5 shows the values obtained for $\Delta r/R$ for a number of locations in the Gulf Coast. The values of Δr are taken from the maximum amplitudes recorded in the neighborhood of .5, 1, 1.5, and 2 seconds. It will be seen that the resistance



variation due to the energy arriving at about one second out on the record is of the order of 1 to 15 parts in 10 million and at two seconds it is about a tenth as much.

The charges used vary from $2\frac{1}{2}$ to 10 pounds and are of about the same size as the average charge for ordinary reflection shooting in the same locality. The distance from the shot to the recorder varies from 2000 to 2500 feet. The largest effect observed, that of No. 4, represents a usable amplitude on the record about equal to that obtained from a standard electromagnetic pickup.

Photographs of two records with seismic electric traces are shown on Fig. 6. On record No. 1 a standard pickup was placed beside the center electrode of the seismic electric set-up which was 1900 feet from the shot; the outside electrodes were fifteen feet on either side of the center electrode. Identical amplifiers of the resistance coupled type with no low frequency elimination filters were used for the two traces. On record No. 2 the fourth trace of a standard field set-up was replaced by a seismic electric trace. The spread for this record was



2100 to 2850 feet, number three pickup was at 2400 feet and the seismic electric electrodes were at 2375, 2400, and 2425 feet. The sensitivity on these records is sufficiently high for practical field use but they represent an effect of about the magnitude given by curve 4 of Fig. 5, that is, they were taken in the most favorable areas found. In many areas a much lower sensitivity was found to exist. The problem of increasing the usable sensitivity is entirely a matter of

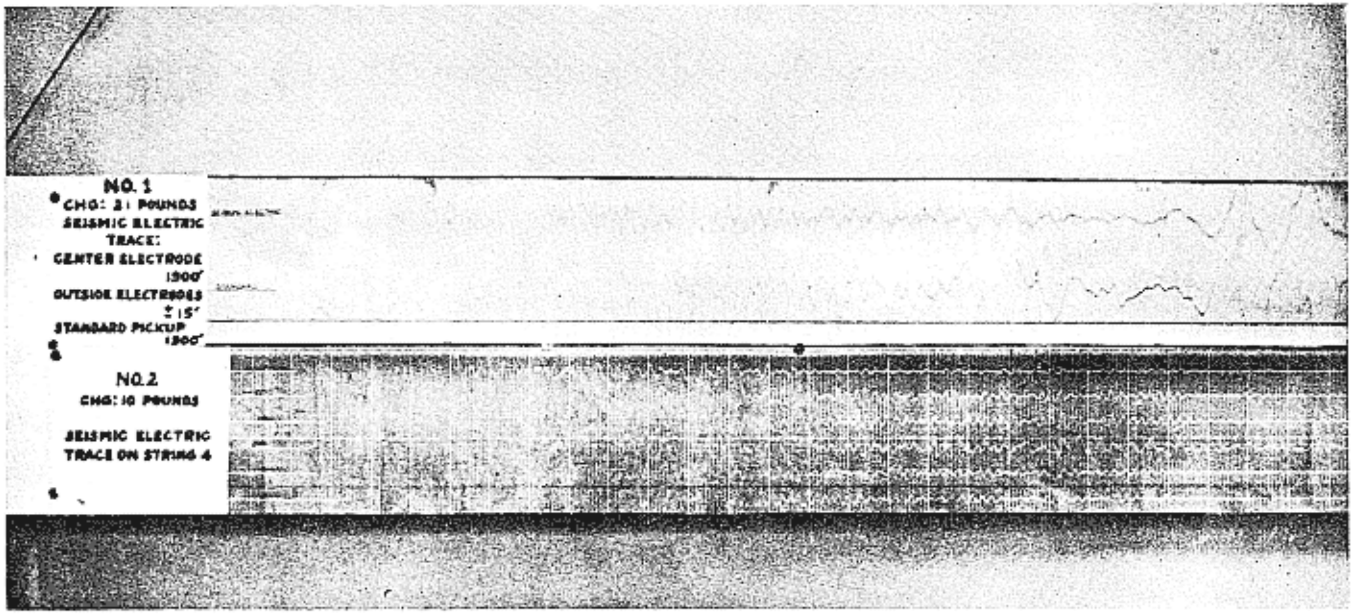


FIG. 6. Comparison of Seismic Electric Recorder Electro-magnetic pickup.

reducing the noise level and it is possible that means for accomplishing this may be found at a future date.

Since the potential gradient, due to the current sent through the earth, is large near the electrodes and drops off rapidly for increasing distances from the electrodes, the principal contributions to the input signals come from the regions near the electrodes. Consequently the seismic electric recorder does not integrate the seismic disturbance uniformly throughout the volume of earth which carries the current, but gives most weight to the disturbance near the electrodes.

As to the mechanism of the resistance change, no definite answer has been found. Experiments on electrodes set close together so that the intervening earth becomes saturated with the electrolyte show very little response, indicating that the effect is in the earth itself and not in the electrolyte or at the electrode surface. It has been suggested that the effect might be due to the small temperature fluctuations which occur with the compression in the earth and that, on account of the temperature coefficient of resistivity of the earth, a resistance fluctuation is produced. It seems unlikely, however, that if this were true, there would exist such large variations in the magnitude of the resistance change as have been observed from one location to another. A more probable explanation seems to be that the effect is some sort of loose contact phenomenon between the particles of the earth.