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3. *Experimental Study on Generation and Propagation of S-waves: I. Designing of SH-wave Generator and its Field Tests.*

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1. Introduction

Many seismologists throughout the world have been keenly interested of late in the study of the vibration characteristics of the superficial soil layers through which we have some information on how to prevent disaster due to strong earthquake motions. For this purpose, primarily, a better understanding of the media is essential. First of all, the elastic constants of the media should be determined from the insitu measurements. As is well known, these values are obtained directly through the measurements of P and S velocities insitu.

In response to the problem, many investigators attempted to obtain the above-mentioned information from direct measurements of the S waves as well as from indirect methods. The direct measurements were carried out through observations of SV waves generated from sources such as falling-weight, explosions and so on.[1] In these cases, the main problem is how to separate the SV arrivals from the P as well as the Rayleigh waves which are inherently generated from same sources and contaminate the desired signals. Incidentally, in some cases, surface S velocities were deduced through the observations of Rayleigh waves, although the accuracy was low.

Now we will mention the method for observing the SH waves as the first arrivals in the seismograms, this paper belonging to this type of study. From the theory of elasticity, we know that the propagation of SH waves in the media is quite simple compared with the other types of waves, such as P and SV waves. Namely, no other type of

1) J. E. WHITE and R. L. SENGBUSH, *Geophysics*, **18** (1953), 54-69.
F. J. MCDONAL et al., *Geophysics*, **23** (1958), 421-439.
R. J. SWAIN, *Geophysics*, **27** (1962), 237-241.
J. E. WHITE and R. L. SENGBUSH, *Geophysics*, **28** (1963), 1001-1019.

waves is expected from the reflection and refraction of incident SH waves to the discontinuity. So that if we could find a device or any other seismic source which generates SH waves only, then the seismograms thus obtained would be quite simple and the interpretation therefore simpler than the other cases. Jolly[2] first carried out this type of experiment successfully using his SH wave generator called "gun". While in Japan, Kobayashi[3] and others introduced a simple method of generating SH waves which is now in practical use in small-scale experiments. His method employs a wooden plate (1.5–2.5 m long, 30–50 cm wide and 5–8 cm thick), placed on the ground surface and pressed down by a sufficient weight so that it contacts the surface well. Then one end of plate is hit with a hammer. The hammer blow generates the impulsive shearing force between the plate and the ground and hence the SH waves. Although the method is very simple and practical, the initial motions of the SH arrivals generated are somewhat dull, the observed maximum distance of the appreciable amplitudes experienced being less than 150 m, because of the human power.

To improve the above-mentioned situation, Komaki[4] subsequently designed a generator similar to Jolly's. He was successful in cases of small charges. However, when bigger charges were fired the generator itself excited rocking because of its own unbalanced weight. Besides this, the spikes used to contact the generator to the media were suspected to be the origin of the P waves. So that in Komaki's case, 30 g of dynamite was the maximum charge, and his seismic source could not overcome the above-mentioned simple source.

In the following, efforts for designing a better SH wave generator to improve the above-mentioned situation together with its field tests are introduced.

2. Designing of SH wave generator

For better designing of a generator, we examined first the merits and demerits of the former ones. Now we will enumerate the requirements of the generator as follows:

i) The generated SH waves must be steady. That is, because we can't get rid of other types of seismic waves in actual experiment, we

2) R. N. JOLLY, *Geophysics*, **21** (1956), 905–938.
3) N. KOBAYASHI, *Zisin*, [ii], **12** (1959), 19–24, (in Japanese).
4) S. KOMAKI, *Rep. Seism. Explor. Group of Japan*, **18** (1959), 91–100, (in Japanese).

must keep the undesired waves to a minimum.

ii) The initial motions of the waves must be sharp and the observable distance extensive.

iii) The handling of generator must be easy.

With the above requirement in mind, we took advantage of the merits of both kinds of source in the designing of our Mark I generator. Referring to i), because the unbalanced weight of the generator is a source of noise, we paid much attention to this matter. A plane wooden plate was used to contact the generator to the ground and no spikes were used for the reason mentioned in the former section. Instead we increased the weight of the generator itself. As regards ii), we decided to use explosives as an energy source so that the necessary high power could be obtained easily.

A schematic diagram of the Mark I generator is shown in Fig. 1.

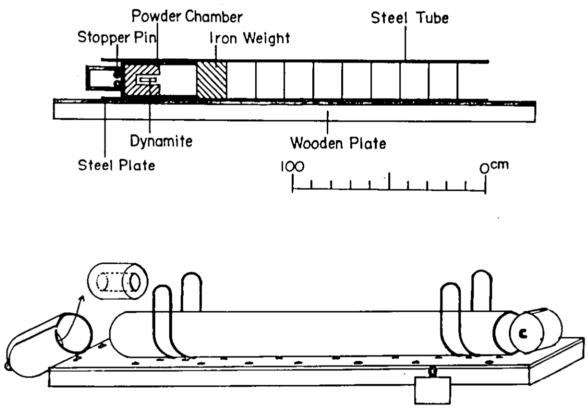

Fig. 1. Schematic diagram of the Mark I SH-wave generator.

An iron pipe (20 cm in diameter, 0.8 cm thick and 200 cm long), was welded on to the plate. As shown in Fig. 1 the upper part of the wooden plate was reinforced with an iron one so that the plate would not bend and also for the convenience of welding the pipe on to. A 250 cm long, 50 cm wide and 5 cm thick plate was used in our generator. In one end of the pipe, a powder chamber doubly protected by the steel was installed and fixed by stopper pins. In the other end of the pipe, 9 iron weights, of 30 kg each, were loaded to maintain a good balance of the generator itself and the equipment as a whole. When fired, the weights were pushed out from the pipe by the impulsive

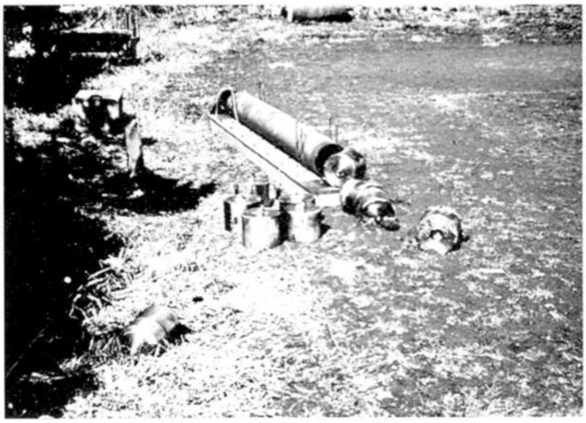

Fig. 2a. General view of Mark I SH-wave generator. Iron weights are seen outside the pipe.

Fig. 2b. Close-up view of the powder chamber of the generator.

pressure due to the explosion. By the reaction, the pipe hence the plate move to the opposite direction, and a strong impulsive shearing force was applied to the ground. It is clear that the generated shearing force is largely affected by the amount of charge and the weight acting on the unit area of the surface. On this matter, however, we did not use an extra weight other than the dead weight, a little less than 600 kg including weights, of the generator itself. Mark I generator was designed so that a maximum charge of 100 g can be safely fired. Fig. 2a and 2b shows the general view of the generator and a close-up view of the powder chamber respectively. The balance weights are also seen outside the pipe in Fig. 2a.

After completion of the generator, preliminary test was carried out succesfully in the premises of the Geological Survey Institute using the charges up to 50 g. Although a minor defect was found in the connection between pipe and stopper pins, this was improved immediately. The wave-forms of the generated SH-waves were excellent.

3. Field Test

In March, 1966, the field test of the generator and the seismic prospecting by means of the generated SH-waves were made in the river beach of Tone River, Narita City, Chiba Prefecture. The experiment was carried out as one of the projects for earthquake disaster preventions. The main purpose of our experiment was the actual test of the generator and to obtain the S-wave information in soil layers at the site. A conventional 24-channel tape recording system (SIE) with monitoring electromagnetic oscillograph was used. Natural frequencies of the seismometers used were 30 cps. Total system response is shown in Fig. 3. In the case of the recording, we did not use the filter. However, in case of playback, the high cut filters (H-27) were employed.

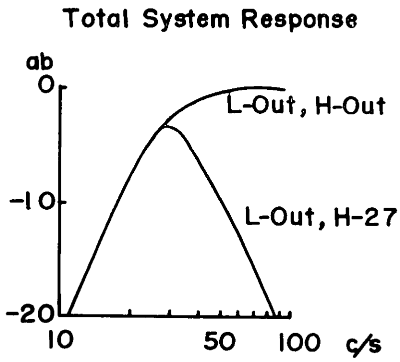

Fig. 3. Total system response.

According to the conventional seismic prospecting carried out at the same site, except the low velocity layer having the P-wave velocity 300 to 500 m/s from the surface to several meter depth, a rather uniform layer consisting of mainly sand and silt, velocity of which was 1400–1700 m/s, to 50–60 m in depth was clarified.

The items of our experiment were as follows:

i) Comparison of the recorded SH-waves generated from both our source and the one from the horizontal force by the hitting of the plate.

ii) Directivity test, through which we confirm that the predominant generated waves are SH-waves.

iii) Reproduction test of the events, and to see if we have any changes of the amplitudes and the periods of the generated wave-forms for various charges, and

iv) to check the maximum observable distance of the waves and the ultimate strength test of the generator.

Tests from i) to iii) were related to the stability of the generator, and also concerned the problem of the sharpness of the initial motions from which the fundamental information for the designing of Mark II generator was derived.

We had to carry out the experiments within a rather short period. Although defects of the generator were found, for instance in strength, results were fairly successful and encouraging. We are now planning the design of the Mark II generator, and experiments by means of it are expected in the near future.

Now a detailed explanation of the results will be given in the following.

3-i) It is well recognized that from the source by the hitting of the plate we will observe the SH-waves provided that we measure the horizontal components parallel to the direction of force. So as a handy test, the seismograms from both cases were compared and are shown in Fig. 4. Comparing them one will find that they are quite similar to each other in detail. It is interesting to note that the energy sources

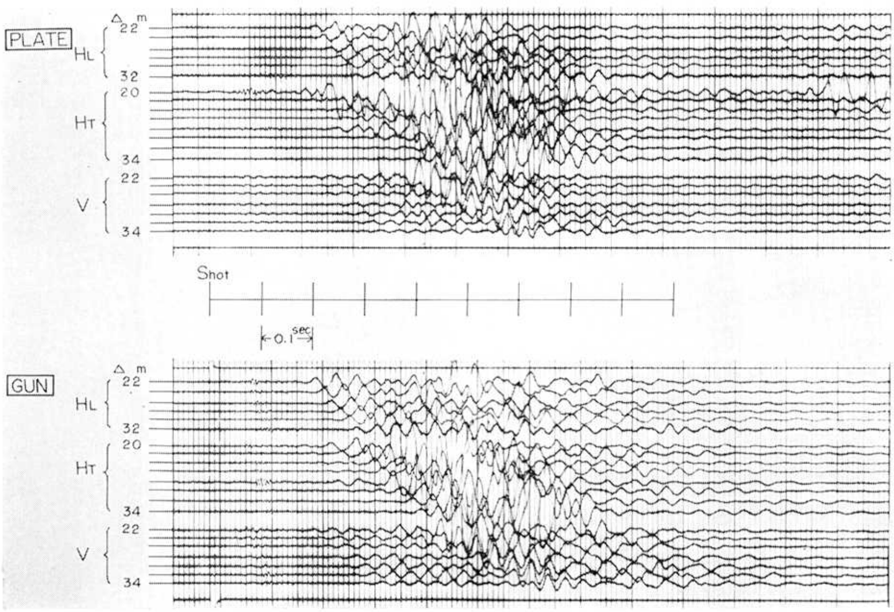

Fig. 4. Comparison of the records obtained from the SH sources, by hitting the plate (PLATE) and the generator (GUN).

in both cases were $100 \times 1/16$ g of dynamite and the human power at maximum strength, and hence the recording gains were the same, we certainly recognized the efficiency of the explosives. Further clear wave groups are seen in other components of the records. This type of situation is unavoidable because of the finite dimension of the generator. The point is, however, whether or not those generated waves are stable. We will cite this matter later on.

3-ii) From the point force being parallel with surface[5], one would expect that the SH-waves generated would have the maximum amplitude in the direction perpendicular to the force and would be absent along the direction of the force. To check this, transverse components of the events were measured along the circle of 30 m radius at every 30 degrees, the result being shown in Fig. 5. Unfortunately, detailed

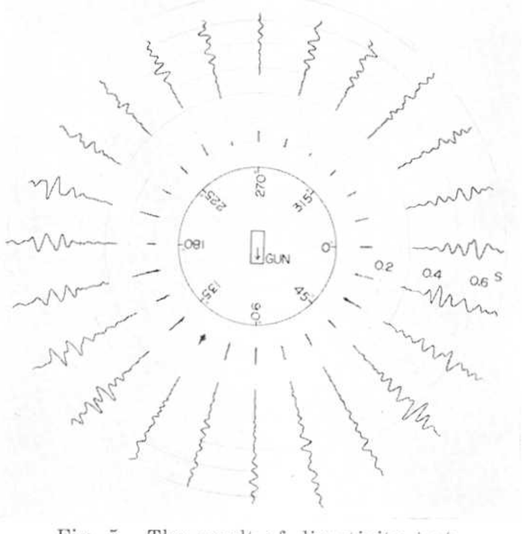

Fig. 5. The result of directivity test.

discussions of the data were difficult although the response characteristics of seismograms were corrected through the total system response. However, we could say that the general trend agrees with the above-mentioned expectation. As one may easily see, the SH-generator is the SV-generator as well provided that we measure the radial component of the events along the direction of the force. Including the above, we will examine the radiation pattern of the source more fully

5) J. T. CHERRRY, *Jr.*, *Bull. Seism. Soc. Amer.*, **54** (1962), 27-36.

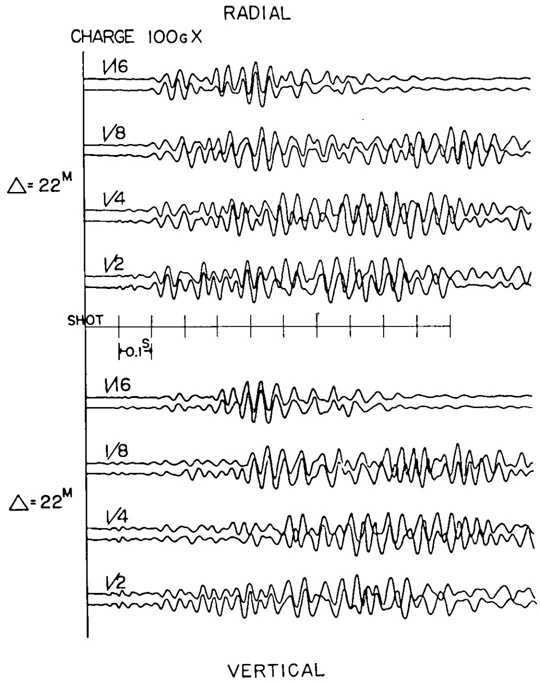

Fig. 6. Examples of reproduction test for both radial and vertical components.

by the use of the well calibrated seismograph system in the near future.

3-iii) For the reproduction tests of the events, and to see if there are any changes of the amplitudes and the periods of the generated waveforms for various charges, three components measurements were performed every 2 m interval between 22 m to 32 m. Charge sizes fired in this test were 100 g × 1/16, 1/8, 1/4 and 1/2, charges being fired twice in each charge size. The example of seismograms thus obtained are compared in Fig. 6 and Fig. 7. As far as the first portions of the records are concerned, one will notice that the similarities of the records are excellent in all cases even in vertical and radial components, although the degree of similarity increases in the order vertical, radial and transverse. From this we could safely say that our seismic source generated rather steadier waves than the one from the plate hitting mentioned before.

Now comparing the seismograms one will see that the duration of waves with appreciable amplitudes apparently increases according to the increment of charge sizes. However, this is caused by the fact that

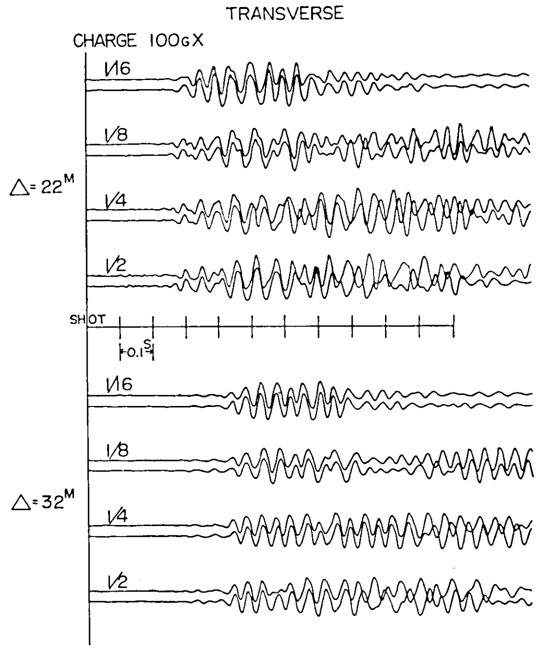

Fig. 7. Examples of reproduction test for transverse components.

the iron weights filled in the pipe are forced to jump out from it by the strong explosion pressure and hit the ground surface generating the secondary waves. Actually, only one weight jumped out from the pipe in the case of 100 g×1/16, but 4, 8 and all of them were pushed out in the cases of 100 g×1/8, 1/4 and 1/2 respectively. Examining the records at 32 m, one will easily recognize the secondary generated waves immediately after the first wave groups. This is why the similarity of the records in the latter portion becomes so much worse. From the practical point of view, however, these waves won't disturb the analysis. (cf. Fig. 8)

Usually in the case of a conventional shot we know that the amplitudes as well as the periods of the generated waves increase according to the increment of the amount of charges. We expected the same thing from our source. However, as one will recognize from Fig. 6 and Fig. 7, no appreciable changes were found. As far as the periods of the waves are concerned, we may say that the mechanism of conversion from the explosion to the seismic waves is completely different in our source compared with the conventional one, hence the increment of the charge size is not so effective in this matter. We also keep in mind as well that the response of our system is a kind of very sharp band-pass filter.

Now let us consider the mechanism of generation of the seismic waves from this type of source. We mentioned before that the shearing force is produced between the plate and the ground surface due to the explosion. The shearing force is nothing but a frictional force acting between them. The frictional force is mainly due to the pressure acting on the plate. The dead weight of Mark I generator is about 600 kg, which may not be sufficient weight for our experiment. When the impulsive explosive force is sufficiently large then it overcomes the frictional force and as a result the plate is forced to move. In our experiment, there was an indication to show that even in the case of $100\,g \times 1/16$ of charge the impulsive force was bigger than the frictional force. Hence we could say that the increment of charge did not increase the magnitude of the shearing force. In the designing of Mark II generator above-mentioned matter will be taken into consideration.

3-iv) Finally we will mention the test, which was one of the main object of our experiment, to check the maximum observable distance of the generated SH-waves and to obtain the S information at the site. The observations were made by the 30-cps seismometers up to 510 m distance from the source. One spread consisted of 17 seismometers, the seismometer intervals being 3 m up to 306 m (6 spreads) and 6 m from 306 m to 510 m (2 spreads) from the source respectively.

From the test mentioned in 3-ii), we did know that the dead weight of the generator was in sufficient, so to improve this situation a concrete block was laid under the plate. Charge sizes mainly fired were 25 g to 50 g. However, to test the ultimate strength of the generator itself, larger amount of charges such as 200 g and 300 g were also fired.

Up to 306 m, the events were recorded on magnetic tape. However, we had to use the conventional electromagnetic oscillograph farther than that distance because the S velocity was very slow and eventually took time to be detected, so we could not record the events within the prescribed length of magnetic tape which could record 4 sec duration from the instant of shot. This situation obstructed the later detailed interpretation of the seismograms. If the seismograms were recorded on the magnetic tape, we might have some way of separating the signals from the strong noises. Because of the high gain, noises due to the construction near the experimental site disturbed the observations farther than 200 m. Besides this, the rain-fall further disturbed the observations of the last 2 spreads. For convenience sake to see the seismograms as a whole the paste-up of low-gain playback records is shown in Fig. 8. The signal to noise ratio in this range (up to 200 m) is excellent and we could read off the first arrivals of SH-waves quite easily. Furthermore, one will find the predominant wave groups having the frequency around 15 cps and the phase velocity between 70 to 75 m/sec. At a glance, one may imagine that they are direct SH-waves. These wave groups are considered to be Love-waves, because there is a distinct difference between the phase velocity (70–75 m/sec.) and the propagation velocity of maximum amplitude (60 m/sec.). We must have observed the typical dispersion of the waves if we have used the broad band system for recording. The secondary generated waves mentioned in 3-iii) are not seen beyond 70 m or so. Further from the origin the

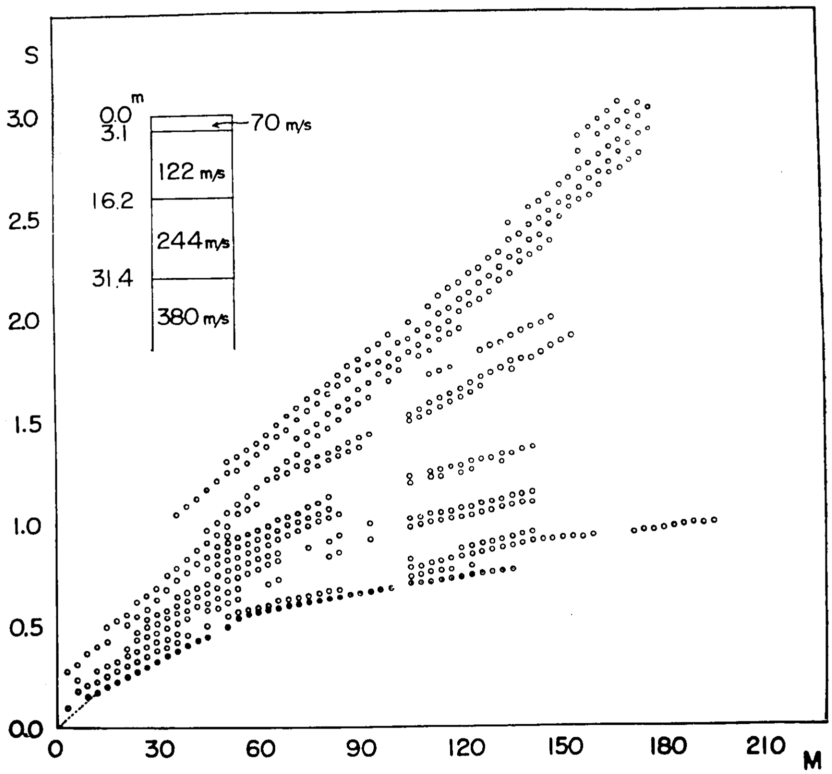

Fig. 10. Travel-time graph of the SH arrivals. The calculated underground structure is also shown.

high frequency (around 100 cps) signals with 330 m/sec. velocity forerunning the SH arrivals are seen. They are sound waves associated with the explosion. So the other signals are the ones purely associated with the SH-source, and comparing the waveforms with the ones from the conventional shots one will notice how simple they are.

Now to see clearly the initial portions of the SH-arrivals, we prepared Fig. 9 which was made by relatively high-gain playback. From the 5th spread, the initial portions of arrivals were not so clear because of the strong noises. However, the later phases were positively able to correlate all through the spread. If the observation was made in good conditions, we could easily correlate the initial motions up to 500 m or more. From Fig. 9 we read off the arrival times of wave groups a part of the results being shown in Fig. 10. S-wave velocities thus derived are 70, 122, 244 and 380 m/sec. respectively. The underground structure of the site was thus calculated and is shown also in Fig. 10, assuming the parallel layering although the spread was not reversed. The structure agrees well with the other derived data such as geological section, electrical resistivity and the N-value of the standard penetration test. No such good correlation was found from the conventional prospecting, probably affected by the high water contents of the subsoils. And this is one of the good reasons we have for studying the S underground structure as well.

4. Concluding remarks

The Mark I SH-wave generator and its field tests were introduced in this paper. It was proved that the generator was successful for producing the stable SH-waves, its capacity proving so excellent that the observable distance of the generated waves are greatly extended. However, the shortage of the dead weight of the generator itself was inconvenient for the study of how amplitudes as well as periods of the generated waves are affected by the increment of charges. When firing a big amount of charge a few weak points in the strength of the generator were revealed although these demerits can be easily improved. We are now designing the Mark II generator taking advantage of the above-mentioned experiences and will continue the improvements until we arrive at the design which can be used widely for the S wave seismic prospecting.

Finally, derived S information insitu is summarized in Fig. 10 (cf.

[Bull. Earthq. Res. Inst., Vol. 45, Pl. 3]

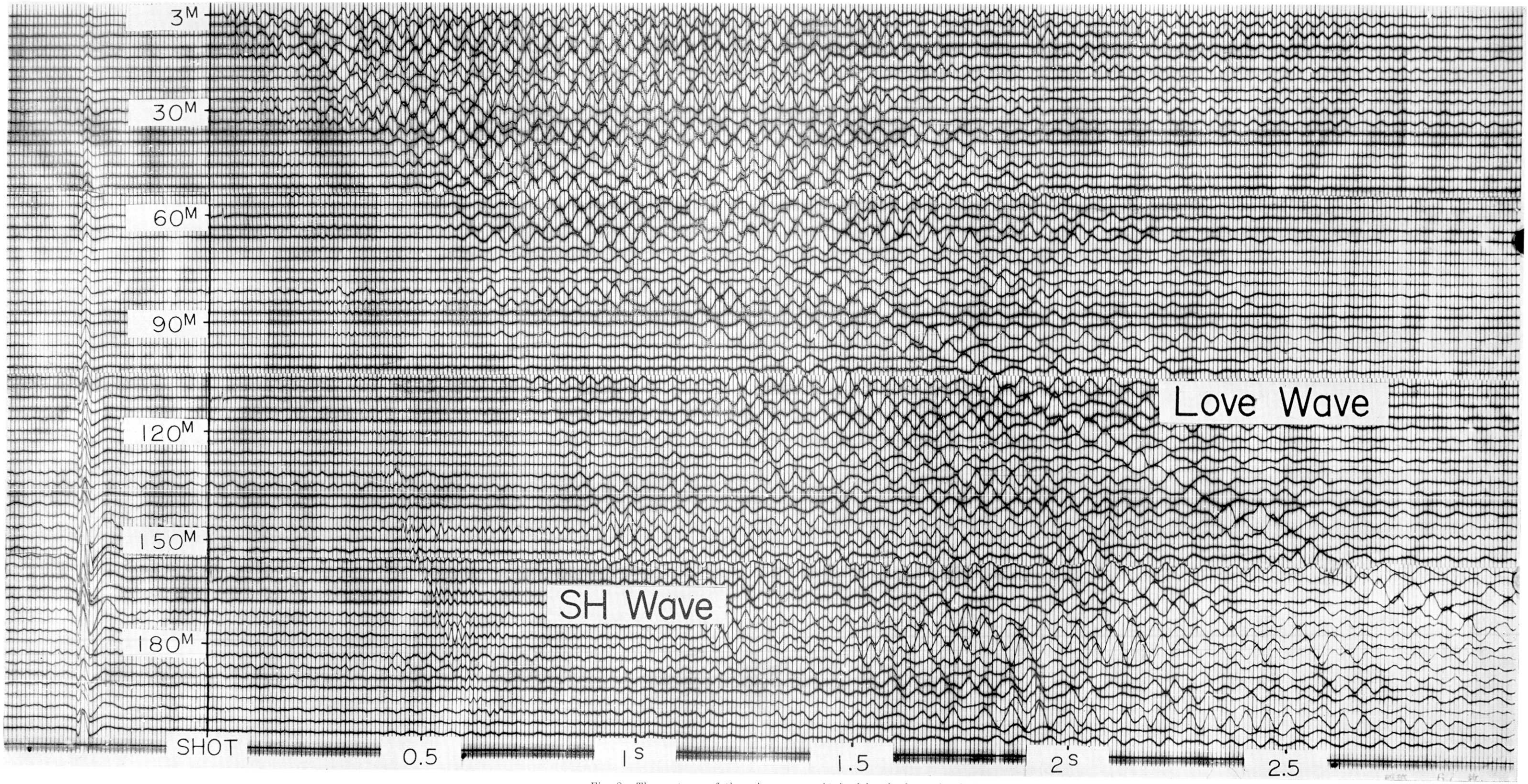

Fig. 8. The paste-up of the seismograms obtained by the low-gain playback.

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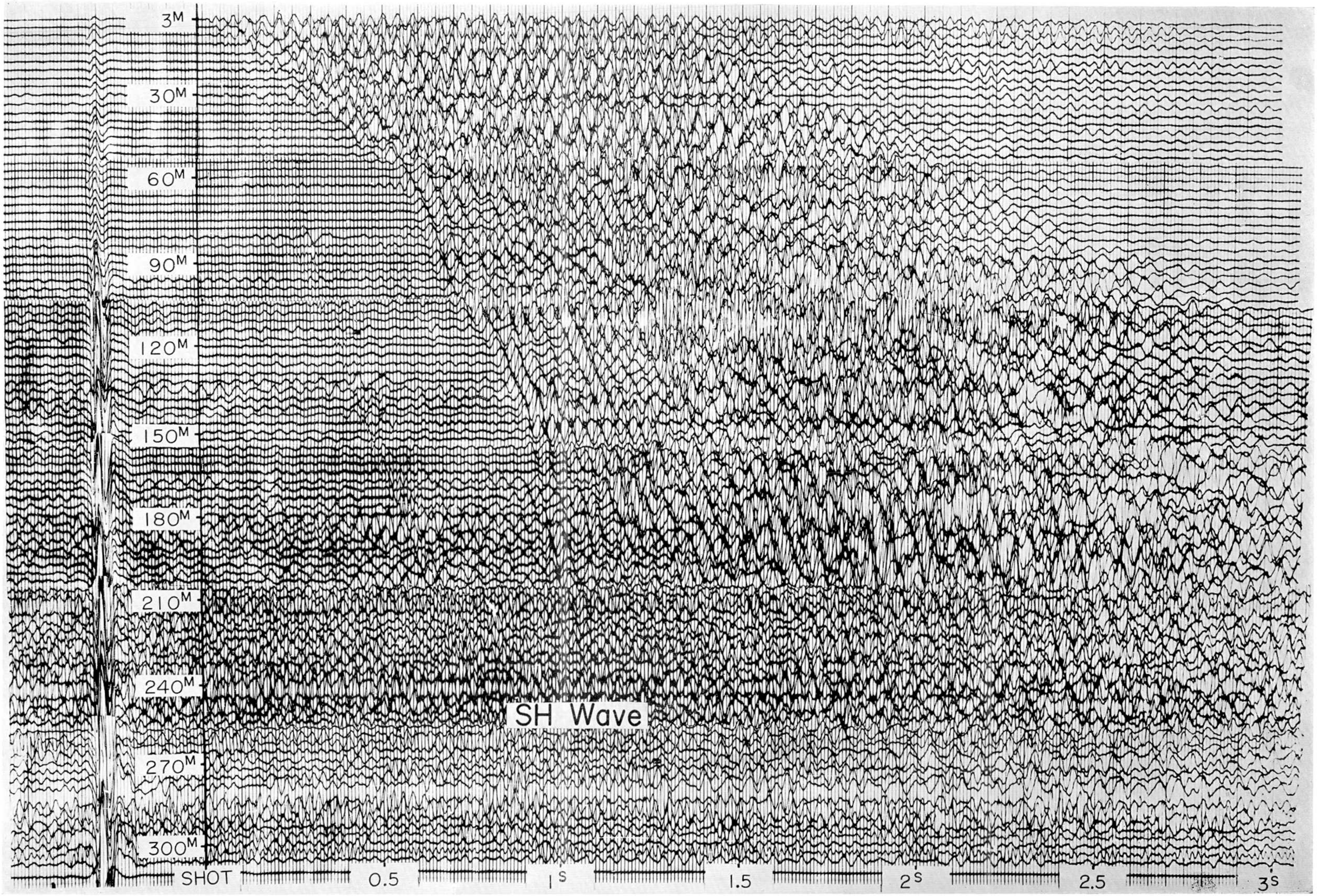

Fig. 9. The paste-up of the seismograms obtained by the high-gain playback.

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Fig. 8 and Fig. 9). Through this study we felt keenly the necessity of S wave seismic exploration. More quantitative study on this matter is certainly indicated.

5. Acknowledgements

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3. S波の発生と伝播に関する実験的研究 I
SH波発生装置の試作とその実験

地震研究所 嶋 悦三
太田 裕

現場的にS波速度を知る測定方法開発の要求は地震工学の分野において特に著しい.

これに応えるため，今回火薬利用のSH波発生装置を作成し，利根川河川敷でテスト実験を行った. 実験は先ず，板叩きの方法による記録との比較，指向性テストによって，SH波発生を確認し，次いで火薬量変化，再現性テストを行なうことによって，本装置が毎回安定したSH波を発生していることを知った.

最後にSH波到達距離の実験を行なったところ，初動は距離200m以遠まで極めて明瞭であった. また，初動に続く波群は測定した全区間500mに至るまで認められた.

なお，実験中に装置の1部に強度不足が見出されたが，この点を改良することによって本装置は十分実用となり得ることが判った.